

# Residual Stress Process Simulation Committee Progress Report

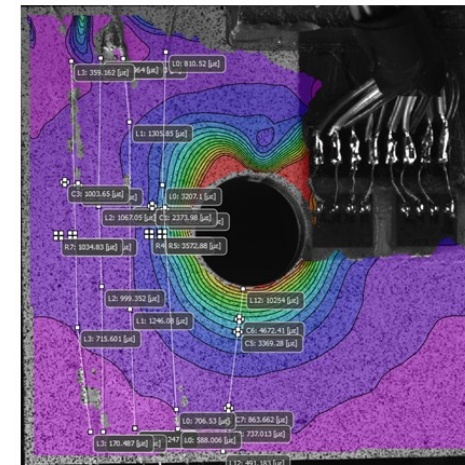
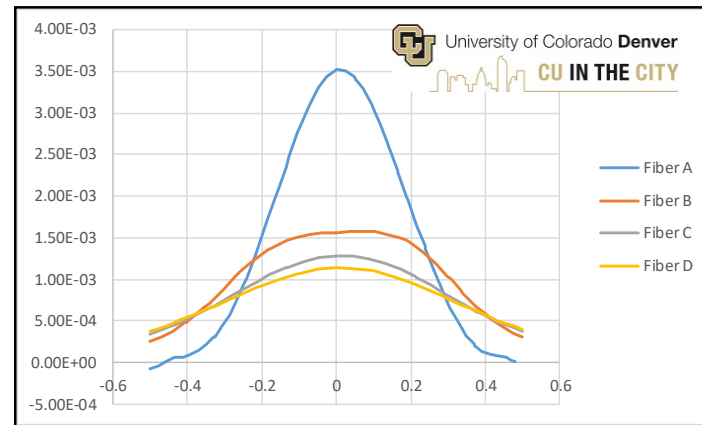
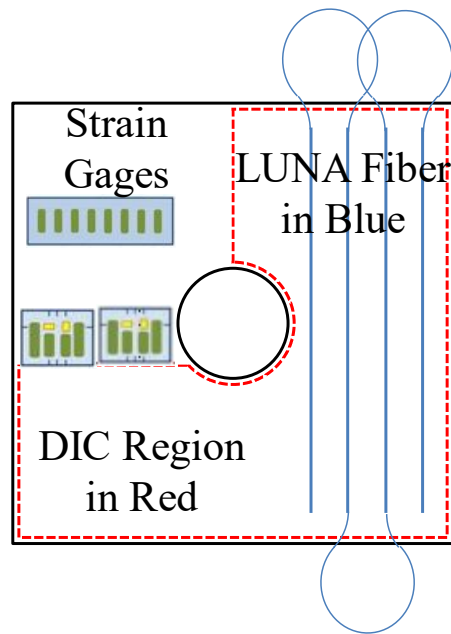
Engineered Residual Stress Implementation Workshop 2019

Layton, Utah, USA

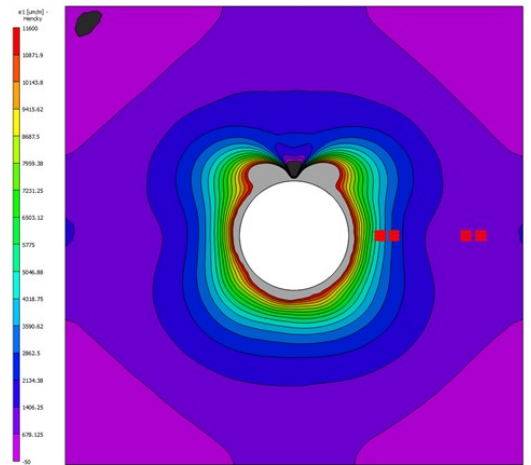
September 12, 2019

# Outline

- Committee Activity and Roster Updates
- Material Testing Update – 7075
- Process Simulation Round Robin



DIC Hoop strains



FEA Hoop strains  
Chaboche Hardening

# Committee Activity & Roster Updates

- Survey December 2018
  - Set Monthly Meeting to 3<sup>rd</sup> Friday of each month
  - Move forward with round robin
- Monthly Meetings – thank you for participation
- Welcomed a number of new committee members

Chris Allen, Booz Allen Hamilton

Eric Greuner, LM Aero

Andrew Jones, USAF

Gavin Jones, SmartUQ

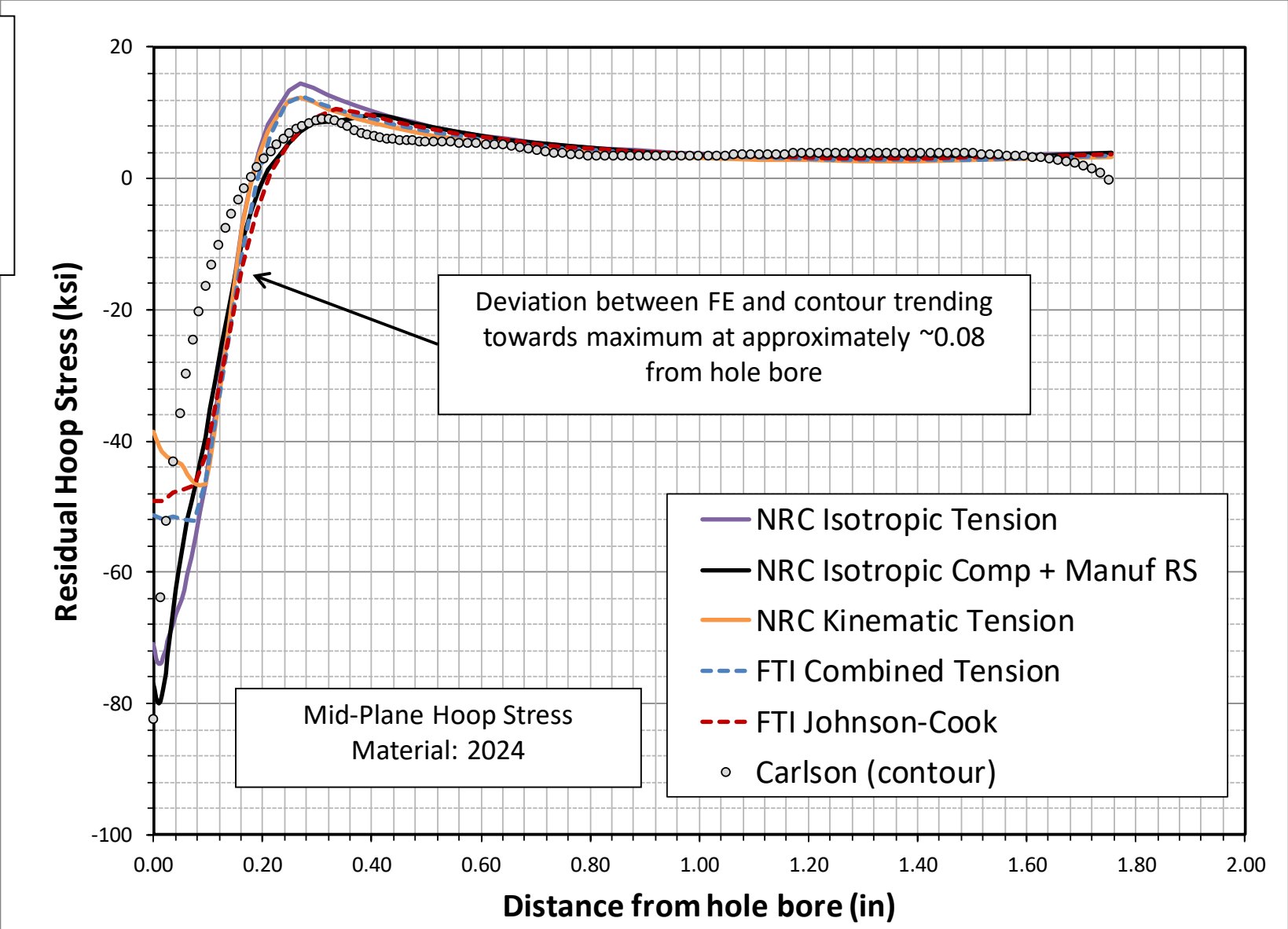
Thuy Nguyen-Quoc, Boeing

Dr. Mike Steinzig, LANL

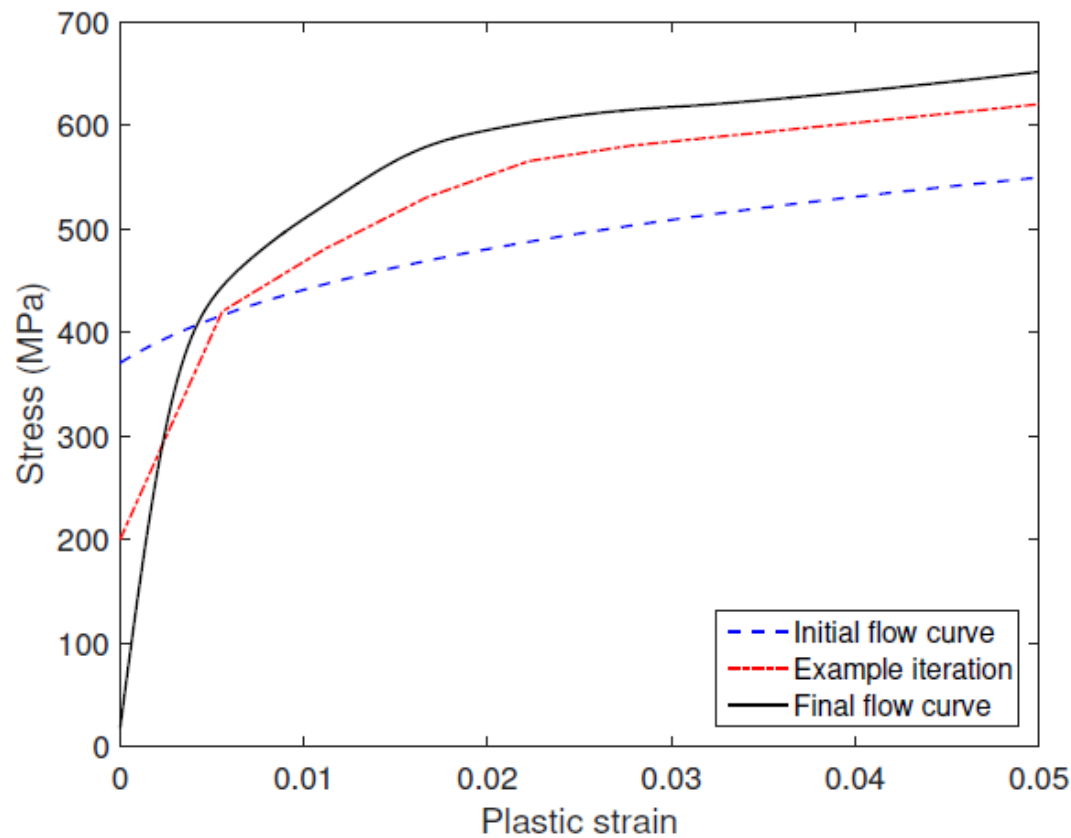
Michael Worley, SwRI

# Material Model Testing - Purpose of Program

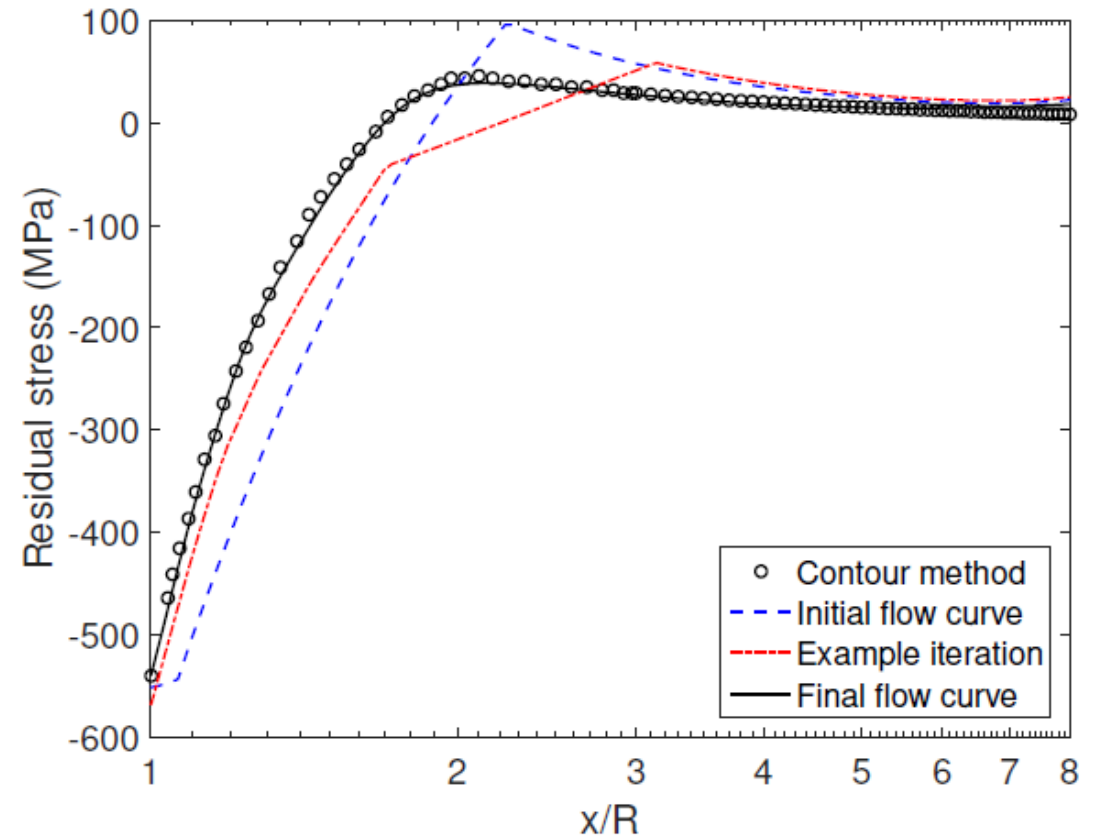
Which constitutive model is most appropriate?



# Material Model Testing - Purpose of Program



(a)



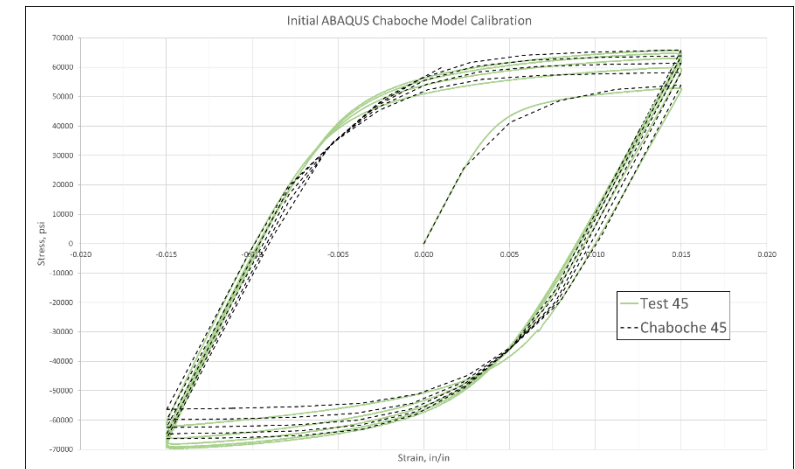
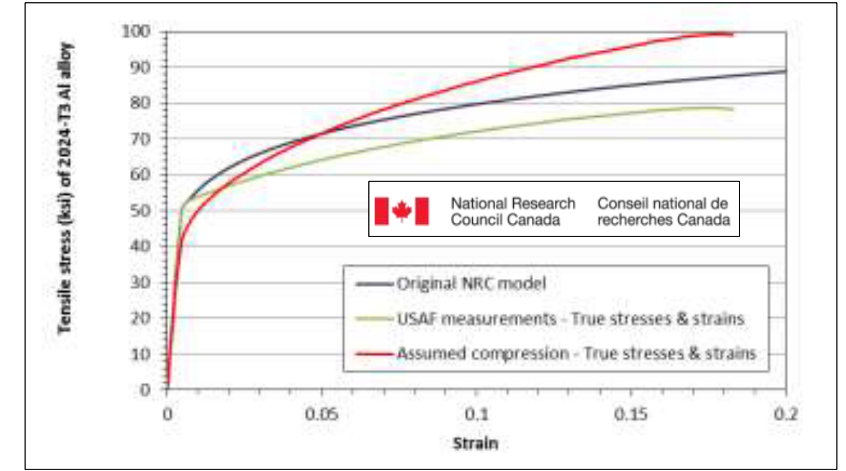
(b)

Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ( $\sigma_{\theta\theta}$ ); note log scale on  $x/R$

Ribeiro, Renan L., and Michael R. Hill. "Residual Stress From Cold Expansion of Fastener Holes: Measurement, Eigenstrain, and Process Finite Element Modeling." *Journal of Engineering Materials and Technology* 139.4 (2017): 041012. <https://doi.org/10.1115/1.4037021>

# Material Model Testing – General Plan

- Based upon E606 LCF, up to  $\pm 4\%$  in./in., reduced to  $\pm 1.5\%$
- Isolating current investigation to orthotropy
- 2024 testing complete 2018
- Currently testing 7075, complete early fall 2019



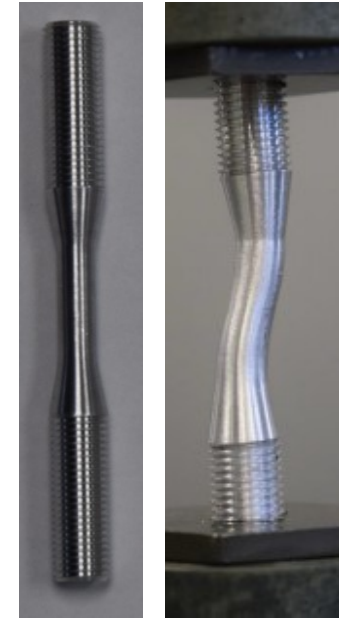
# Material Model Testing – Previous Results, 2024

Chaboche Parameter	<b>NRC-CMRC</b>	<b>NRC-CMRC</b>	<b>NRC-CMRC</b>	<b>NRC-CMRC</b>	Clausen, et. al.*
	Long.	Trans.	45°	Avg.	
$\sigma_{ys}$ , psi	30281	28942	32786	30670	31894
<b>C</b> , psi	7.35e6	8.69e6	8.19e6	8.08e6	9.74e6
$\gamma$	346.88	412.96	399.09	386.31	412.0
<b>Q</b> , psi	21202	21042	20526	20923	23637
<b>b</b>	3.37	3.85	5.53	4.70	7.00
<b>E</b> , psi	10.56e6	10.36e6	11.10e6	10.67e6	10.62e6
$\epsilon$	0.33	0.33	0.33	0.33	0.33

# Material Model Testing – Lessons Learned: 2024 to 7075

## 2024 coupons

- Typical ASTM 606 cylindrical design
- Started to rotate/bend at compressive strains of  $\sim 1\%$
- Rotation of the cross-section was detected using a video camera



2024

## 7075 coupons

- Thick rectangular cross-section to ease detection of bending or rotation
- Dual clip gauge to monitor strain on both surfaces



7075



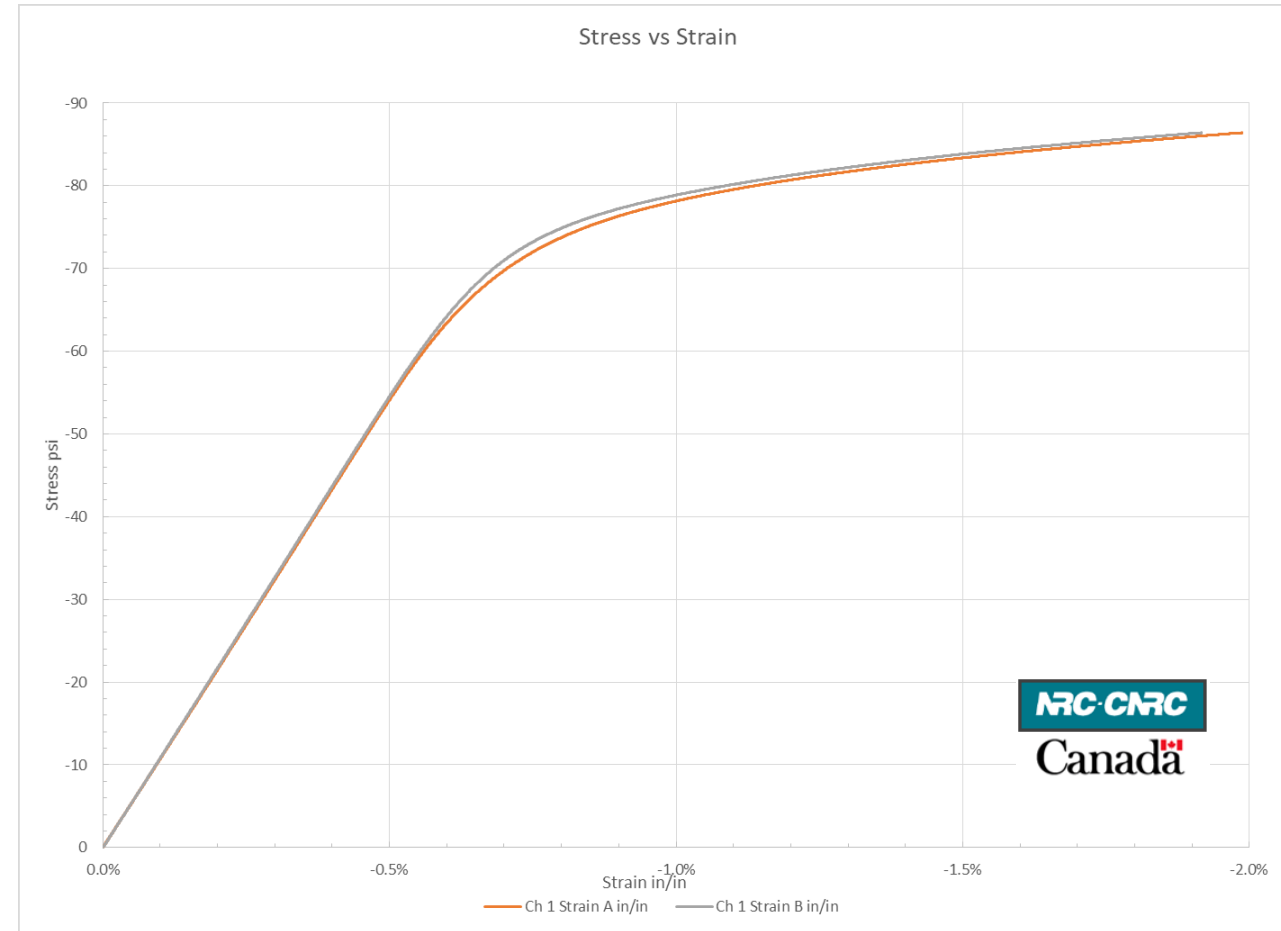
# Material Model Testing – 7075 Modifications

- Initial trials showed strain measurement start diverging at approx. 1.5% strain
- Can we still use the average of the two strains to generate material data  to be verified with FE modeling
- Modifications were made to improve the results:
- The coupons were shortened
- A piston guide for compressive loads was designed and manufactured



# Material Model Testing – Current 7075 Status

- Relatively uniform compressive strains up to 2% (limit of the current clip gauges) can now be measured.
- Clip gauge that can go up to 10% strain are currently being installed. Will be tested soon.
- Methods to avoid clip gauge slipping will be tested.
- Once the max uniform measurable compressive load is known, discussion will take place with the committee about the test levels and 1-cycle tests will be performed.



# RS Process Simulation Round Robin

- Open to anyone, high interest!
  - Abaqus, StressCheck
  - Pending from MARC, closed form
- Analysis of the 2"x2" coupon cold expansion
  - See right for coupons of interest
  - Current compilation limited to 2024-L2
- Multiple measurement techniques offer a unique opportunity for process simulation validation and correlation.

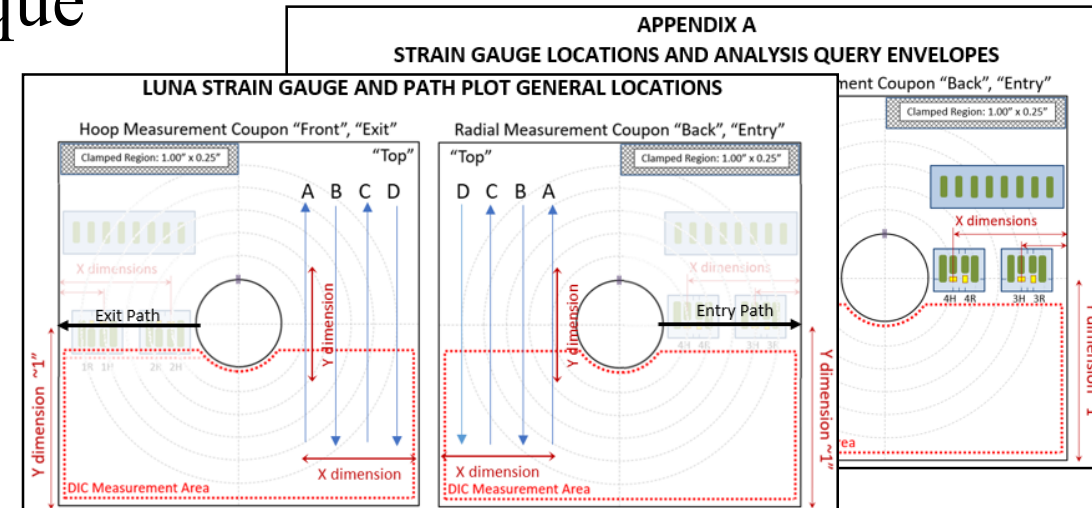
Coupon Name	Target Applied Expansion Level	Sleeve Orientation (0° = vertical)	Measured Starting Hole Diameter (inch)	Measured Plate Thickness (inch)	Mandrel Major Diameter (inch)	Sleeve Thickness (inch)	Final (Post-ream) Hole Diameter (inch)
"2024-L2" 2024-Cx-DIC/LUNA/XRD/CM/SG-02-L2	3.16	10.0°	0.4775	0.253	0.4684	0.0120	0.5000
"2024-H1" 2024-Cx-DIC/LUNA/XRD/CM/SG-03-H1	4.16	-1.2°	0.4743	0.254	0.4697		
"7075-L1" 7075-Cx-DIC/LUNA/XRD/CM/SG-01-L1	3.16	3.2°	0.4769	0.252	0.4684		
"7075-H1" 7075-Cx-DIC/LUNA/XRD/CM/SG-03-H1	4.16	-9.5°	0.4741	0.251	0.4697		



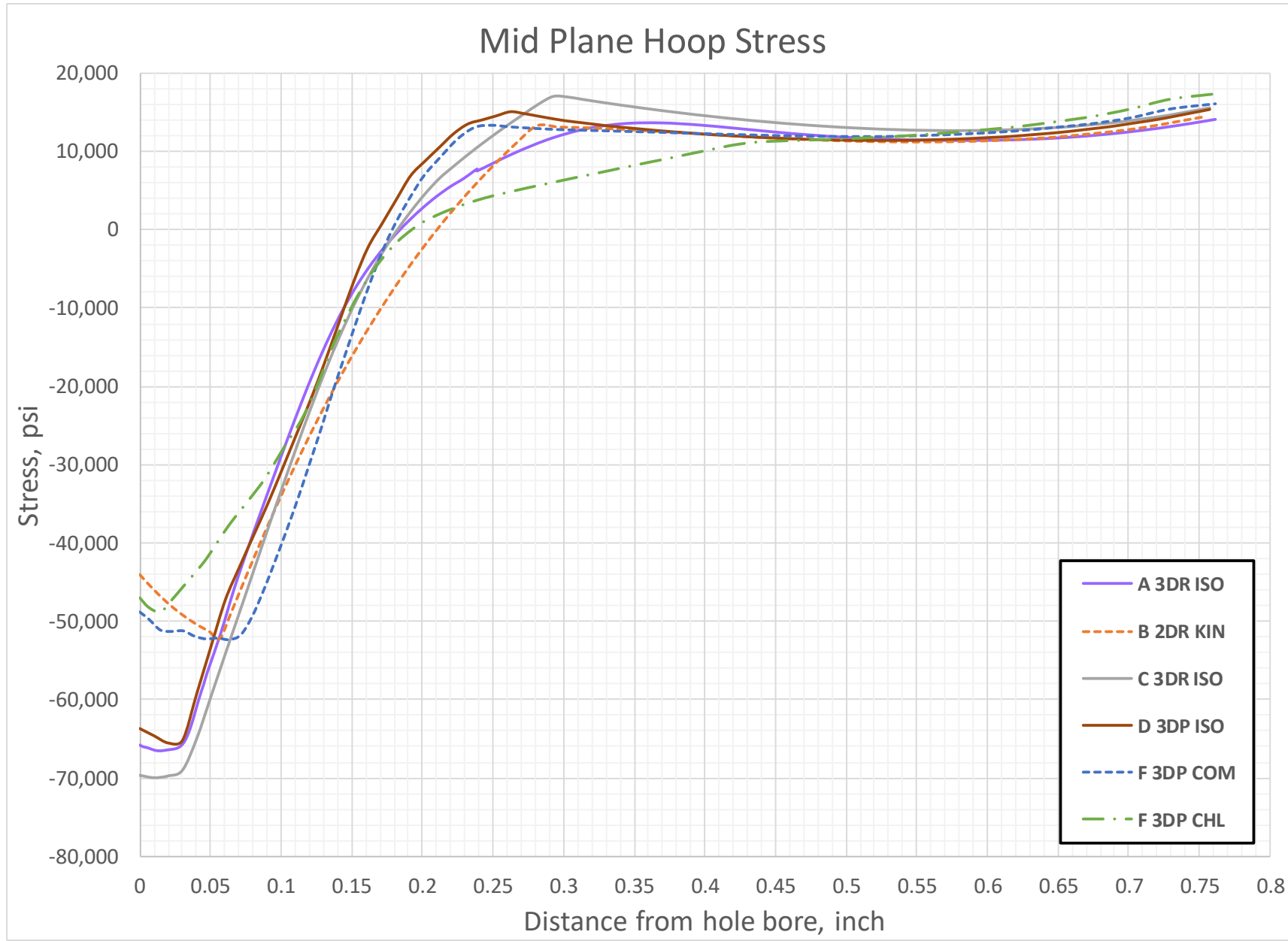
**HILL ENGINEERING**  
Predict. Test. Perform.



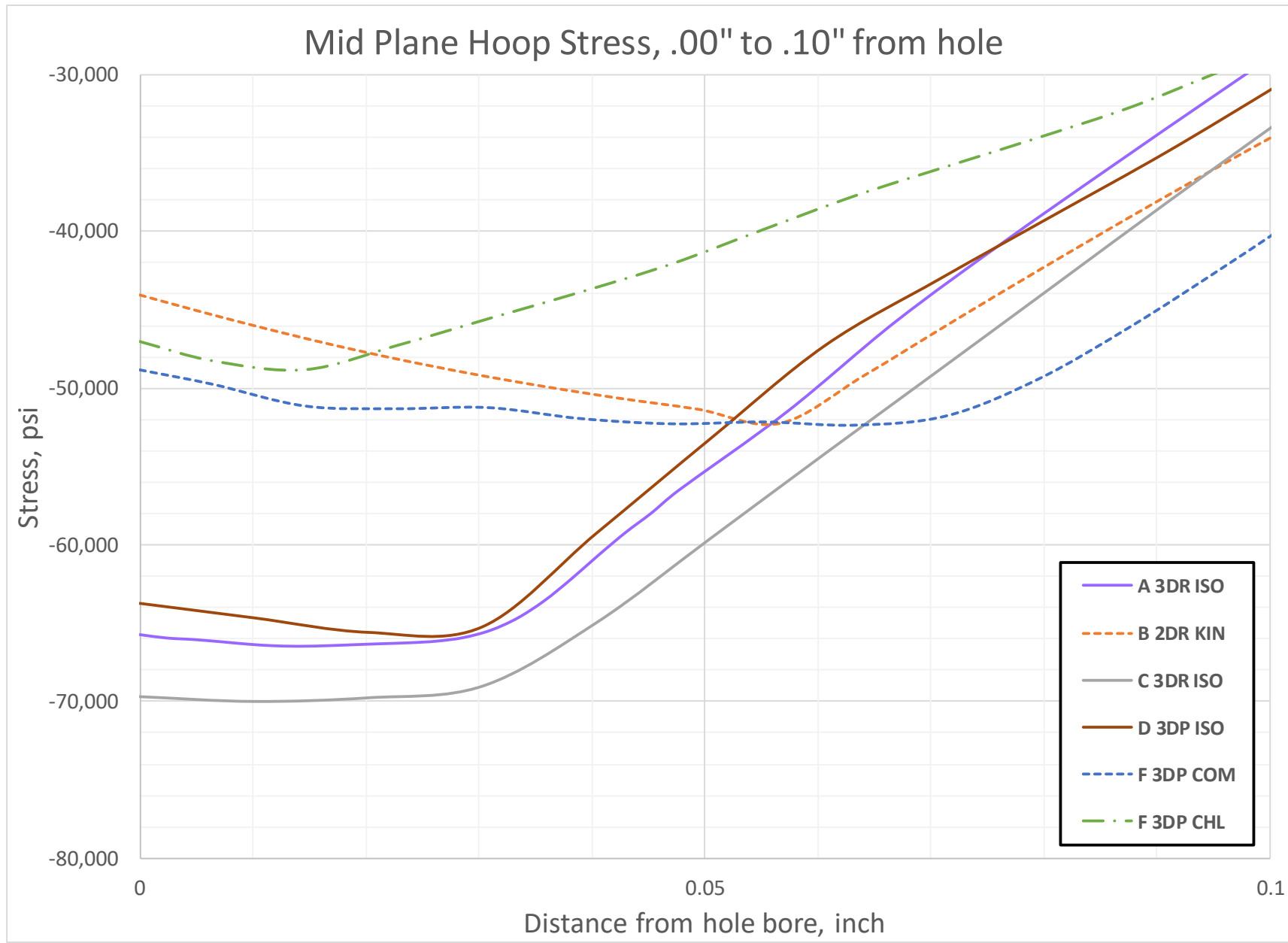
University of Colorado Denver  
**CU IN THE CITY**



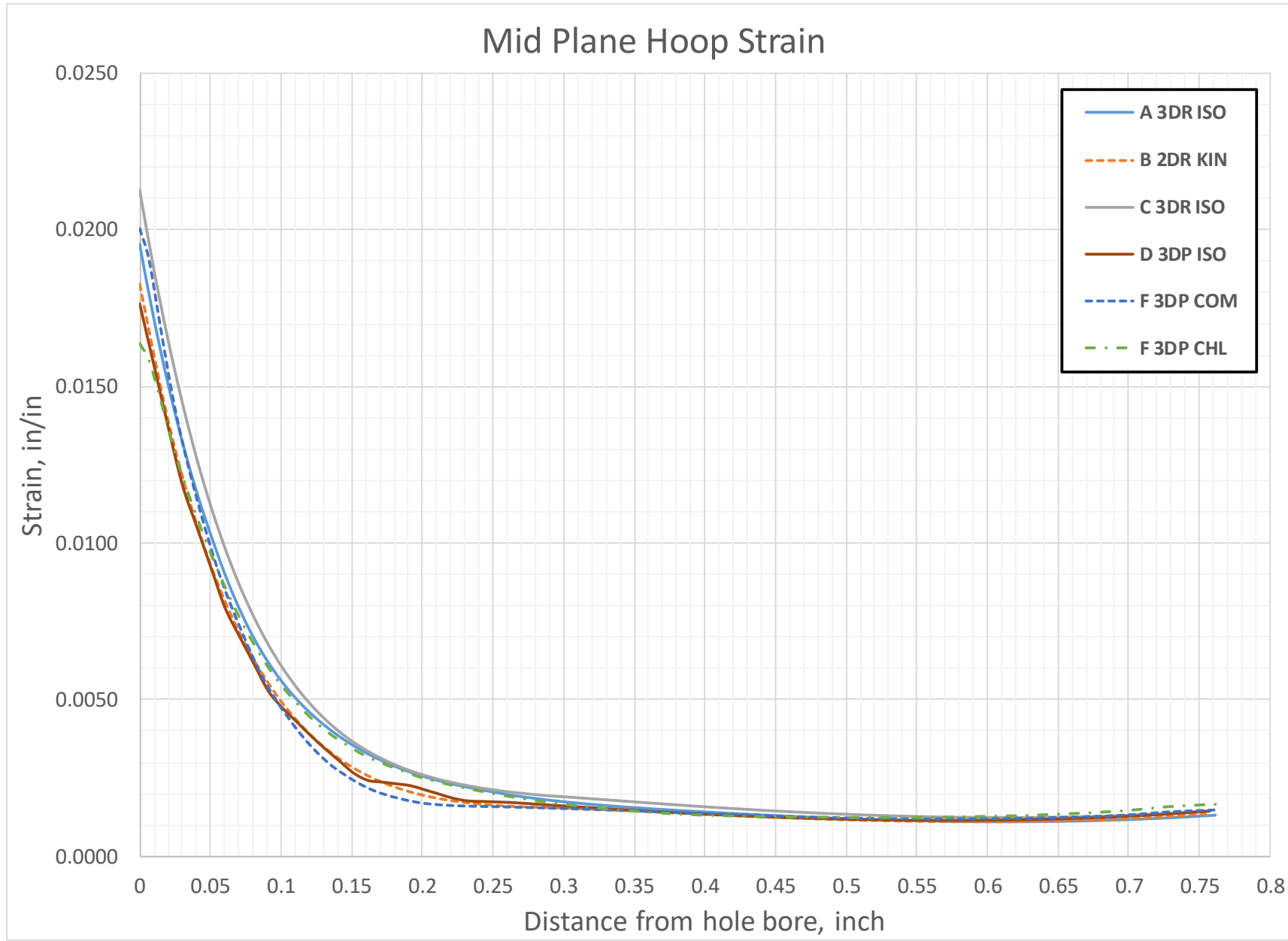
# RS Process Simulation Round Robin – Results



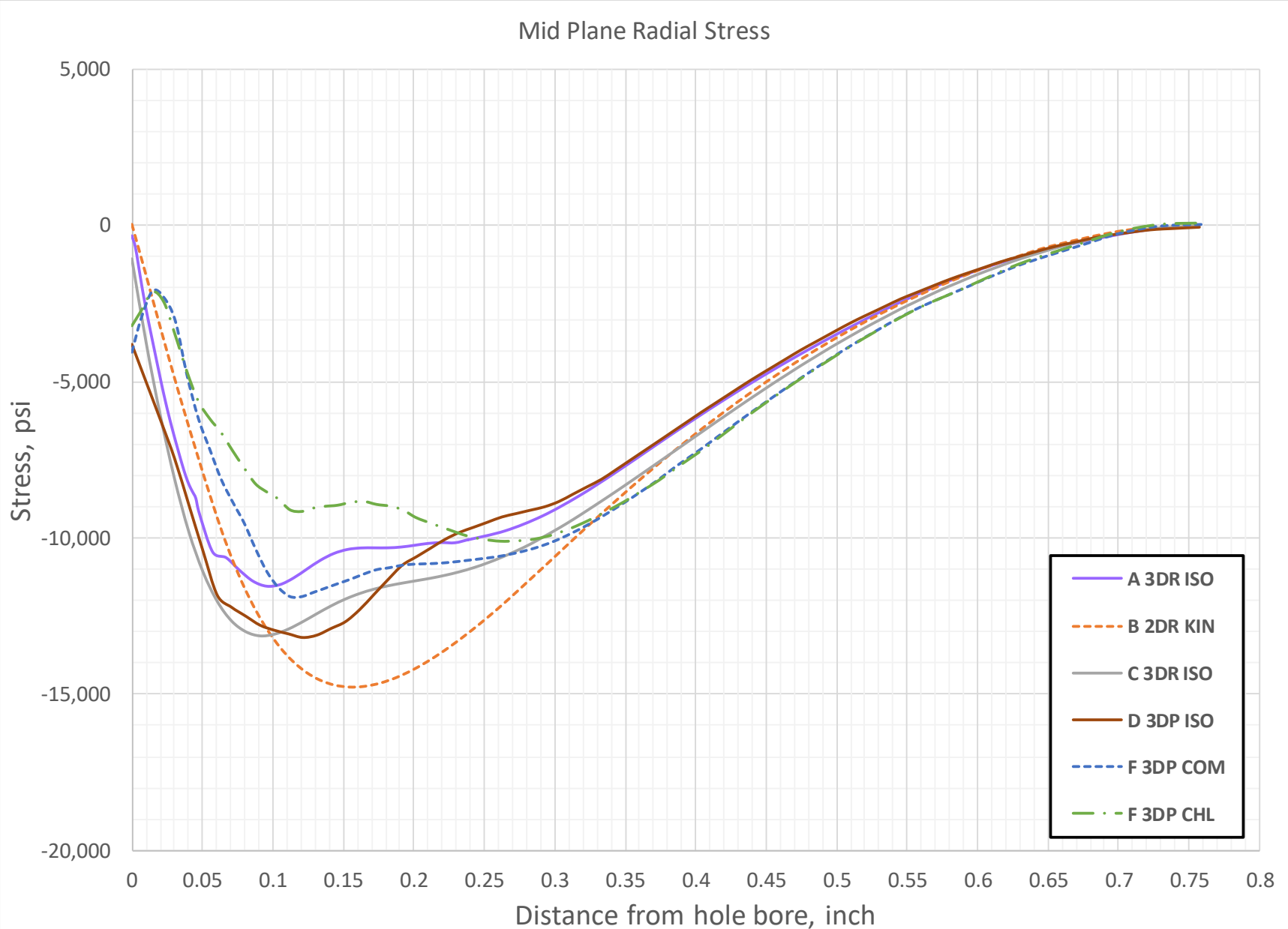
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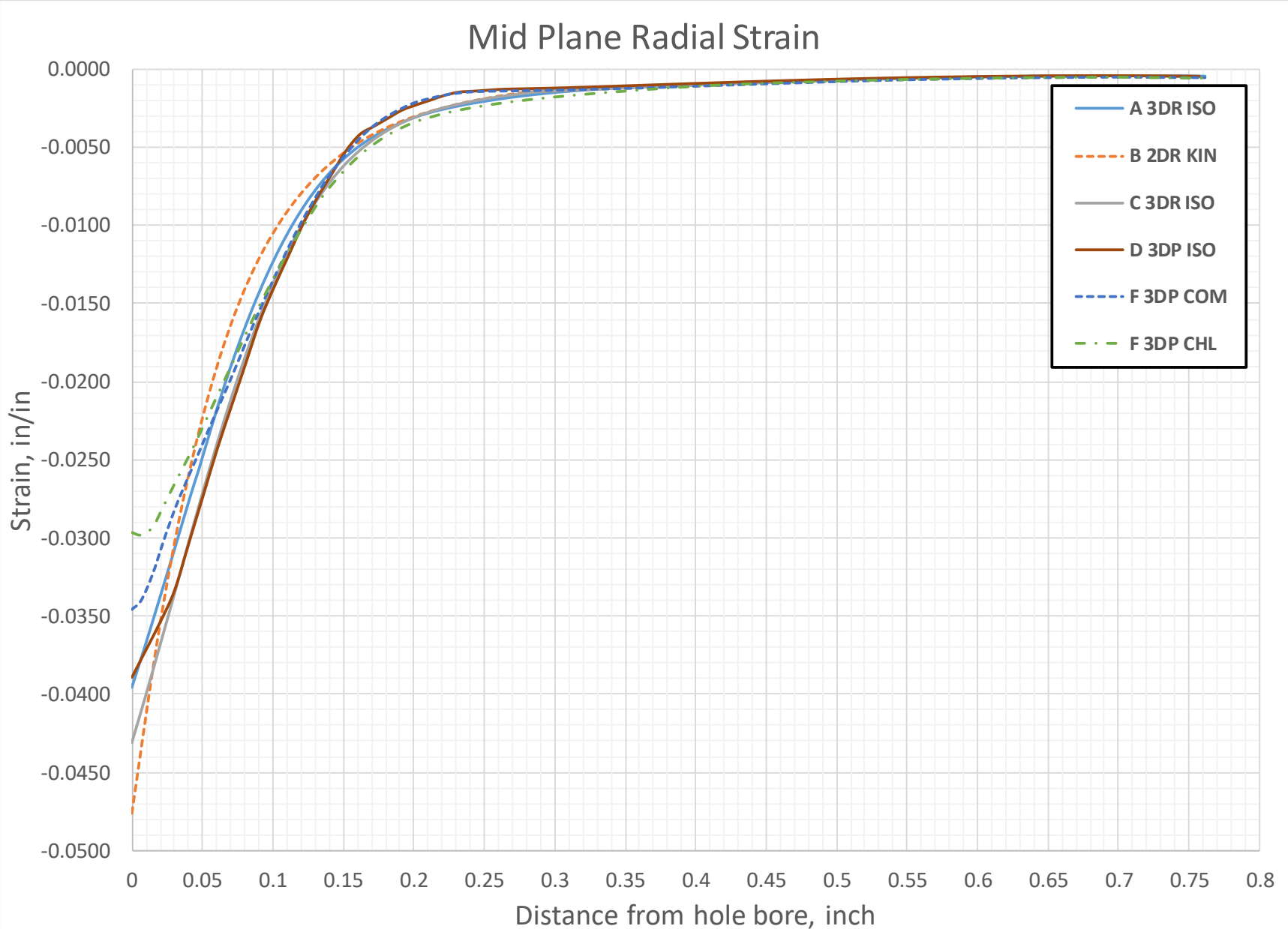
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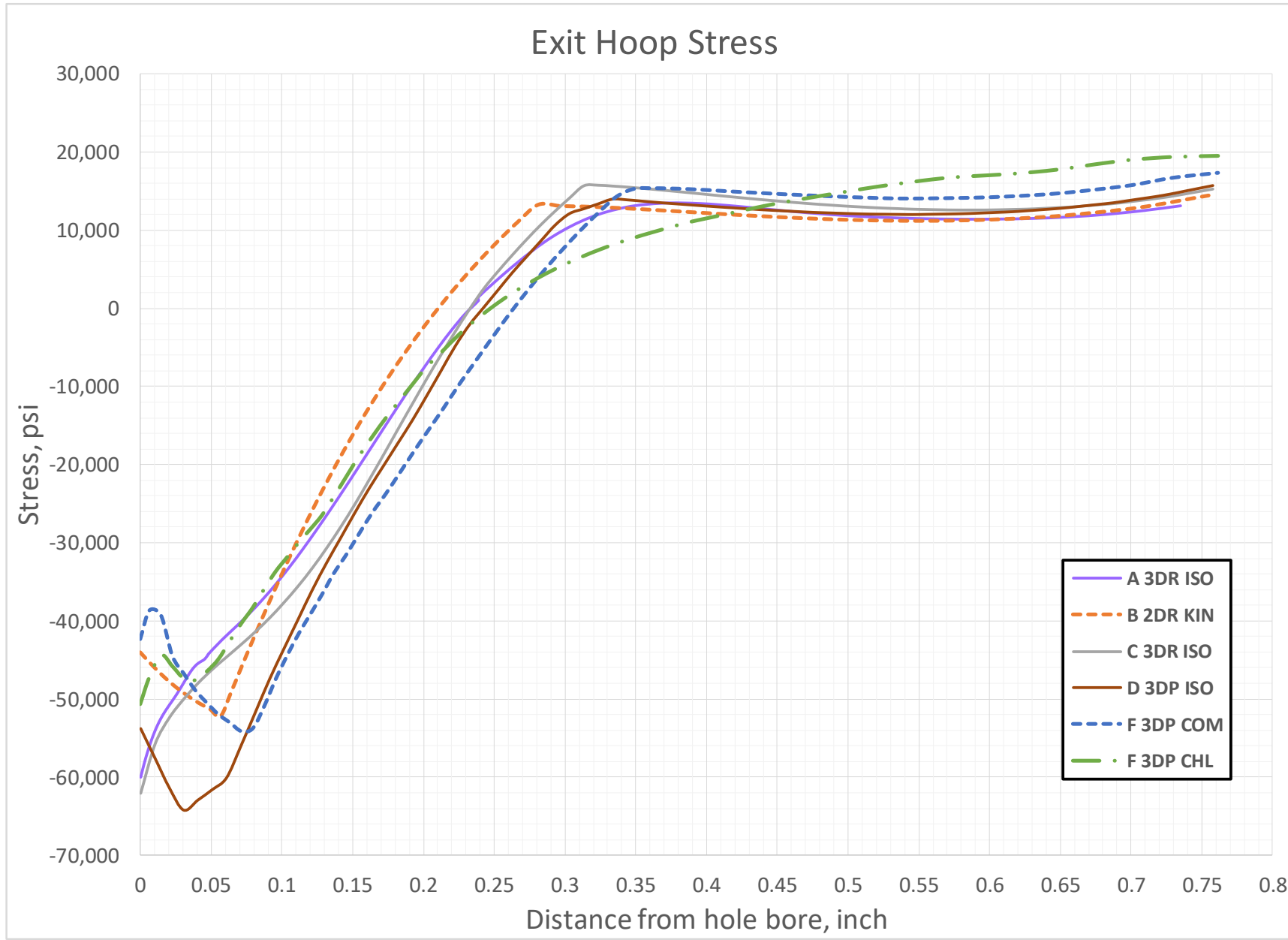


# RS Process Simulation Round Robin – Results





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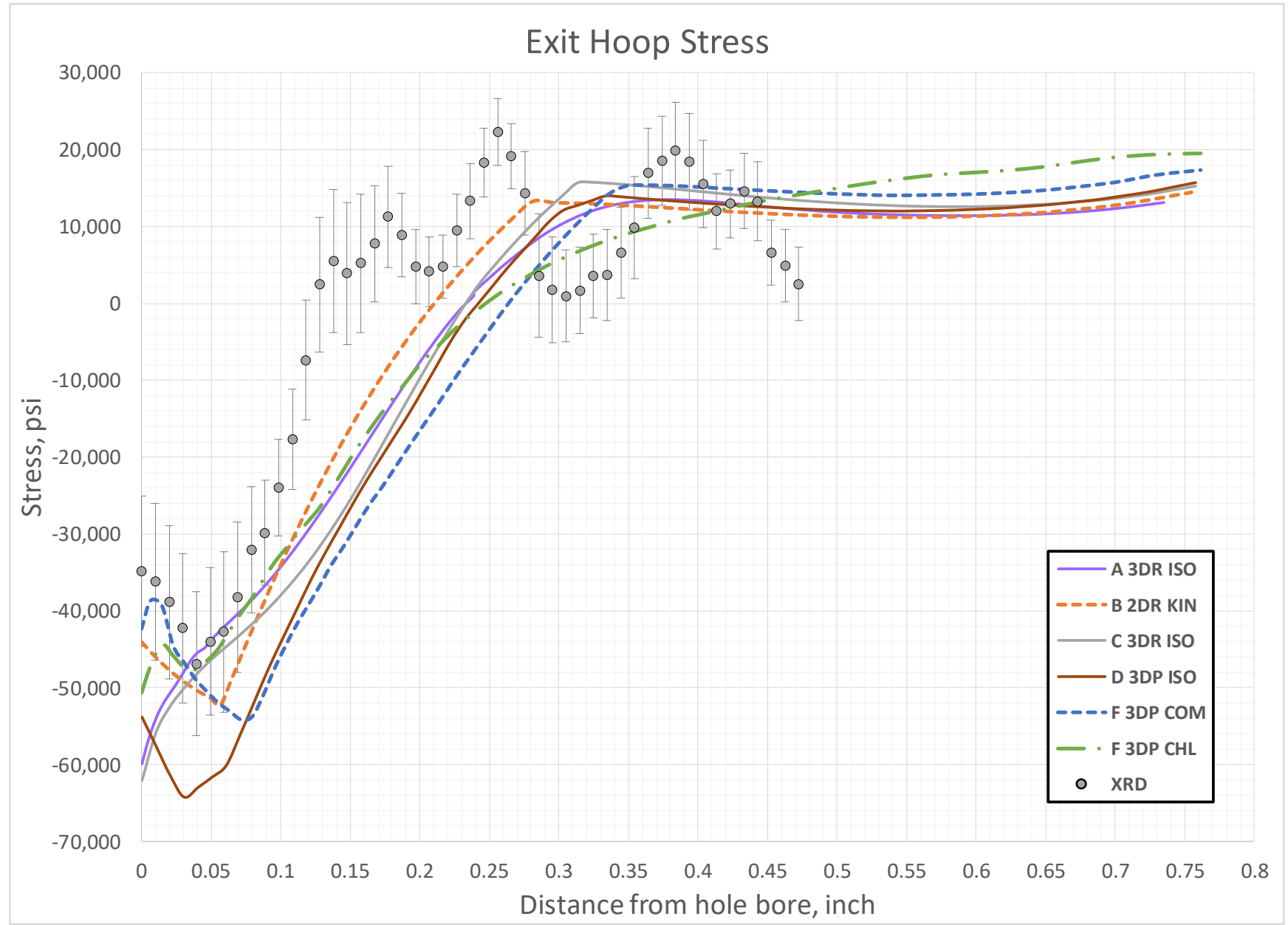


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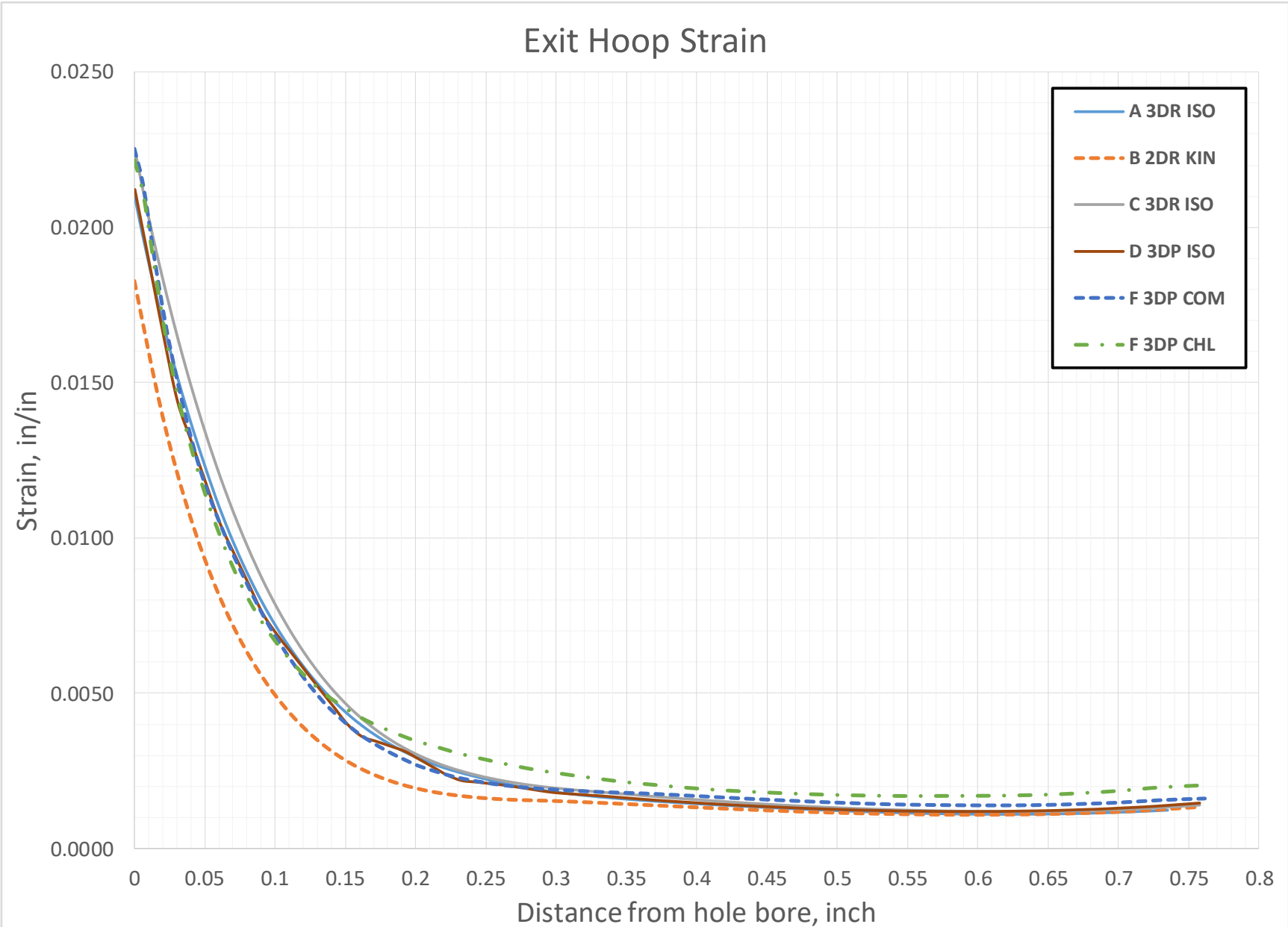


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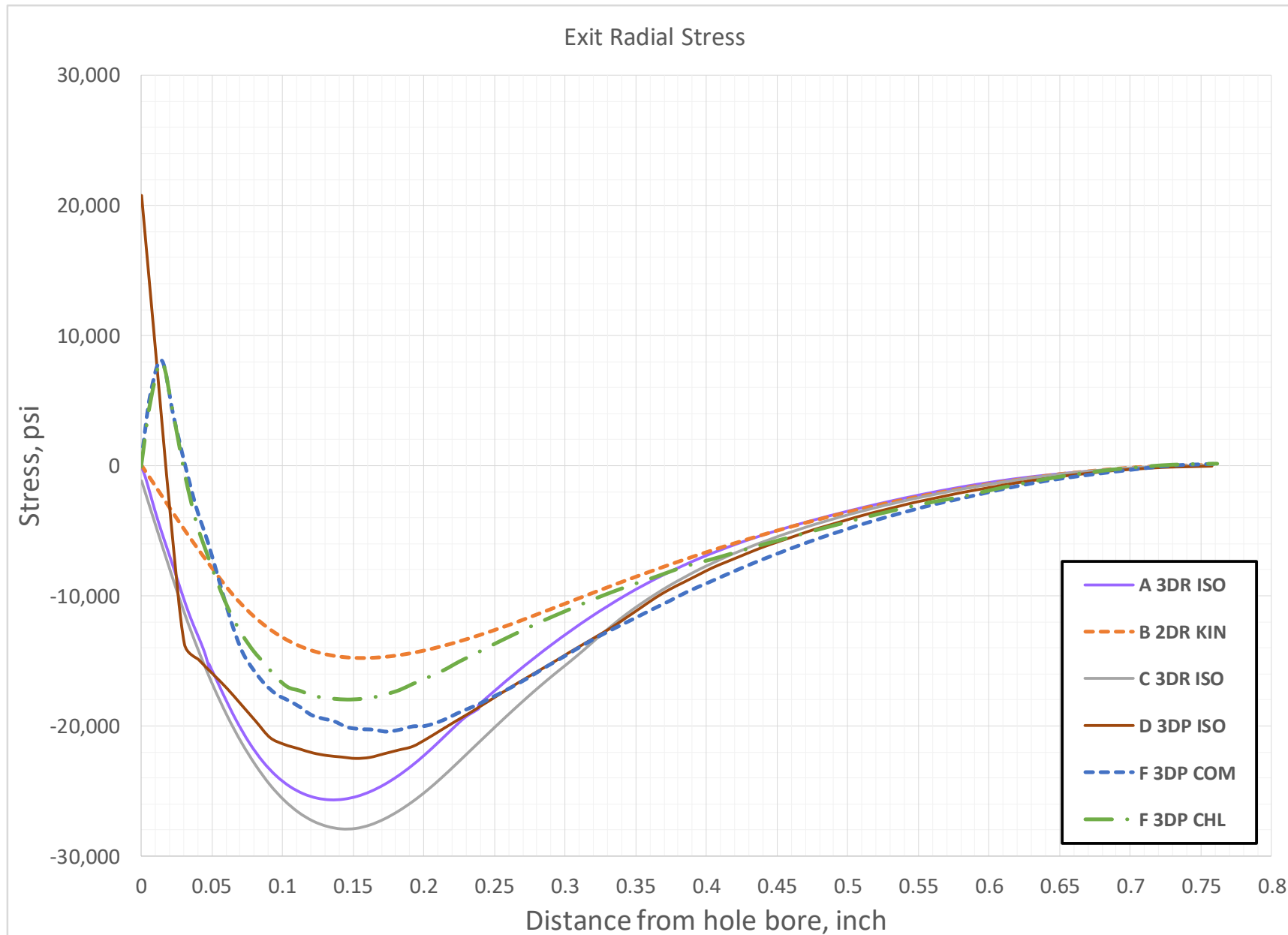
	L norm	Cosine
A 3DR ISO	0.7461	0.2223
B 2DR KIN	0.5904	0.1415
C 3DR ISO	0.8338	0.2700
D 3DP ISO	0.6500	0.1824
F 3DP COM	0.9030	0.3140
F 3DPCHL	0.6703	0.1920



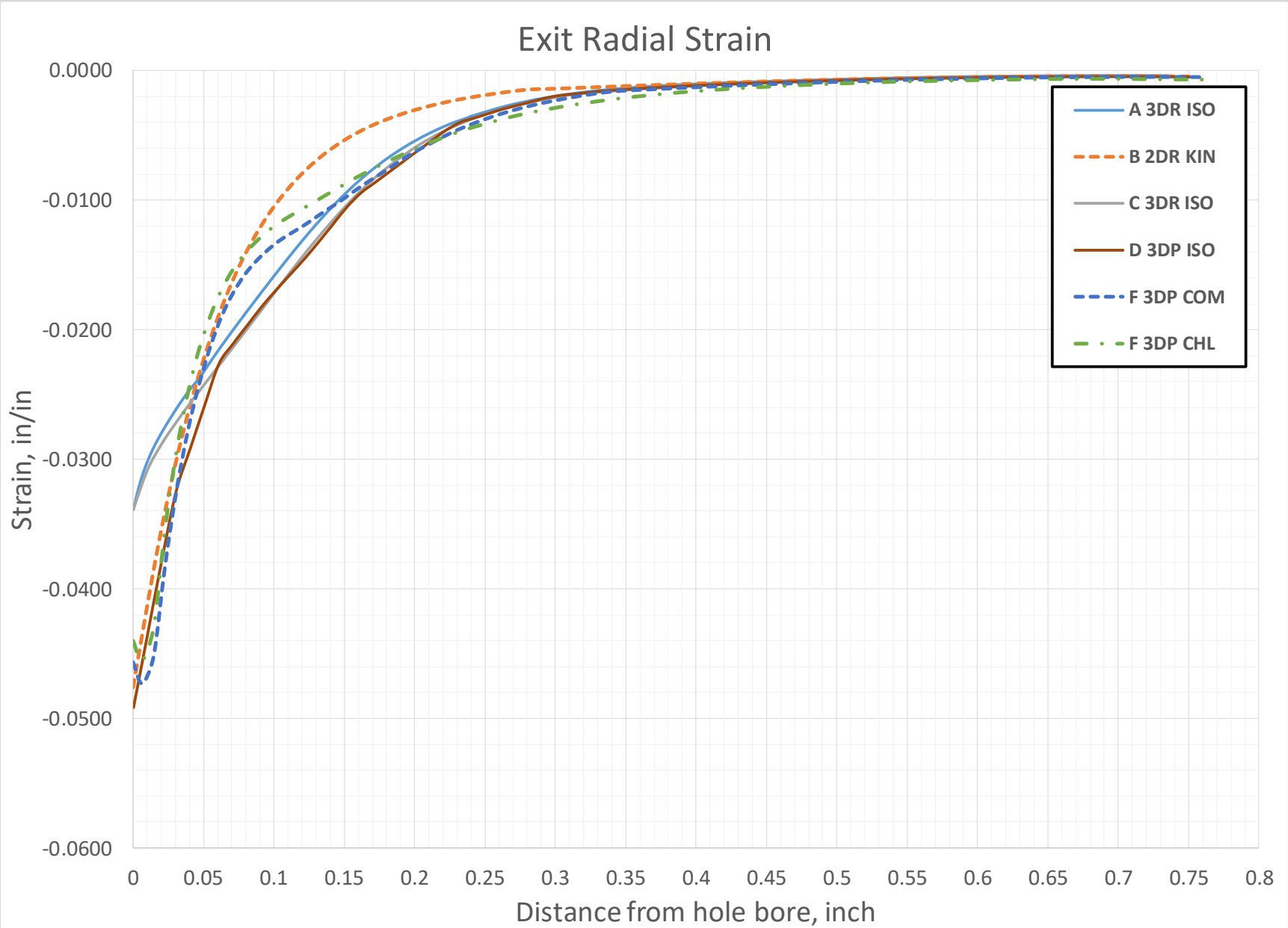
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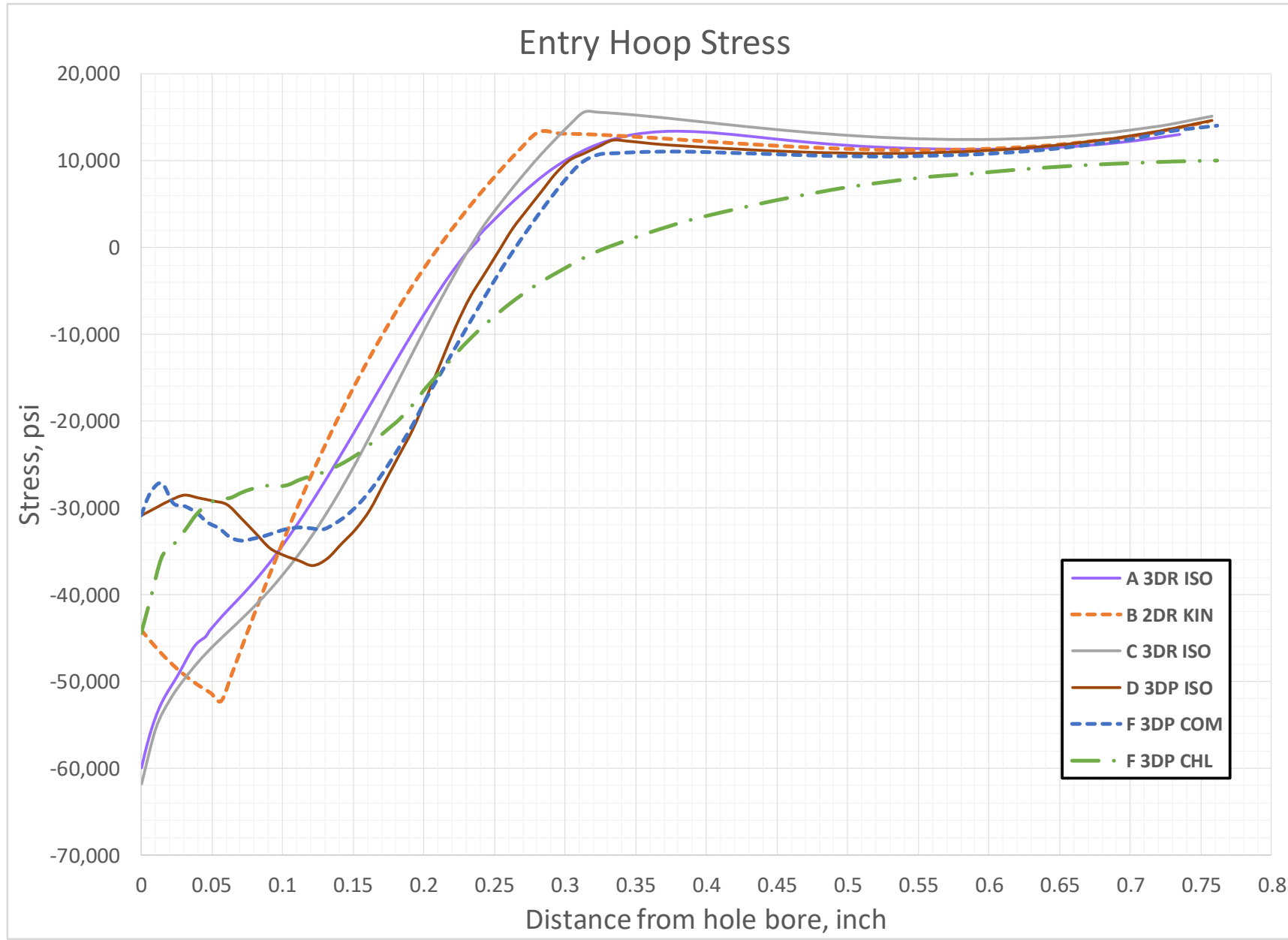
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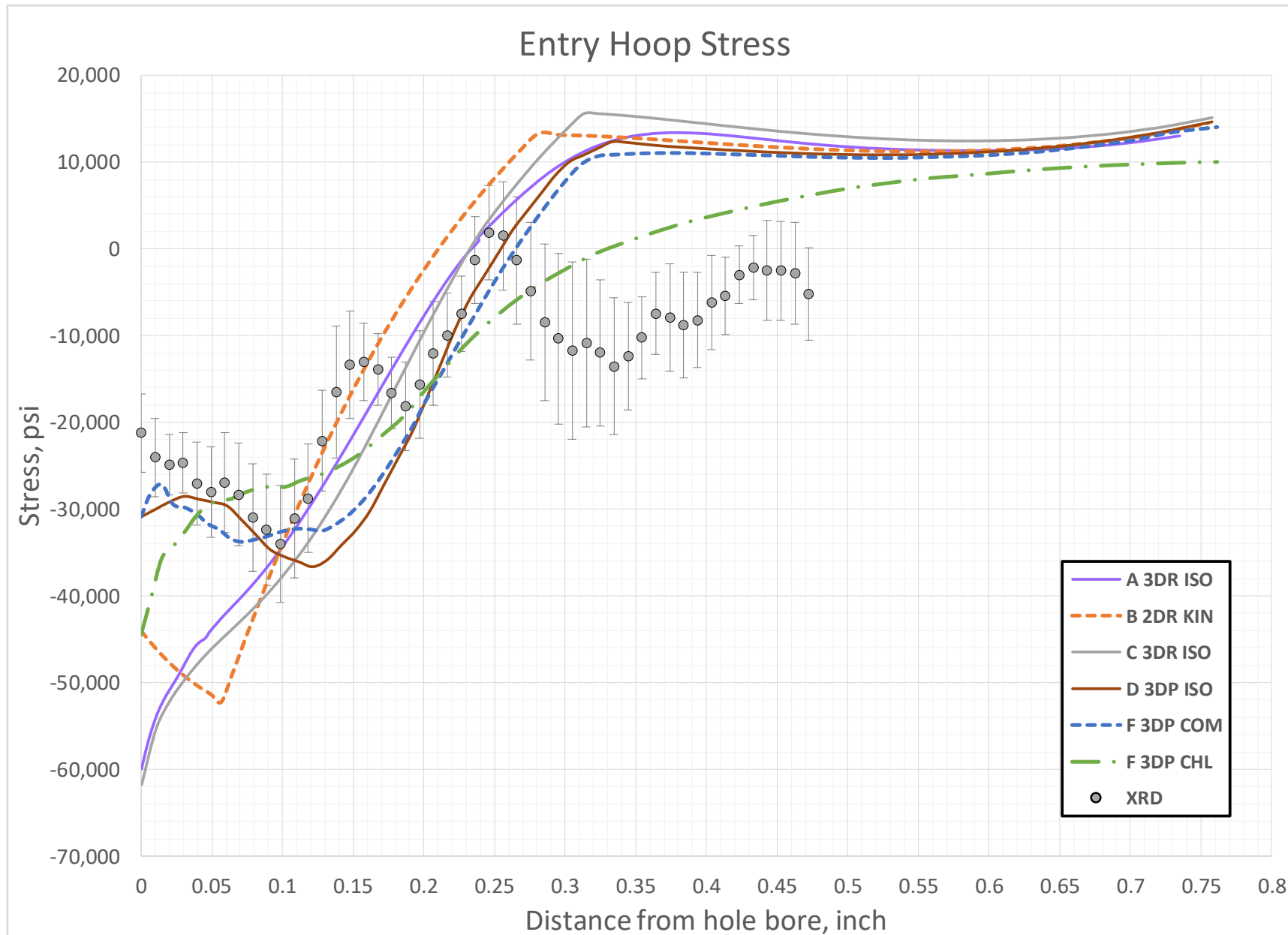


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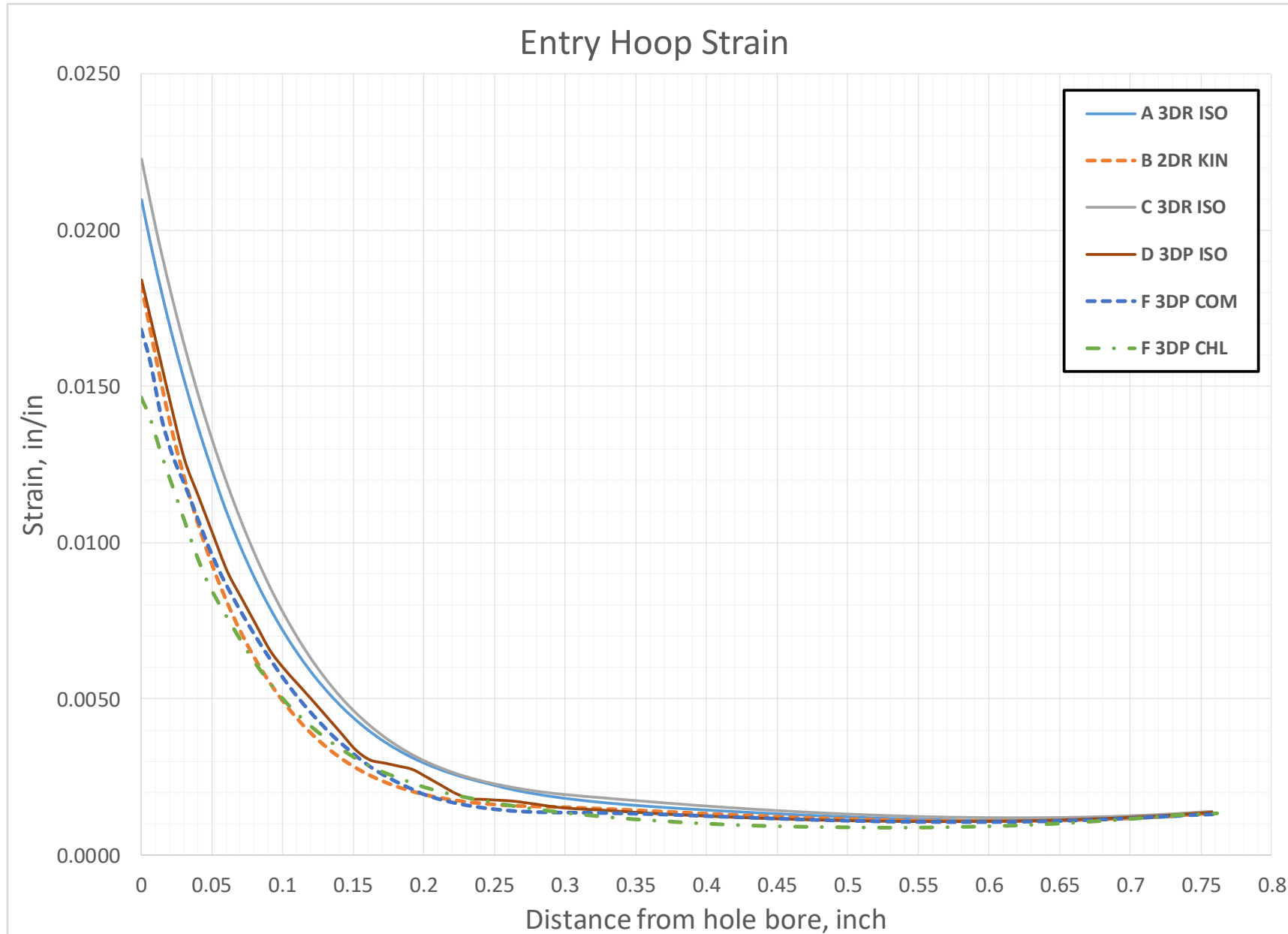




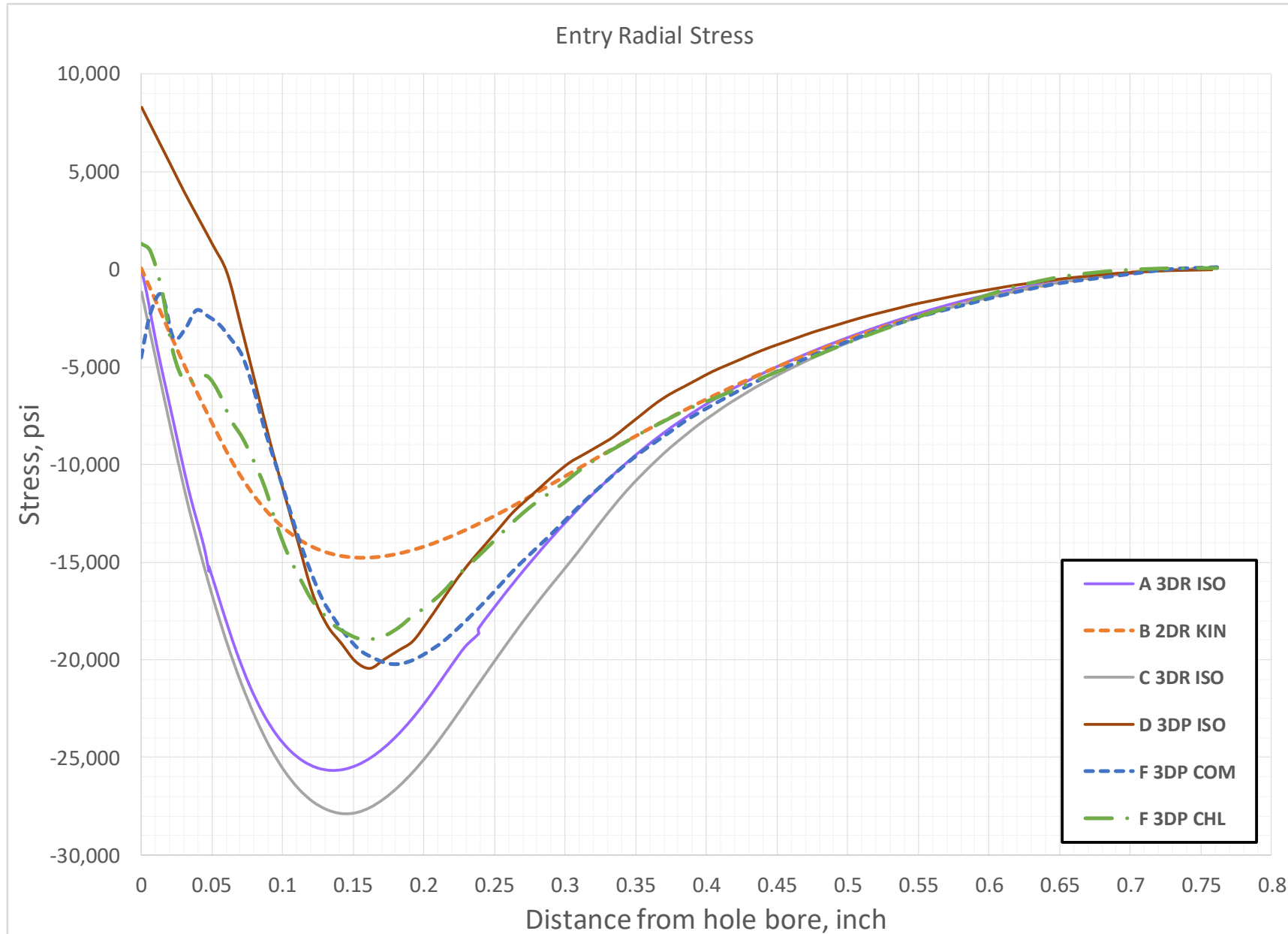
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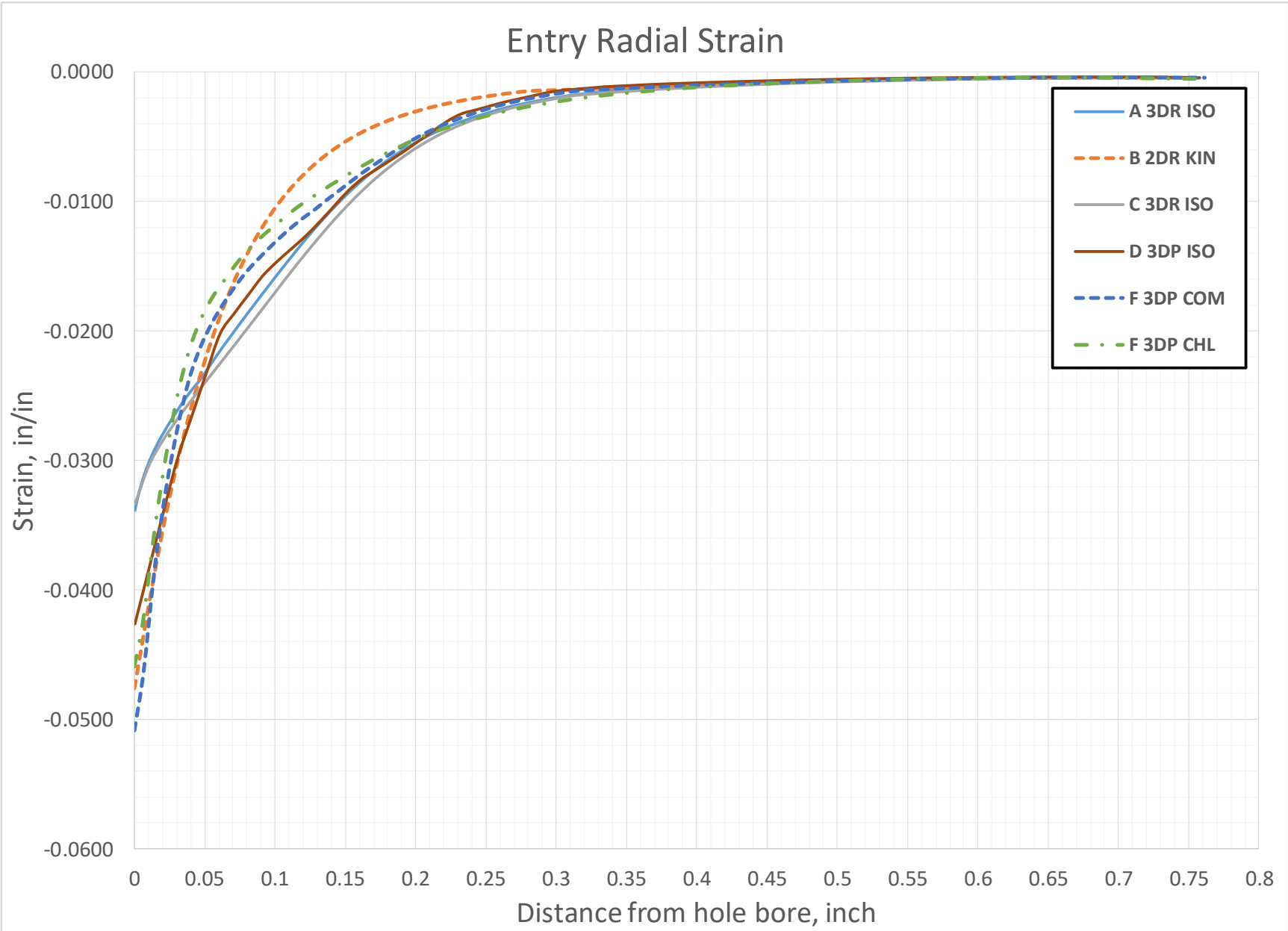
# RS Process Simulation Round Robin – Results



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# RS Process Simulation Round Robin – Results

Process Simulation Residual Strains – averaged over area subtended by strain gage.

All values in microinch/inch.

Green: less than  $\pm 10\%$

Red: more than  $\pm 30\%$

2024 - L2			SG Value	A 3DR ISO		B 2DR ISO		C 3DR ISO		D 3DP ISO		F 3DP COM	
			Residual	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error
Entry	Hoop	Inner	3570	4436	24.2%	5316	48.9%	5659	58.5%	4341	21.6%	3761	5.3%
		Outer	982.8	1187	20.8%	1529	55.6%	1306	32.9%	1089	10.8%	801	-18.5%
	Radial	Inner	-5699	-4417	-22.5%	-4657	-18.3%	-6042	6.0%	-5530	-3.0%	-5454	-4.3%
		Outer	-460.8	-487	5.7%	-733	59.1%	-567	23.0%	-467	1.3%	-433	-6.1%
Exit	Hoop	Inner	5703	4436	-22.2%	5316	-6.8%	5712	0.1%	5078	-11.0%	5004	-12.3%
		Outer	1238	1187	-4.1%	1529	23.5%	1312	6.0%	1247	0.7%	1804	45.7%
	Radial	Inner	-6906	-4417	-36.0%	-4657	-32.6%	-6096	-11.7%	-6402	-7.3%	-6778	-1.9%
		Outer	-570.6	-487	-14.6%	-733	28.5%	-570	-0.1%	-579	1.5%	-768	34.6%

# RS Process Simulation Round Robin – Wrap Up

## INITIAL FINDINGS

- Different modeling techniques provide broadly comparable results for similar material models
- Bore hoop stress ranges from -30 to -70 ksi over all material models and locations
- Comparisons to XRD appear to diverge in far field
- Need to evaluate radial strain discrepancies

## NEXT STEPS

- Receive additional entries – at least two more on the way
- Complete compilation of remaining results
  - Time based strain gage
  - LUNA fiber strain measurements
  - Three other cases (2024-H1, 7075-L1, 7075-H1)

# Residual Stress Process Simulation Committee

**Dr. Scott Prost-Domasky, Analytical Processes/Engineering Solutions (AP/ES), Inc.**

**Dr. Guillaume Renaud, National Research Council Canada**

**Marcus Stanfield, Southwest Research Institute**

**Dr. Min Liao, National Research Council Canada**

**Dr. Marcias Martinez, Clarkson University**

**Dr. Adrian DeWald, Hill Engineering, LLC**

**Robert Pilarczyk, Hill Engineering, LLC**

**Matt Shultz, Fatigue Technology**

**Dr. Ralph Bush, USAF Academy**

**Thuy Nguyen-Quoc, Boeing**

**Michael Worley, SwRI**

**Tim Philbrick, MERC**

**Mike Steinzig, LANL**

**Andrew Jones, USAF**

**Gavin Jones, SmartUQ**

**Dr. Robert McGinty, MERC**

**Chris Allen, Booz Allen Hamilton**

**Eric Greuner, Lockheed Martin Aero**

**Dr. Daniele Fanteria, University of Pisa**

**Dr. Scott Carlson, Lockheed Martin Aero**

**David Denman, Fulcrum Engineering, LLC**

**David Carnes, Mercer Engineering Research Center (MERC)**

**Chair: Keith Hitchman**

*Project Engineer, Analyst*

*Fatigue Technology*

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**Sincere thanks to all active committee members!**