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The World Rides On Us®

Experience with Strain Energy Based Strain-Life Property Prediction

James J. Patterson, PhD.

10-28-20

ε-N Curve Prediction (Hyst. Loops): Background…

- Dr. Peter Huffman, an SAE FD&E member, has developed a method to predict ε-N fatigue life curves.
- The only inputs needed are from a single fatigue test sample at a "high" strain rate…
  - E – Modulus of Elasticity
  - K` and n` - Ramburg-Osgood fit of the hysteresis loop
  - ε and $2N_f$ - Coordinate from the test
- If proven to be viable, this method could significantly reduce the time and cost associated with developing this data.

ε-N Curve Prediction (Hyst. Loops): Background…

- Data sets were provided to Dr. Huffman, but they were from the final fit of the full test regimen.
- A more likely, and favorable, scenario would be to supply a hysteresis loop from a single test…
  - Choose a stable loop midway (???) through the test.
  - Use a test with a reasonable strain level…
    - Large or small hysteresis loop?
- Derive E, K`, and n` from this data.
- Still need to supply the value for $2N_f$ at this strain level.

ε-N Curve Prediction (Hyst. Loops): Background…

DETERMINATION OF STRAIN-LIFE FATIGUE **PROPERTIES**

- When fitting the data to obtain the four strain-life properties, stress or plastic strain amplitude should be treated as independent variables, whereas the fatigue life is the dependent variable (i.e. fatigue life cannot be controlled and is dependent upon the applied strain amplitude).

- The cyclic strength coefficient, K′, and cyclic strain hardening exponent, n′, are obtained from fitting stable stress amplitude versus plastic strain amplitude data. Rough estimates of K′ and n′ can also be calculated from the low cycle fatigue properties by using:

$$K' = \frac{\sigma'_f}{(\varepsilon'_f)^{\frac{b}{c}}} \qquad n' = \frac{b}{c}$$

$(\sigma`_f/\varepsilon`_f^{b/c})/K` = 1$

$(b/c)/n` = 1$

These equations are derived from compatibility between strain-life equations.

ε-N Curve Prediction (Hyst. Loops): Background…

- Compare the curves as a % difference from the final known curve.
- Compare the parameters between the test and the prediction.
- These would obviously not be possible in an actual situation.

Strain-Life Curve Prediction from Hysteresis Loops MAR-5589a – Gr 50 Plate

ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…

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TRAILER COMMERCIAL VEHICLE SYSTEMS

To

From *File.*

Subject *Date*

This report to cover one subject only

TEST PROGRAM SUMMARY

– Turn on formatting marks (¶) to show help text –

Cyclic Stress-Strain	$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E^*} + \left(\frac{\Delta\sigma}{2K'}\right)^{n'}$	Cyclic St… Cyclic Strain-… …ent, K' = 1… n' = 0.120 …= 29.7E6 ps…
Elastic Strain-Life	$\frac{\Delta\epsilon_e}{2} = \frac{\sigma_f'}{E^*}(2N_f)^b$	Fatigu… …h Coefficien… …554 p… Fatigu… …h Exponent, …
Plastic Strain-Life	$\frac{\Delta\epsilon_p}{2} = \epsilon_f'(2N_f)^c$	Fatigue Duc… Fatigue Du…

This data was *not* provided

Referenced Documents:

[1] RDP 1060 – 322 Load Frame Configuration for Cyclic Testing

[2] RDP 1061 – Uniaxial Strain-Controlled Fatigue Testing

Written by:

Preview Copy

Test Summary

Table VII: Summary of constant-amplitude test results

Sample ID	S…		Reversals to …lure, $2N_f$	Remarks[A]	Analysis[B] SS	E	P
SEQ15…			…00	Load control, runout			
SEQ…		35,…		Load control		x	
S…	…0120	35,502		Load control		x	
		39,238				x	
		41,729	4…			x	
		40,728	43…			x	
…9	0…	…27	144…		x	x	x
…6	0.00…		142…		x	x	x
…5	0.00200		104…		x	x	x
	0.00270		5…		x	x	x
	0.00270	5…			x	x	x
	0.00320	55,31…		…00 @ 0.002 in/in	x	x	x
	0.00320	54,483			x	x	x
SEQ…		56,0…		100 @ 0.002 in/in	x	x	x
SEQ03…			…64		x	x	x
SEQ01-01			12,784	100 @ 0.002 in/in	x	x	x
SEQ04-07			10,144		x	x	x
SEQ07-11	0.00500	61,487	8,860		x	x	x
SEQ08-13	0.00500	60,918	8,778		x	x	x

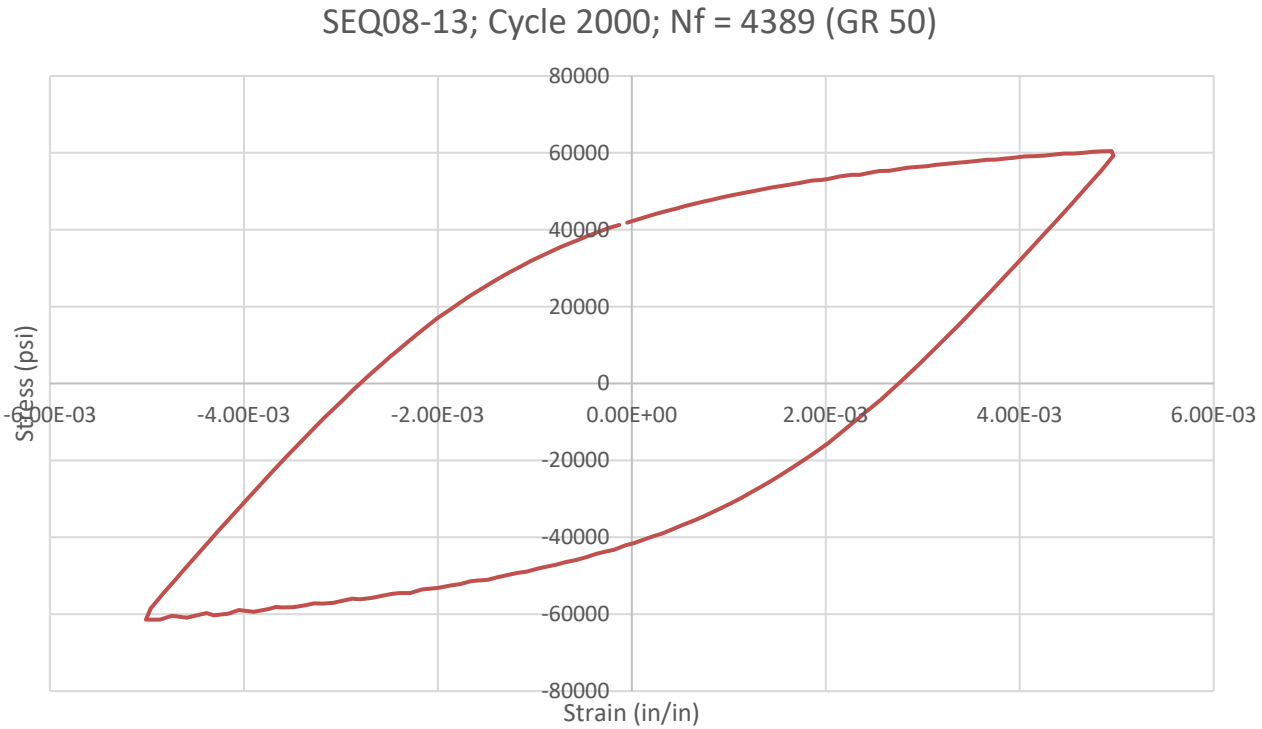
See *Ref 2.* for procedures regarding strain-controlled…

[A] Complete **Remarks** can be found in the associa…

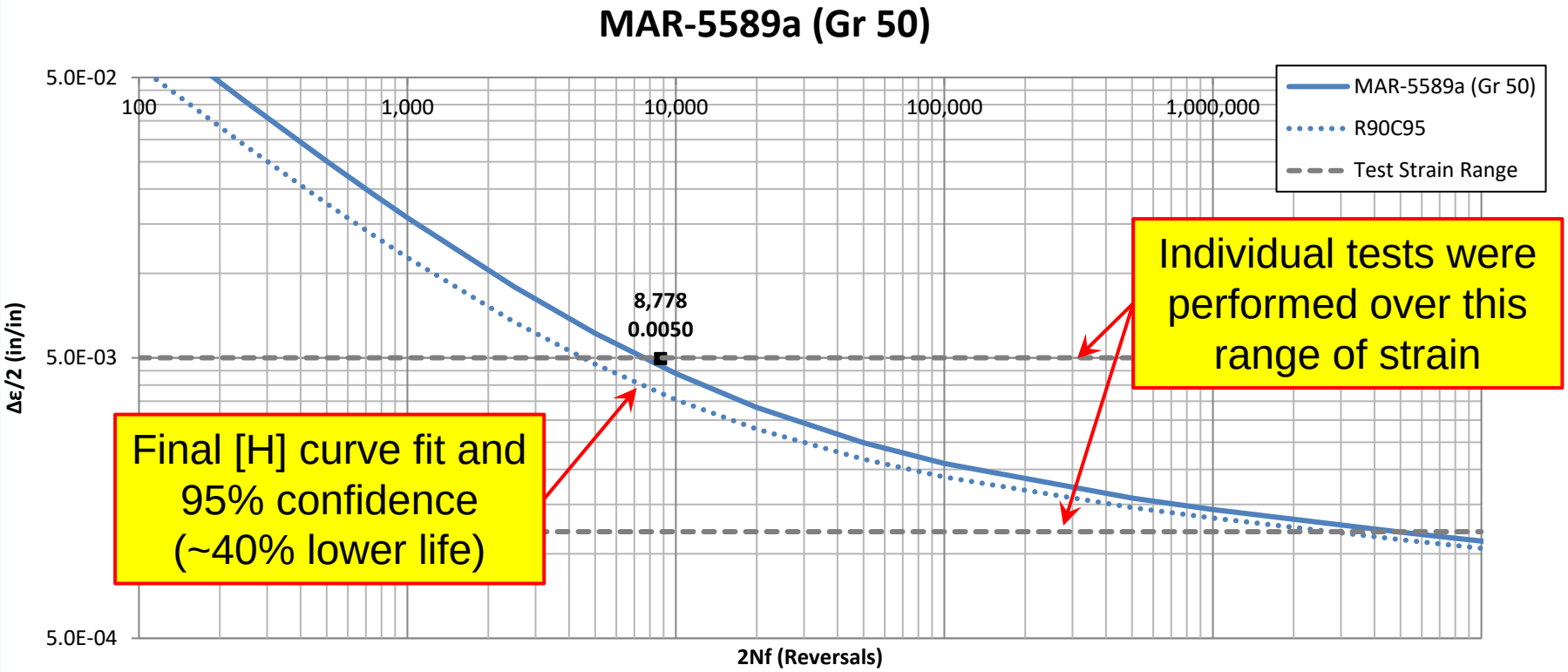
[B] The **Analysis** columns identify which specimen… as follows: *SS*, Cyclic Stress-Strain Curve; *E*, Elastic Strain… analysis can be found in the associated companion test sprea…

This loop and point was provided

ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



ε-N Curve Prediction (Hyst. Loop): Dr. H MAR-5589a – Gr 50…

Re: e-N Prediction...

PH Peter Huffman <huffman.peter.j@gmail.com>
To Patterson, James

WARNING:EXTERNAL EMAIL!

Hi Jim,

For the SEQ08:

E	28.17MSI
n'	0.115
K'	107.7KSI
Sf'	120.2KSI
b	-0.0855
ef'	2.594
c	-0.7435
UTS	76.31KSI

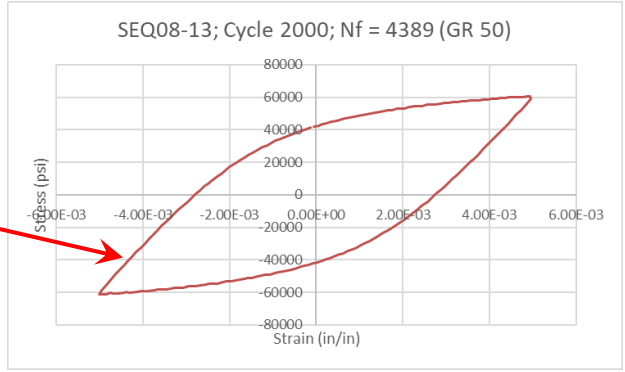
and for the SEQ1:

E	31.16MSI
n'	0.1105
K'	155.4KSI
Sf'	160.1KSI
b	-0.0830
ef'	1.307
c	-0.7510
UTS	111.64KSI

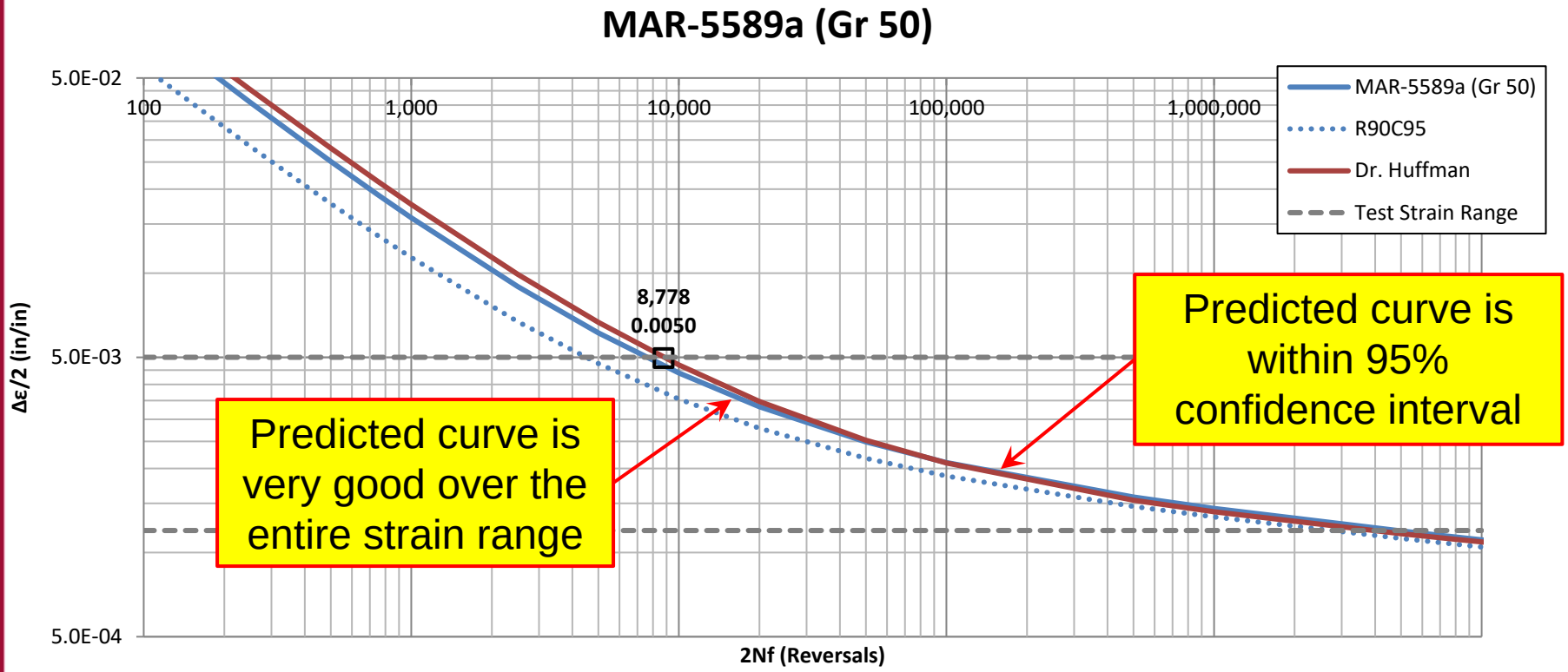
Sorry for the late reply, today has been nuts!

Prediction from single hysteresis loop

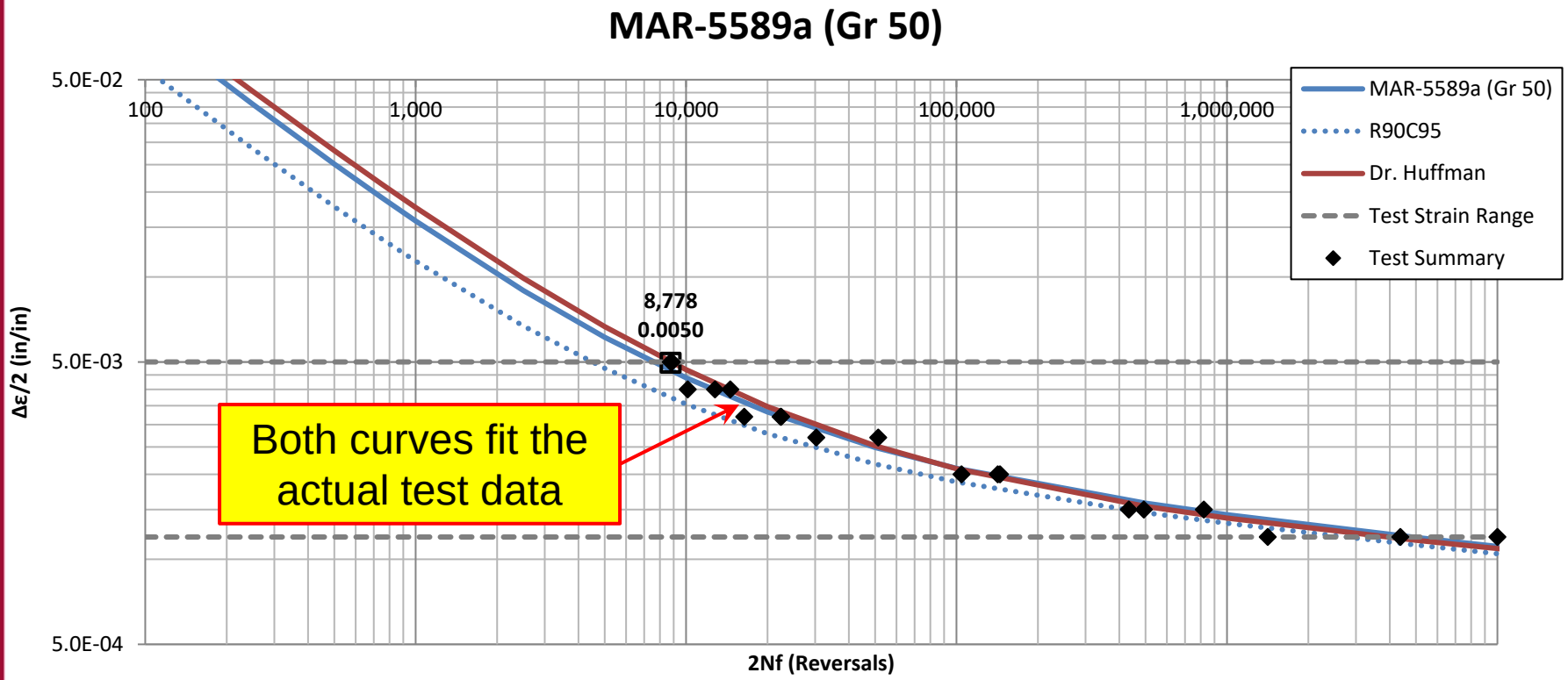
UTS Prediction



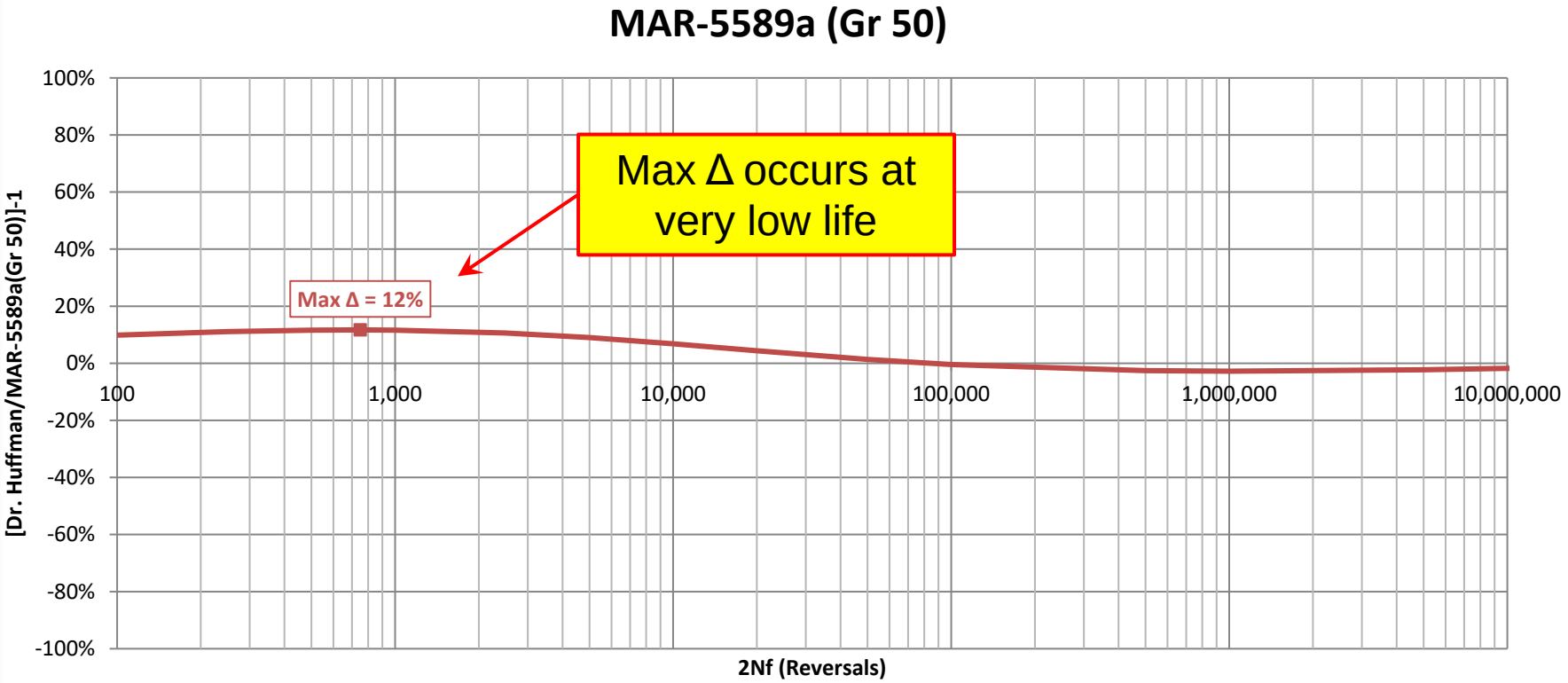
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



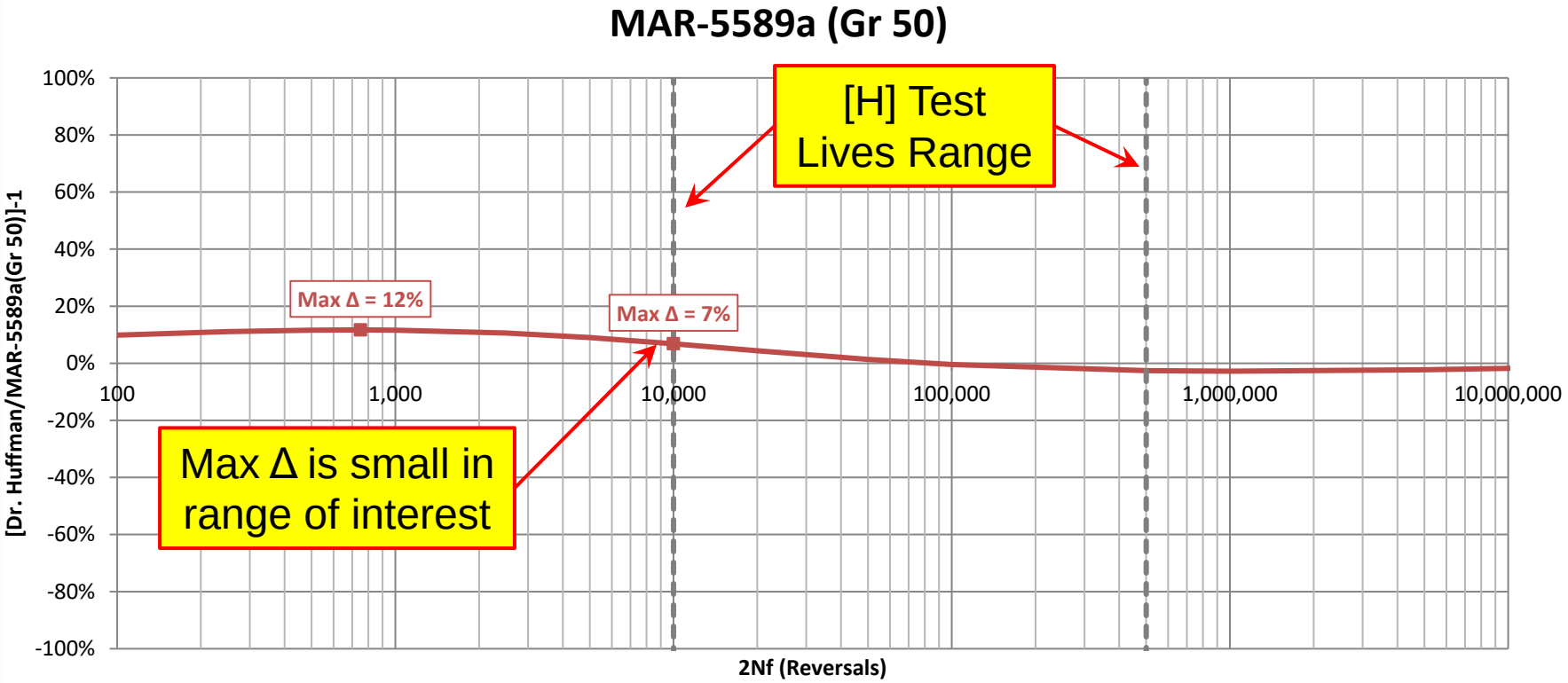
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



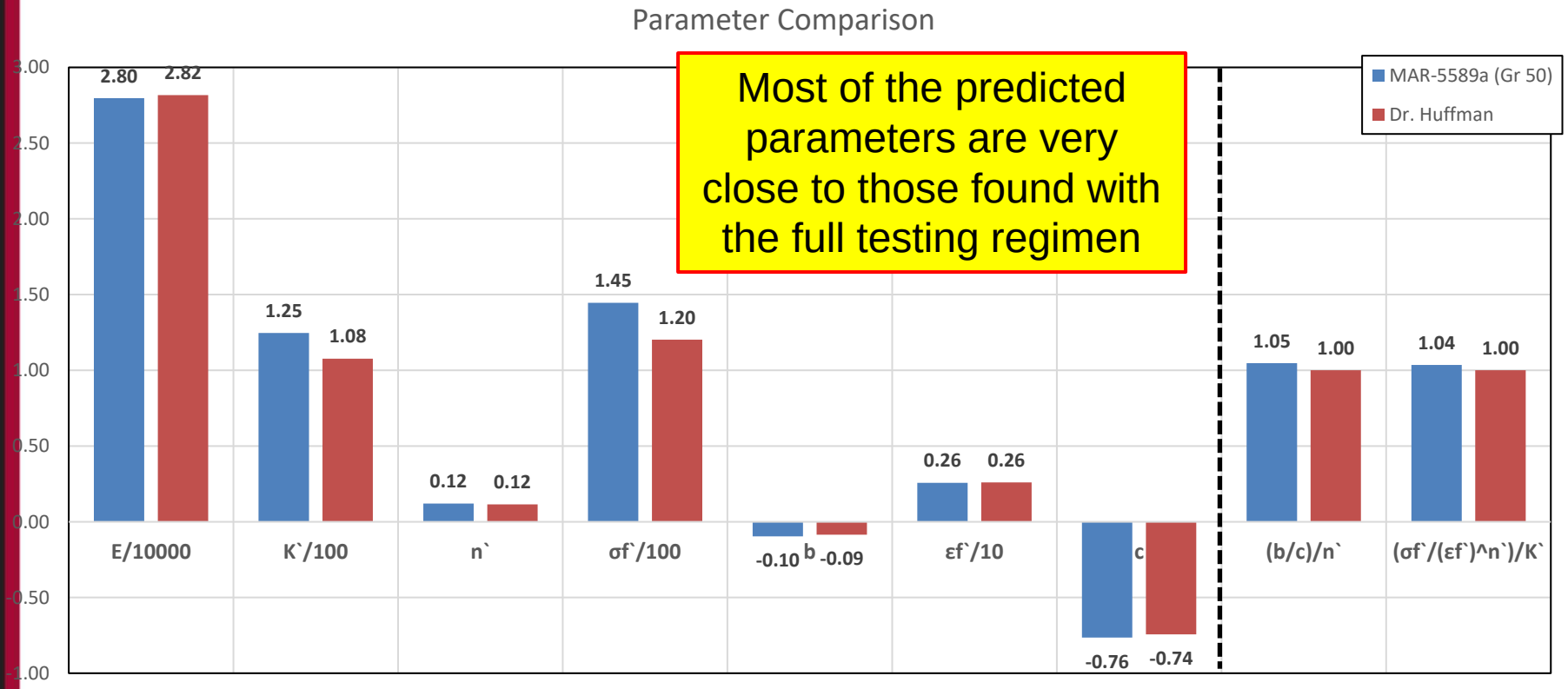
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



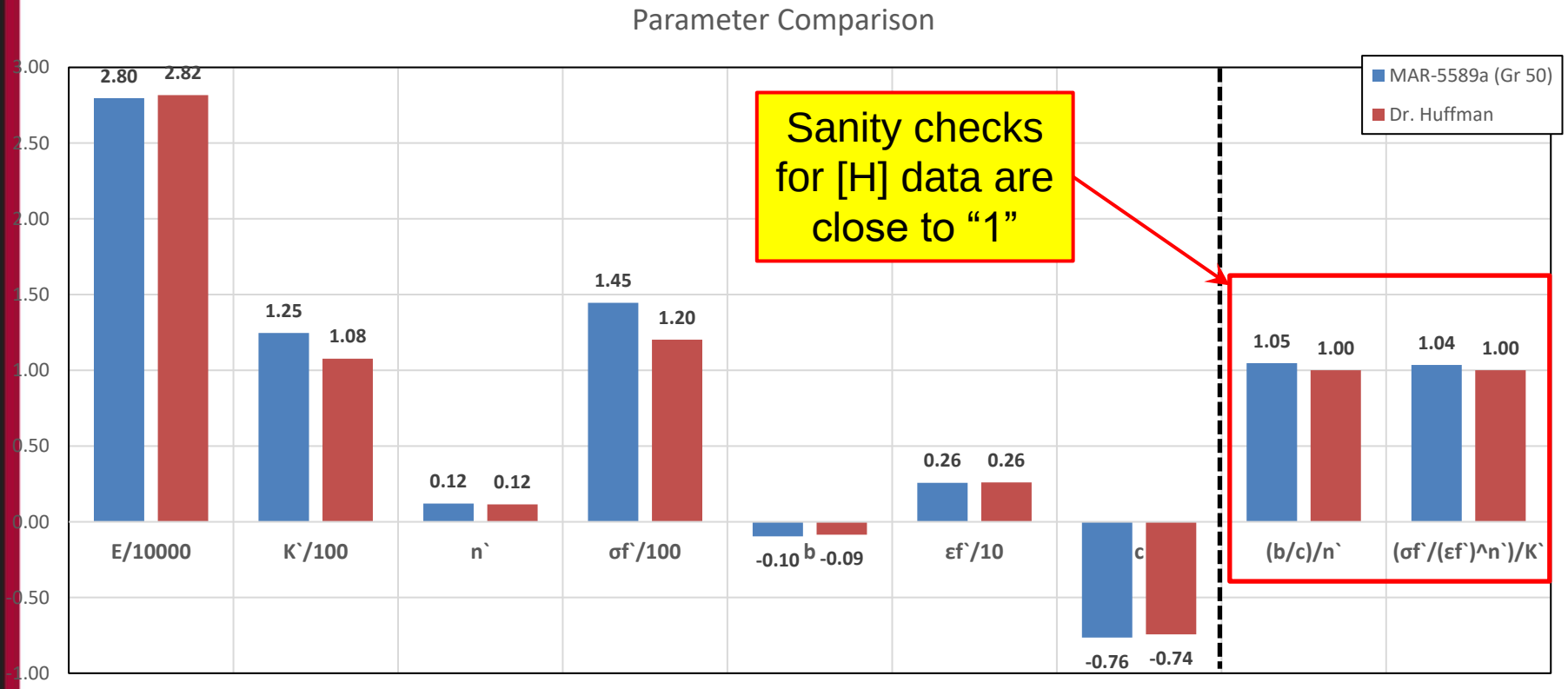
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



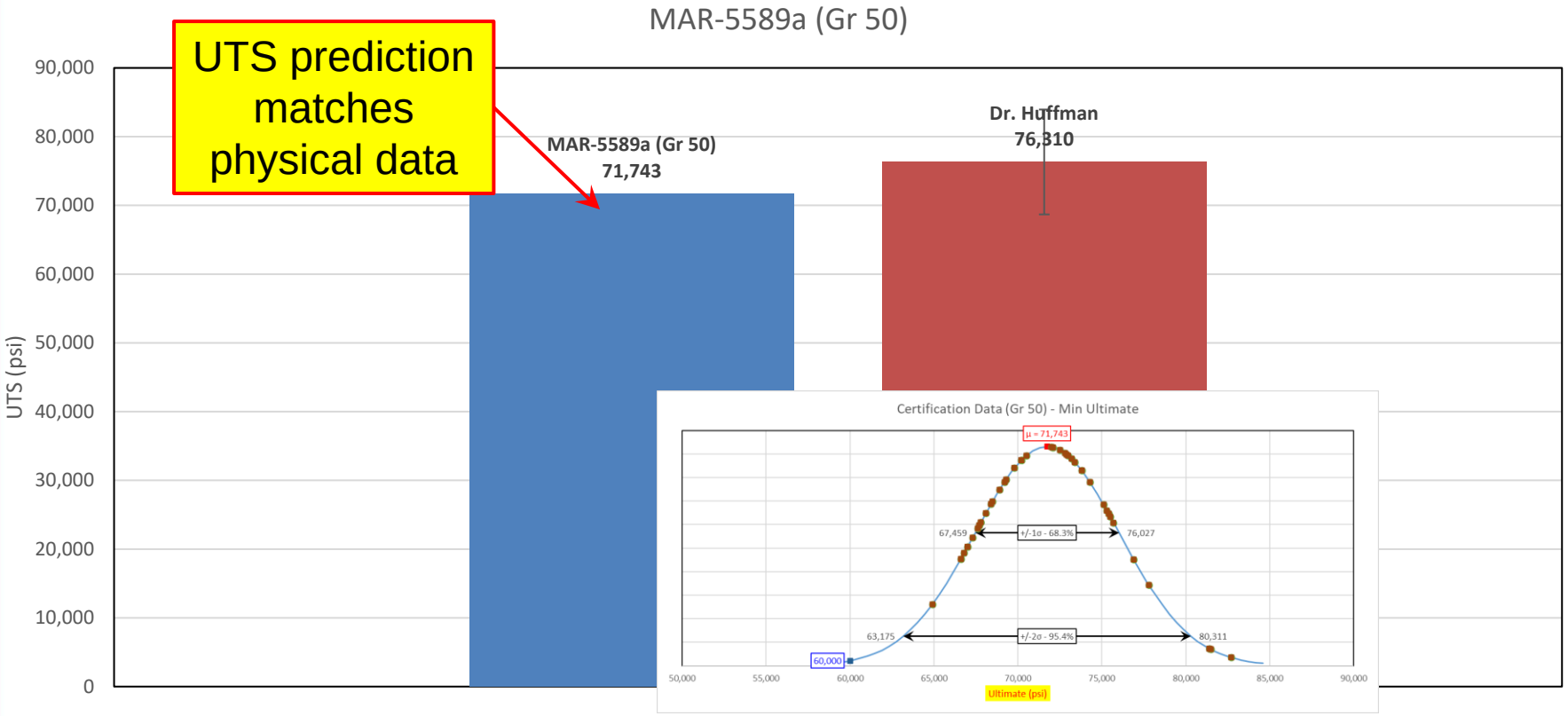
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-5589a – Gr 50…



ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-4108a – Gr 80…



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ε-N Curve Prediction (Hyst. Loop): Dr. H MAR-5589a – Gr 50…

- **Conclusions…**
  - To test the method, MAR data was provided to Dr. Huffman…
    - MAR-5589a – Gr 50 Plate
    - Single hysteresis loop and corresponding $2N_f$.
  - The predicted curve…
    - Matched well (~12%) over the entire strain range.
    - Matched very well (~7%) within the normal range of [H] testing.
    - Was within the 95% Confidence Interval over the entire strain range.
  - The Predicted Parameters…
    - Were in general very close to the test predictions.
    - The [H] data sanity checks were close to one.

Strain-Life Curve Prediction from Hysteresis Loops MAR-4127a r1 – D65-45-12

ε-N Curve Prediction (Hyst. Loop): Dr. Huffman

MAR-4127aR1 – D65-45-12…

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TRAILER COMMERCIAL VEHICLE SYSTEMS

To J. PATTERSON – PRINCIPAL VEHICLE SYSTEM ENGINEER

From A. YOURIL – METALLURGICAL ENGINEER **File.** MAR-4127A R1

Subject CYCLIC PROPERTIES OF 65-45-12 DUCTILE IRON HUBS – KIC & GUNITE **Date** 1 November 2016

This report to cover one subject only

TEST PROGRAM SUMMARY

To characterize the cyclic properties of ASTM A536 Grade 65-45-12 ductile iron hub castings, a fatigue test program was performed according to the recommendations of ASTM E606. Samples were obtained from production hub castings from two manufacturers, KIC (four hubs, C-33387) and Gunite (two hubs, C-28366). Clear differences were observed manufacturer to manufacturer in terms of microstructural appearance and monotonic properties, but the fatigue results could not be differentiated statistically. As such, the fatigue parameters below were produced by pooling the data sets together into a single stress-strain curve. For information, the data are presented separately in the Appendix.

Cyclic Stress-Strain	$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E^*} + \left(\frac{\Delta\sigma}{2K'}\right)^{n'}$	Cyclic Str… …689 psi Cyclic Strain-… …xponent, … …icity, $E^* = 1$… …si
Elastic Strain-Life	$\frac{\Delta\epsilon_e}{2} = \frac{\sigma_f'}{E^*}(2N_f)^b$	Fatig… …ngth Coe… …$_f' = 12$… …osi Fati… …ngth Expone…
Plastic Strain-Life	$\frac{\Delta\epsilon_p}{2} = \epsilon_f'(2N_f)^c$	Fatigue Du… …2 in/in Fatigue Ductil… …-0.931

This data was *not* provided

Table V: Summary of constant-amplitude test results

Sample ID	Strain, Δε/2 (in/in)	Stress, Δσ/2 (ksi)	Reversals to Failure, 2Nf	Remarks[A]	Analysis[B] SS	E	P
K1-5	0.001…						
K1-7							
K2-16							
K3-…							
…		29,611	10,…				
		33,577	10,000,000				
		28,894	2,661,730			x	
		…4	2,478,912			x	
			724,852	Slight co…		x	
	0.00…		592,726			x	
	0.00137		459,756			x	
	0.00156		…9,980	Slight tensile		x	
	0.00137	3…	…			x	
	0.00178	42,75…				x	
	0.00149	37,333				x	
	0.00178	43,255				x	
	0.00181	44,162				x	
	…81	44,498	57…	…s zeroed		x	
K…		…52,770			x	x	x
G1-…					x	x	x
G3-27					x	x	x
G3-23					x	x	x
K4-34	0.00265				x	x	x
G3-26	0.00263	55,368	10,046	Slight mean compressive stress	x	x	x
G1-8	0.00221	50,126	10,040		x	x	x
K4-29	…00300	59,277	9,410		x	x	x
K3-32	0.00263	56,946	9,090		x	x	x
K1-9	0.00269	55,680	8,096		x	x	x
K2-14	0.00300						x
K1-4	0.00250						x
K2-18	0.00263						x
G1-6	0.00269						x
G1-10	0.00328						x
G3-30	0.00300	55,288	1,548		x	x	x
G1-15	0.00300	54,922	1,240		x	x	x
K2-3	0.00310	54,176	1,052	Diam and E corrected (Mic)	x	x	x
K2-1	0.00470	61,903	740	Diam and E corrected (Mic)	x	x	x

These loops and points were provided

ENGINEER for EFFICIEN…

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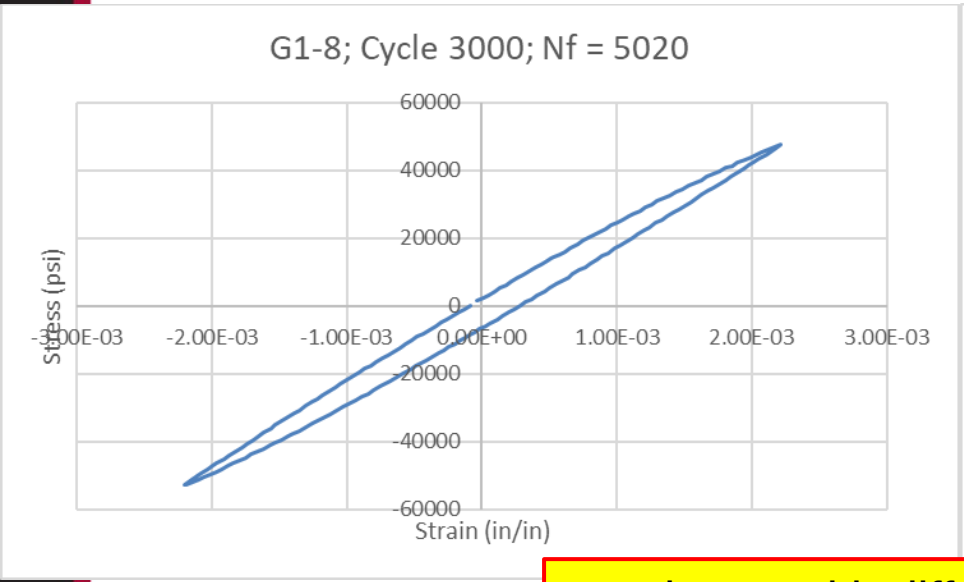
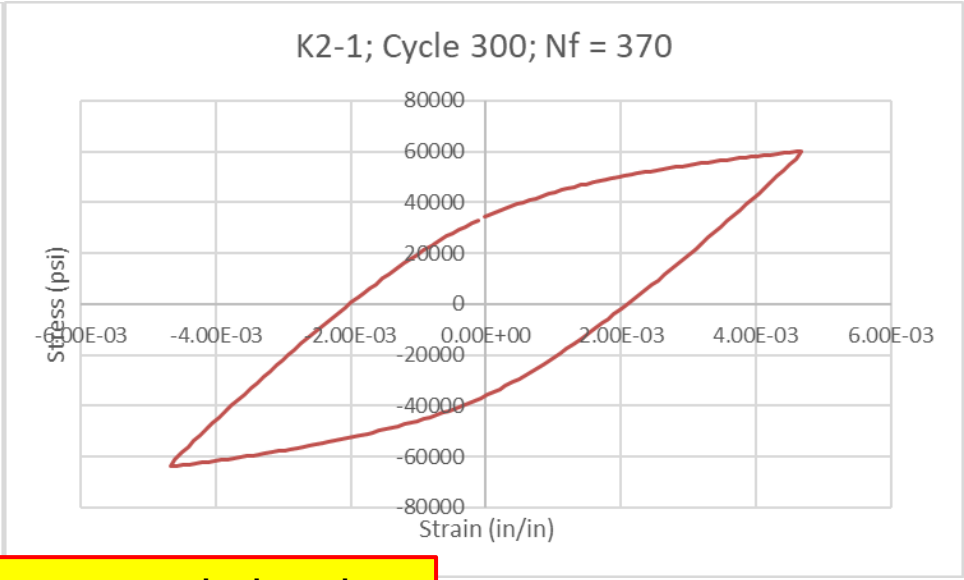
ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-4127aR1 – D65-45-12…

G1-8	0.00221	50,126	10,040

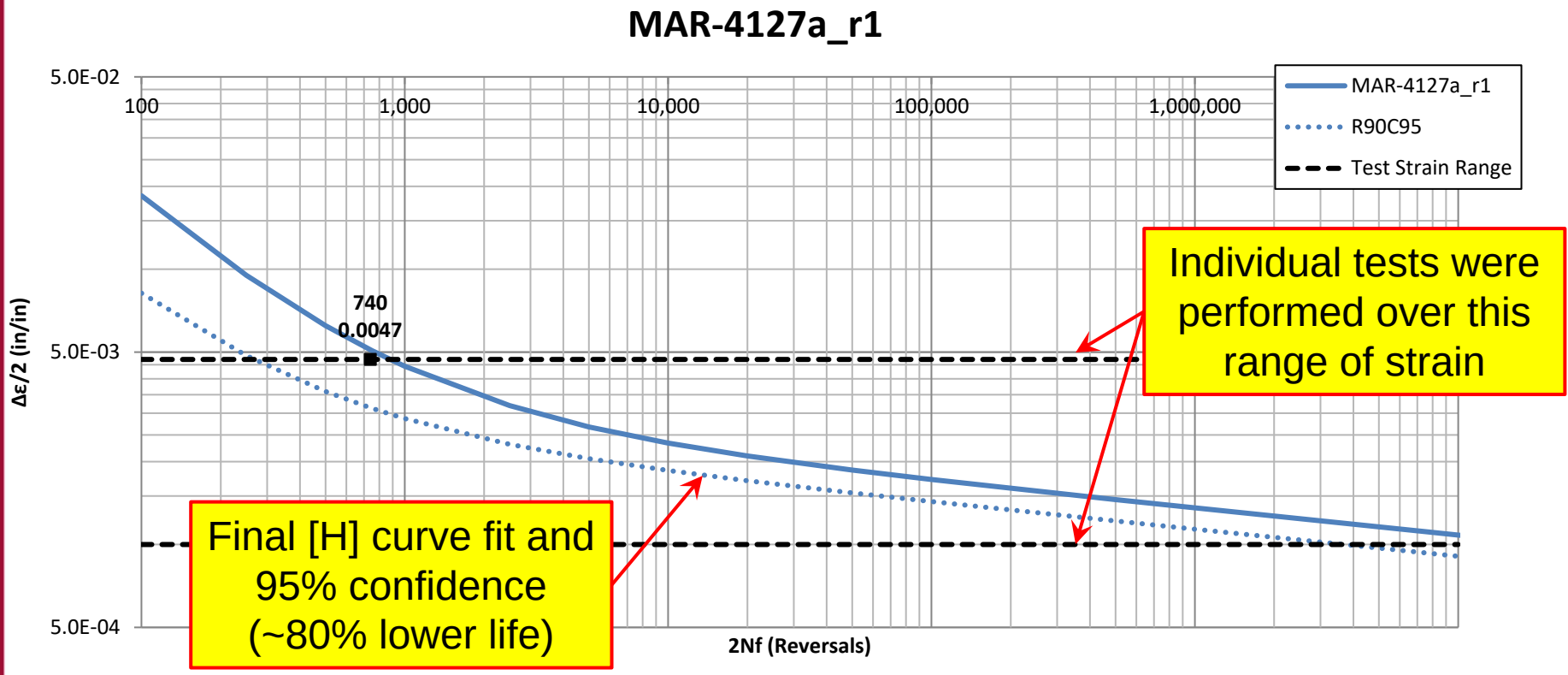
K2-1	0.00470	61,903	740





Two loops with different strain levels. What level of hysteresis is needed for a good prediction?

ε-N Curve Prediction (Hyst. Loop): Dr. Huffman MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…

Re: e-N Prediction…

PH

Peter Huffman <huffman.peter.j@gmail.com>
To Patterson, James

Reply | Reply All | Forward | …

Thu 9/17/2020 2:44 PM

You replied to this message on 9/17/2020 3:39 PM.

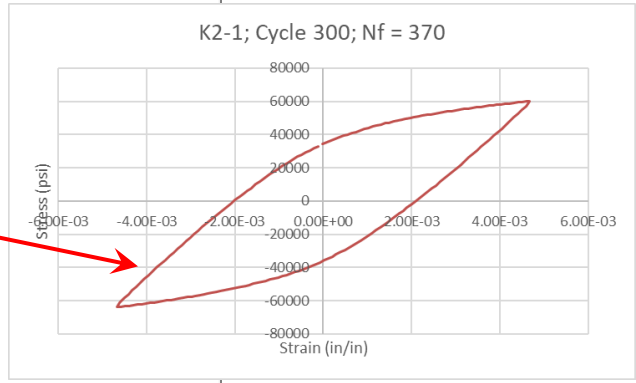
WARNING:EXTERNAL EMAIL!

So far I've only looked at the 300 cycle loop. I have not opened the other two files. If my hysteresis calculation is working correctly,
E = 25.69 Mpsi
which leads me to believe this is some kind of stainless steel. If that's not the right modulus, probably everything else will be off too.

n' = 0.1356
K' = 130 ksi

Sf' = 108.8 ksi
b = -0.0964
ef' = 0.266
c = -0.7108

Prediction from loop with larger hysteresis



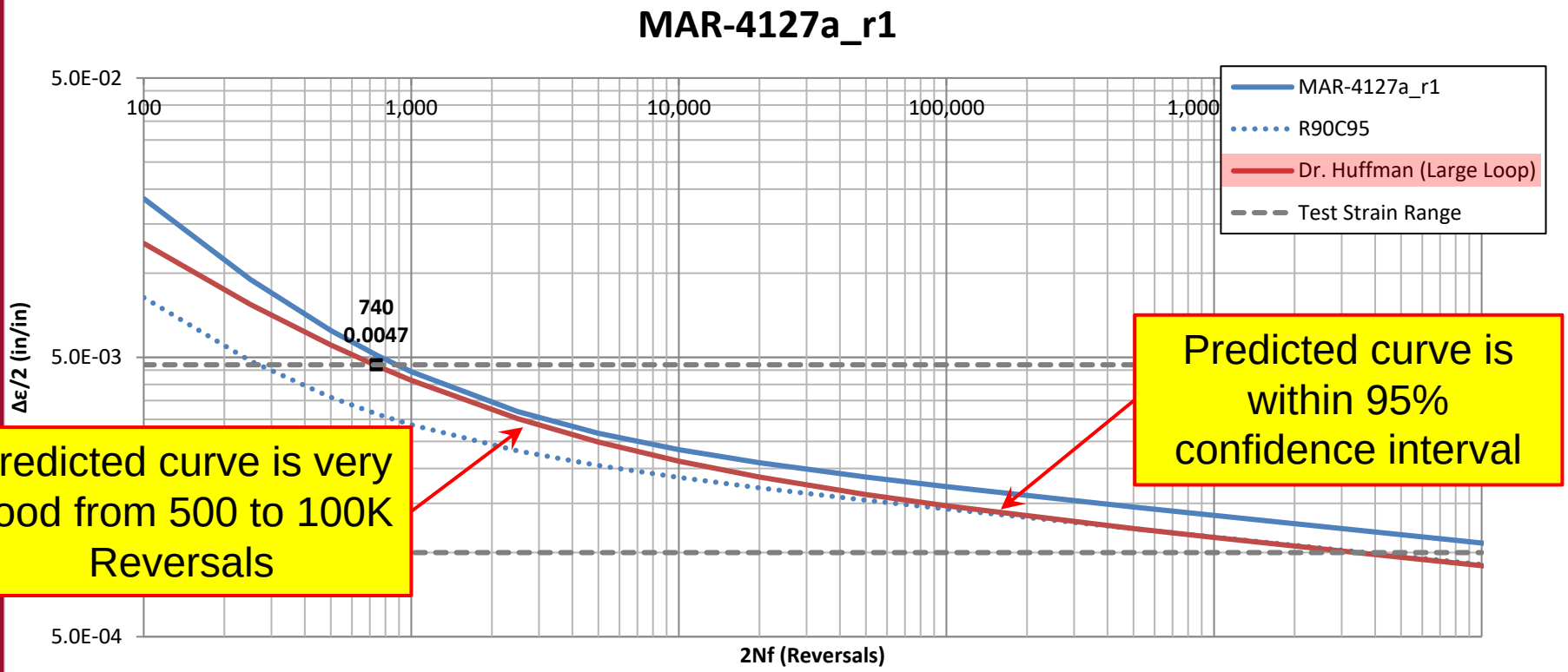
the b/c etc. can be found here, but it's just mentioned:
https://www.efatigue.com/training/Chapter_5.pdf
Page 79

The K' part of the relationship is mentioned in SAE "Proposed Technical Report on Fatigue Properties for the SAE Handbook" from 1974 But at a glance I'm not seeing the b/c bit
https://www.sae.org/publications/technical-papers/content/740279/

and if you're feeling really peppy, it's not too hard to derive.

I'll look forward to hearing back. It's really hard not to open up that material reveal file… :-)

ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



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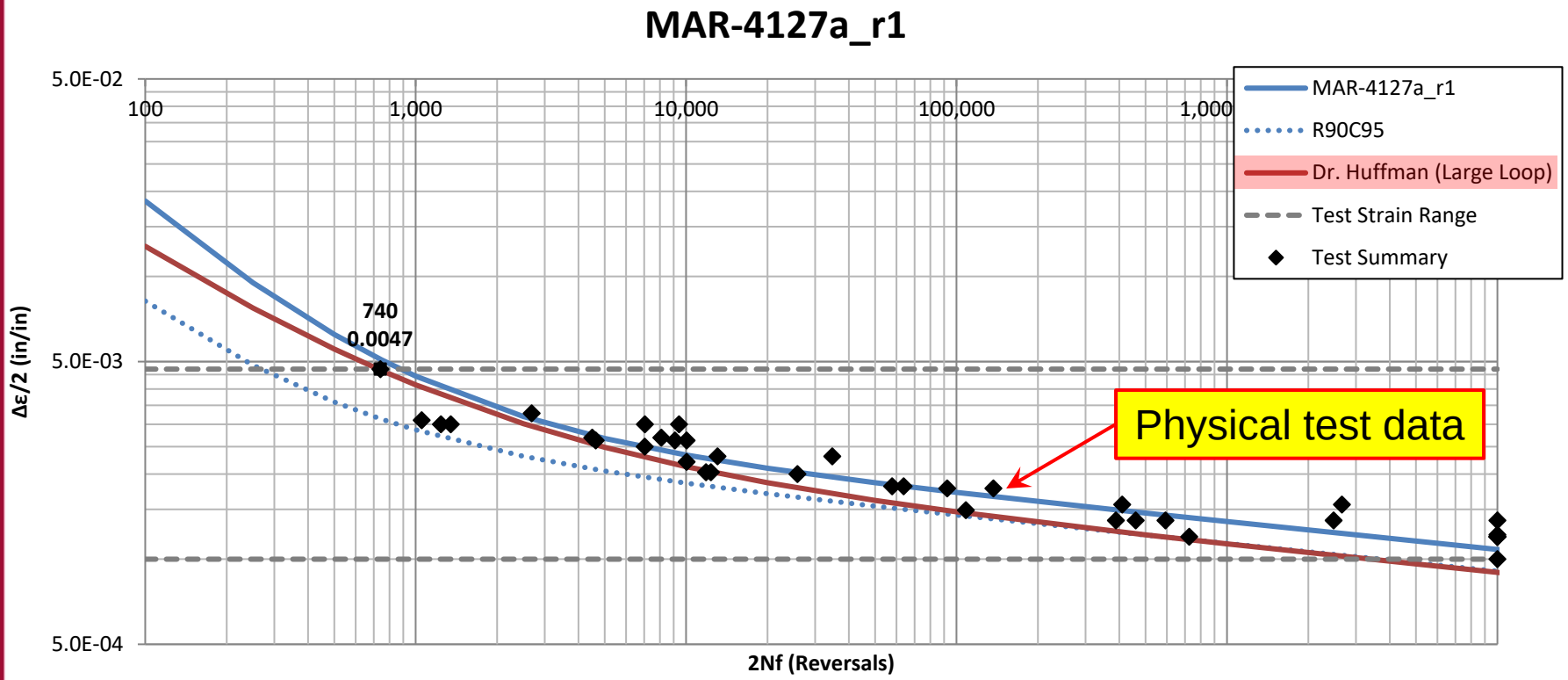
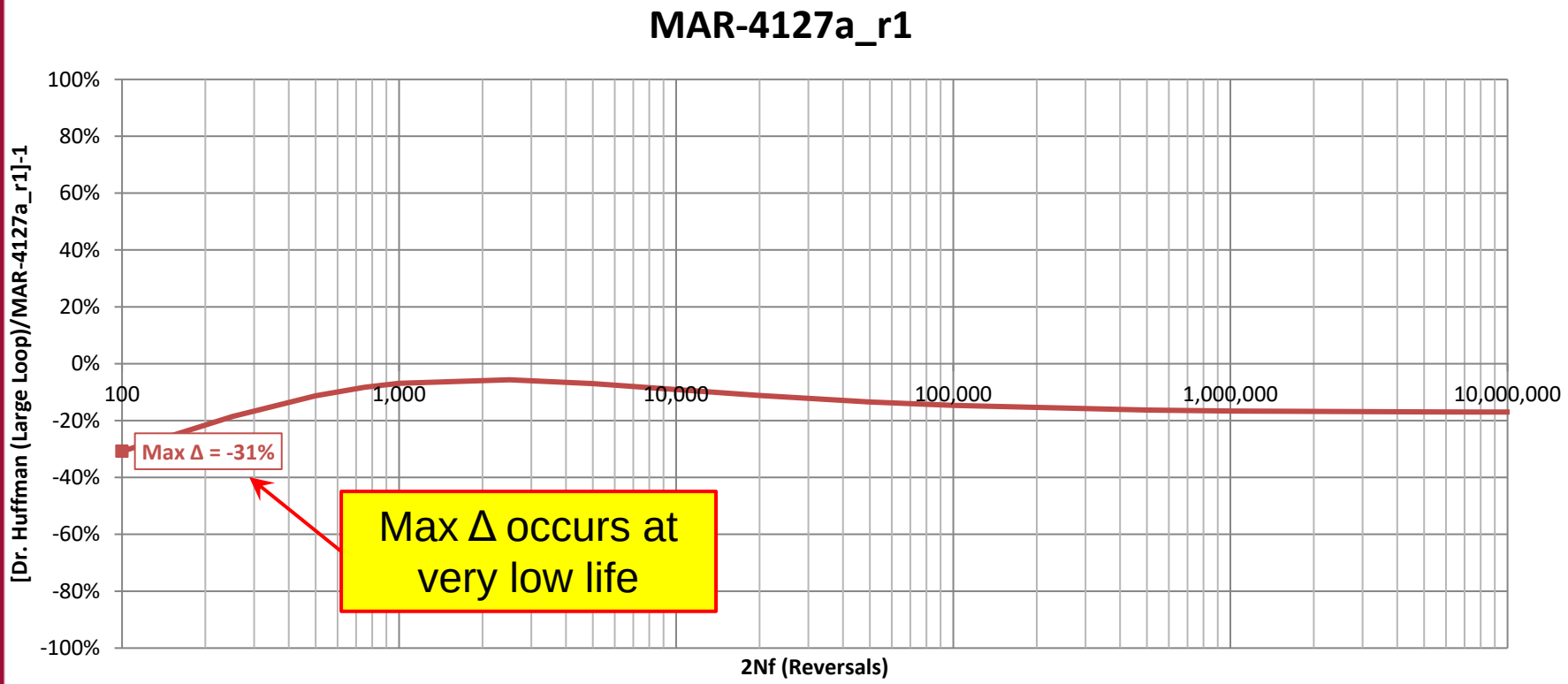
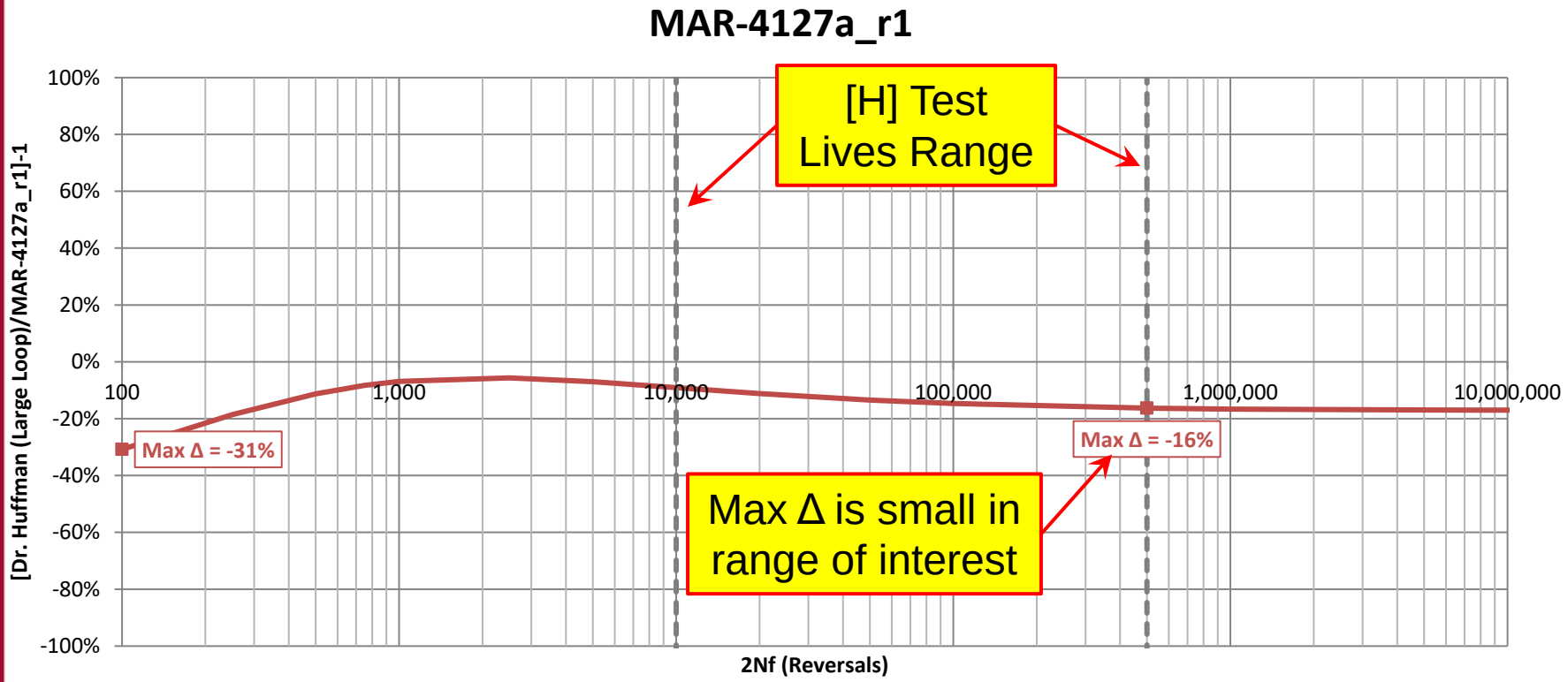
ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



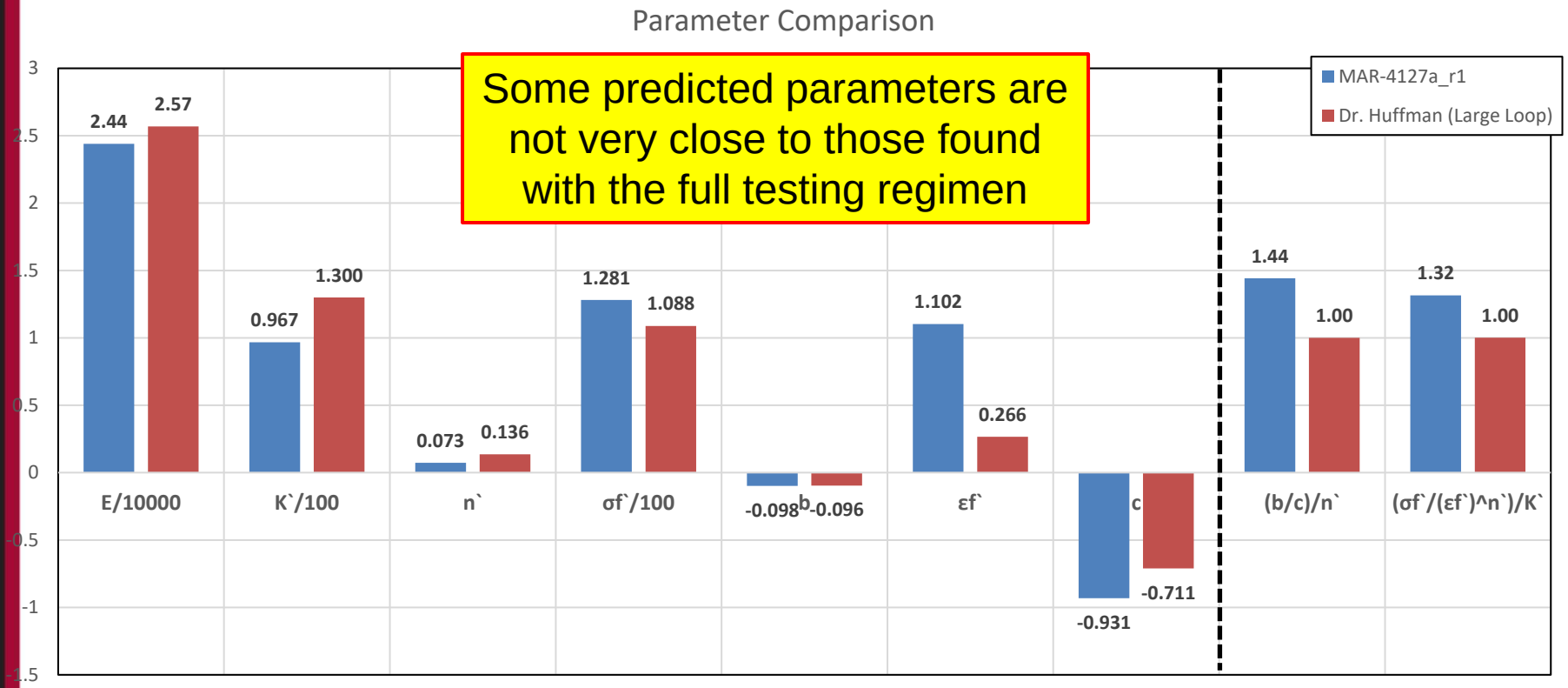
ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



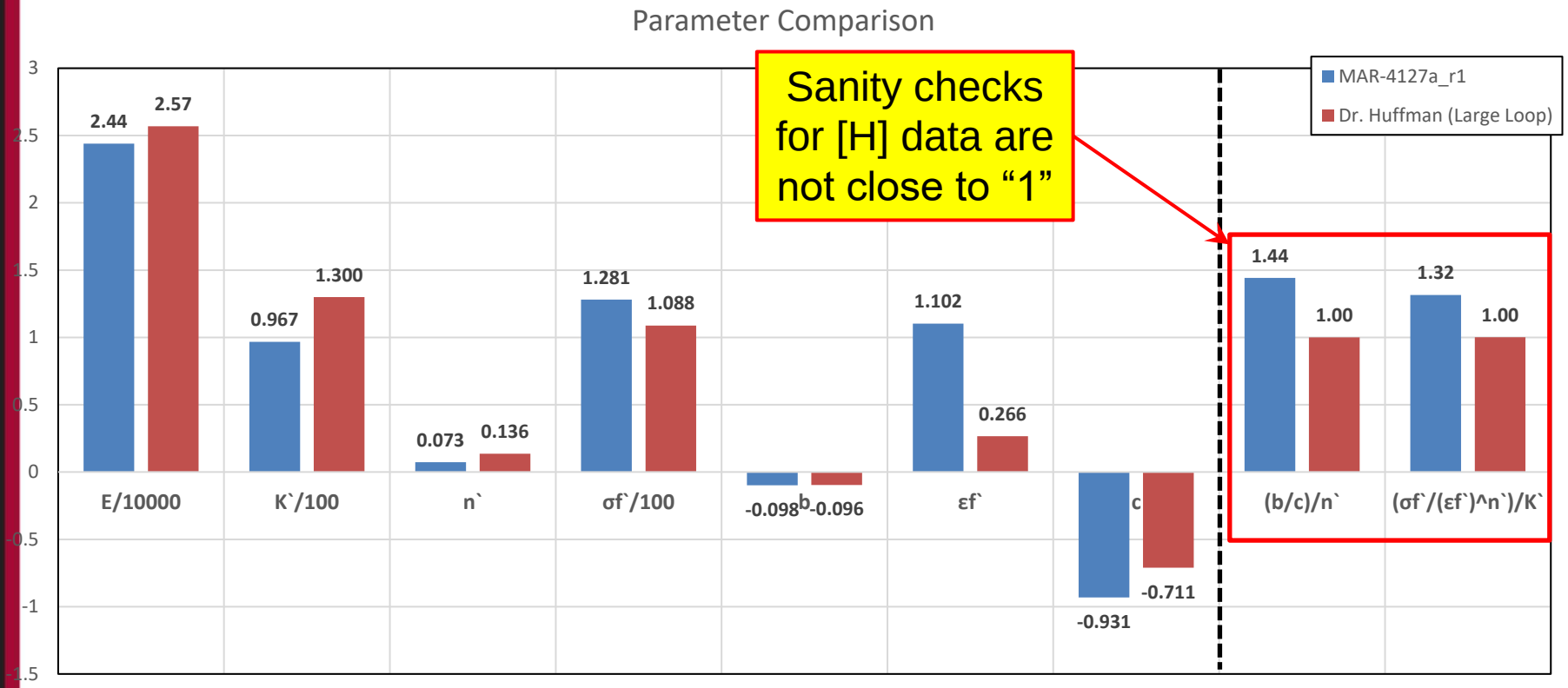
ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Large Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…

- **Conclusions…**
  - **To test the method, MAR data was provided to Dr. Huffman…**
    - **MAR-4127a r1 – D65-45-12**
    - **Large hysteresis loop and corresponding $2N_f$.**
  - **The predicted curve…**
    - **Matched somewhat (~31%) over the entire strain range.**
    - **Matched well (~16%) within the normal range of [H] testing.**
    - **Was within the 95% Confidence Interval over the entire strain range.**
  - **The Predicted Parameters…**
    - **Showed some variation.**
    - **The [H] data sanity checks were not close to one.**

ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…

Re: e-N Prediction...

PH Peter Huffman <huffman.peter.j@gmail.com>
To Patterson, James

Reply | Reply All | Forward | ...

Thu 9/17/2020 4:43 PM

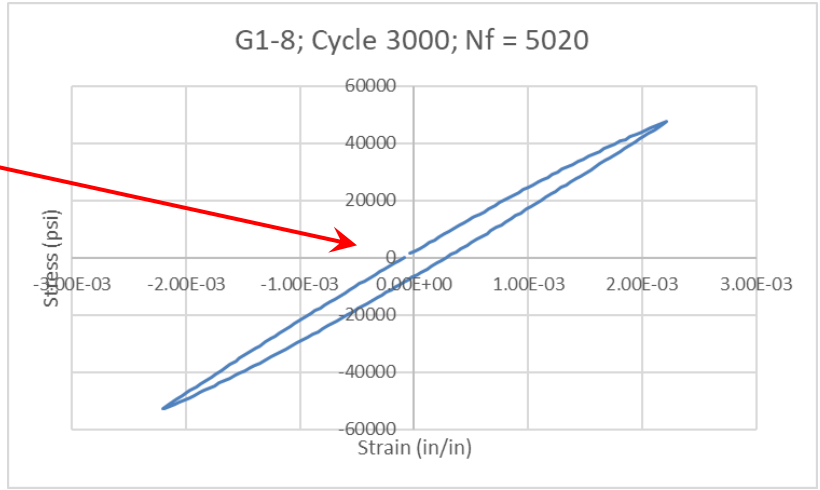
WARNING:EXTERNAL EMAIL!

using only the small loop, I get E = 26.3 Mpsi

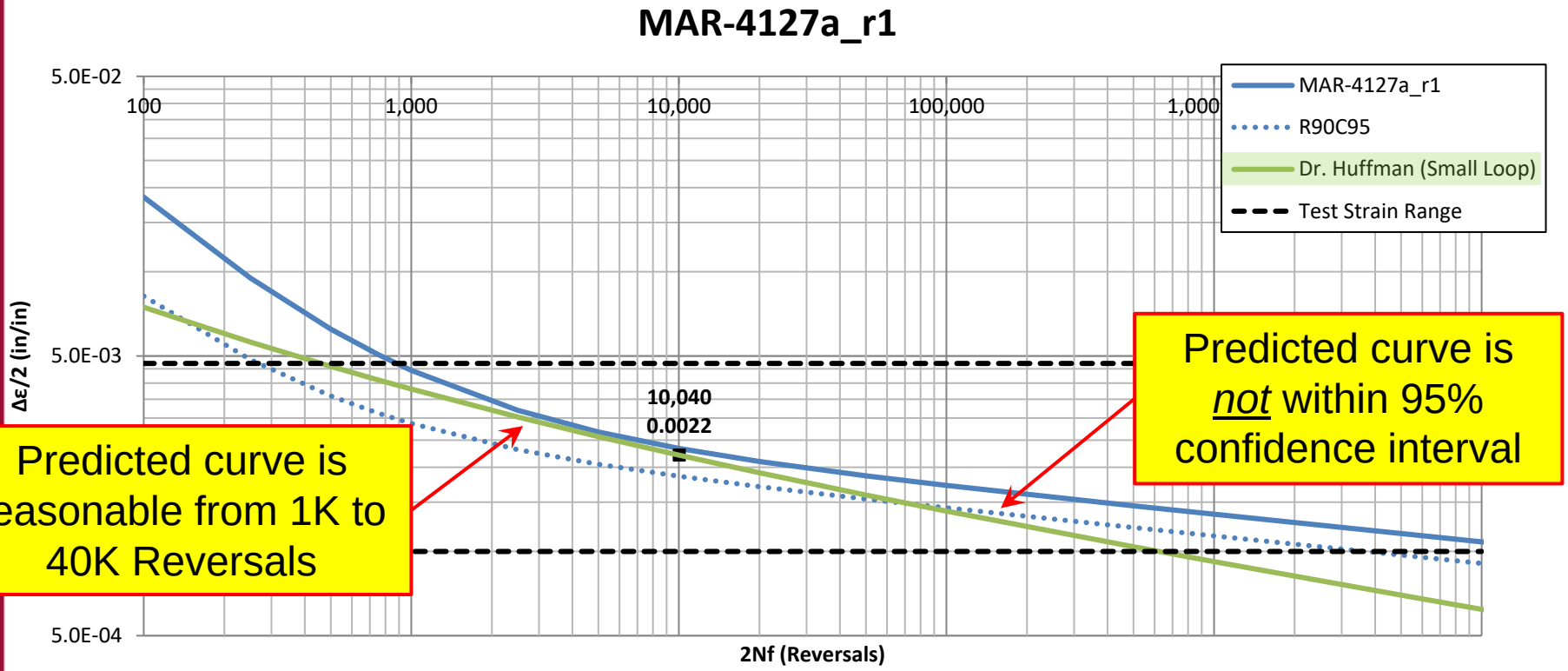
n' = 0.3173
K' = 63.1 ksi

Sf' = 221 ksi
b = -0.1626
ef = 0.037
c = -0.5123

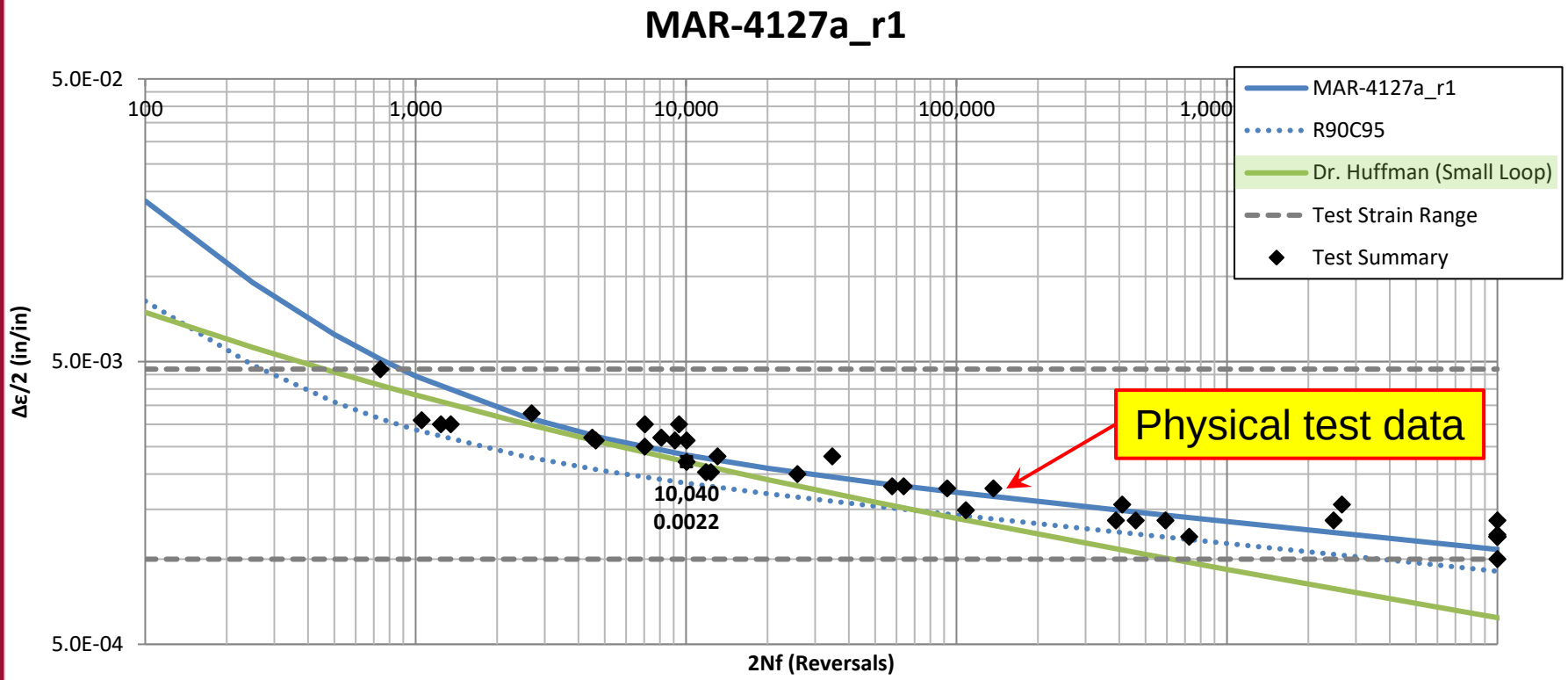
Prediction from loop with smaller hysteresis



ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



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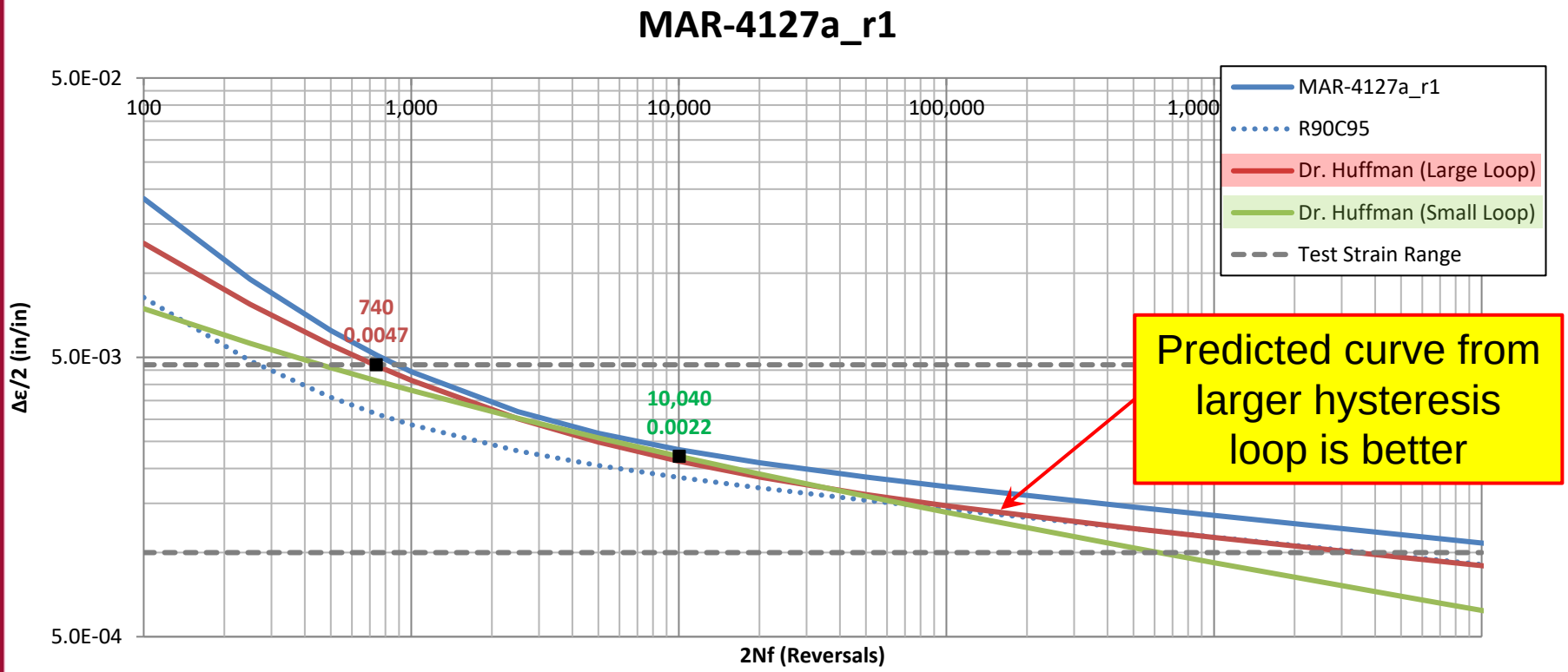
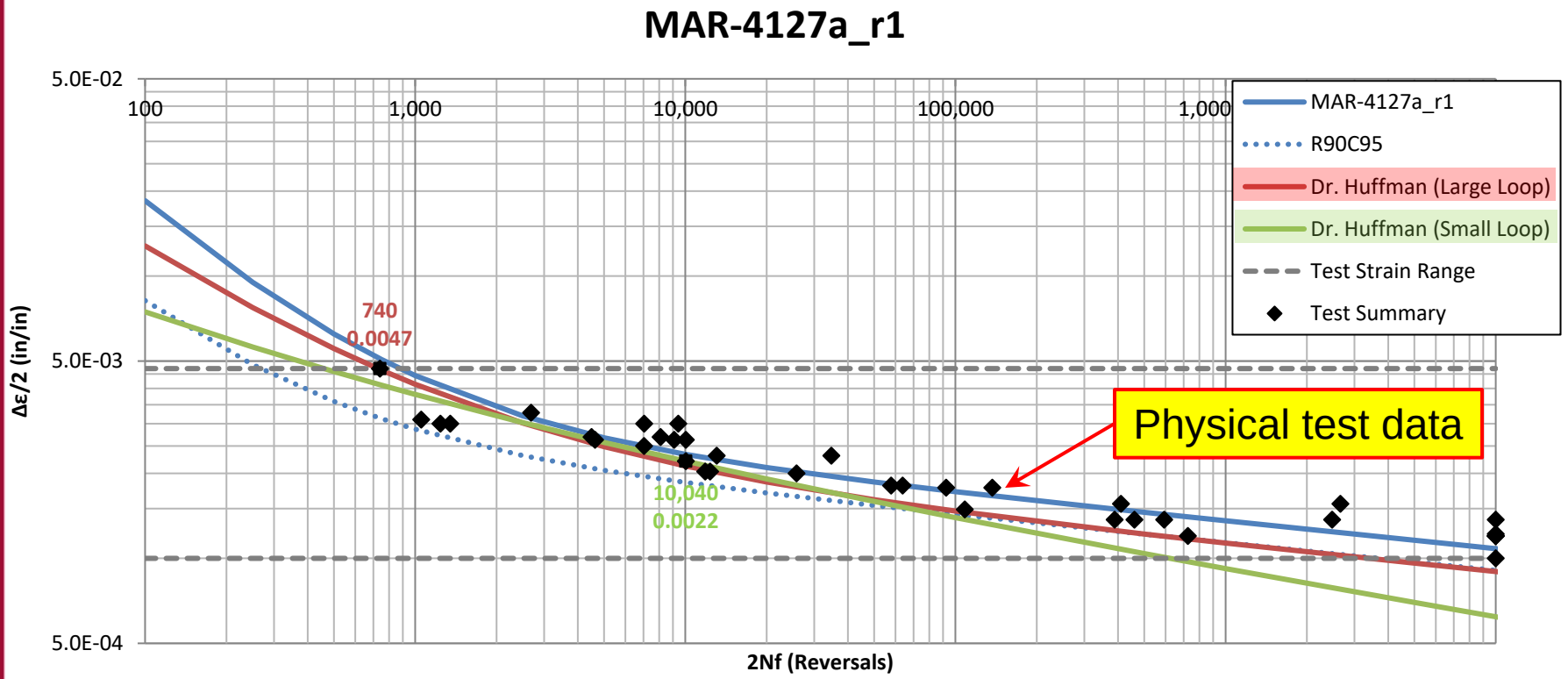
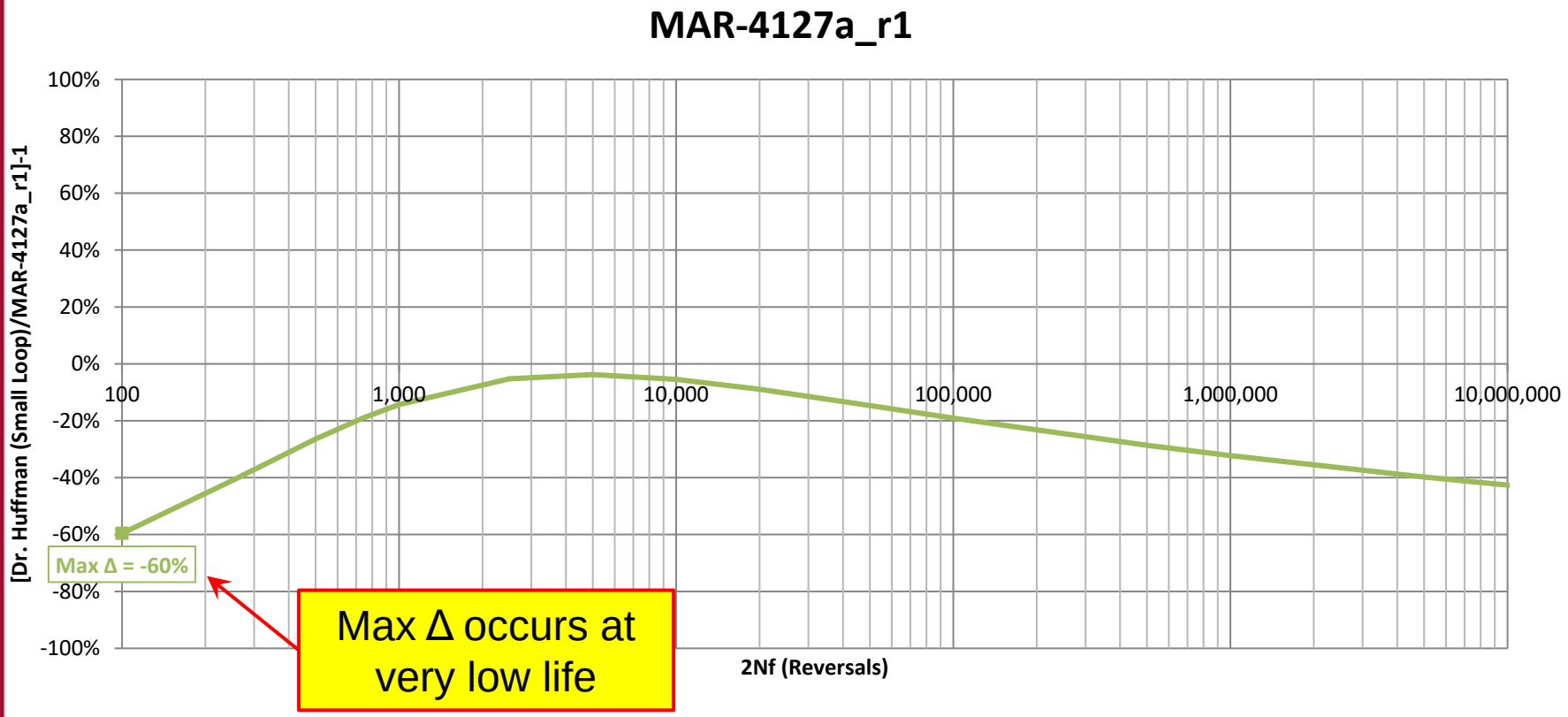
ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



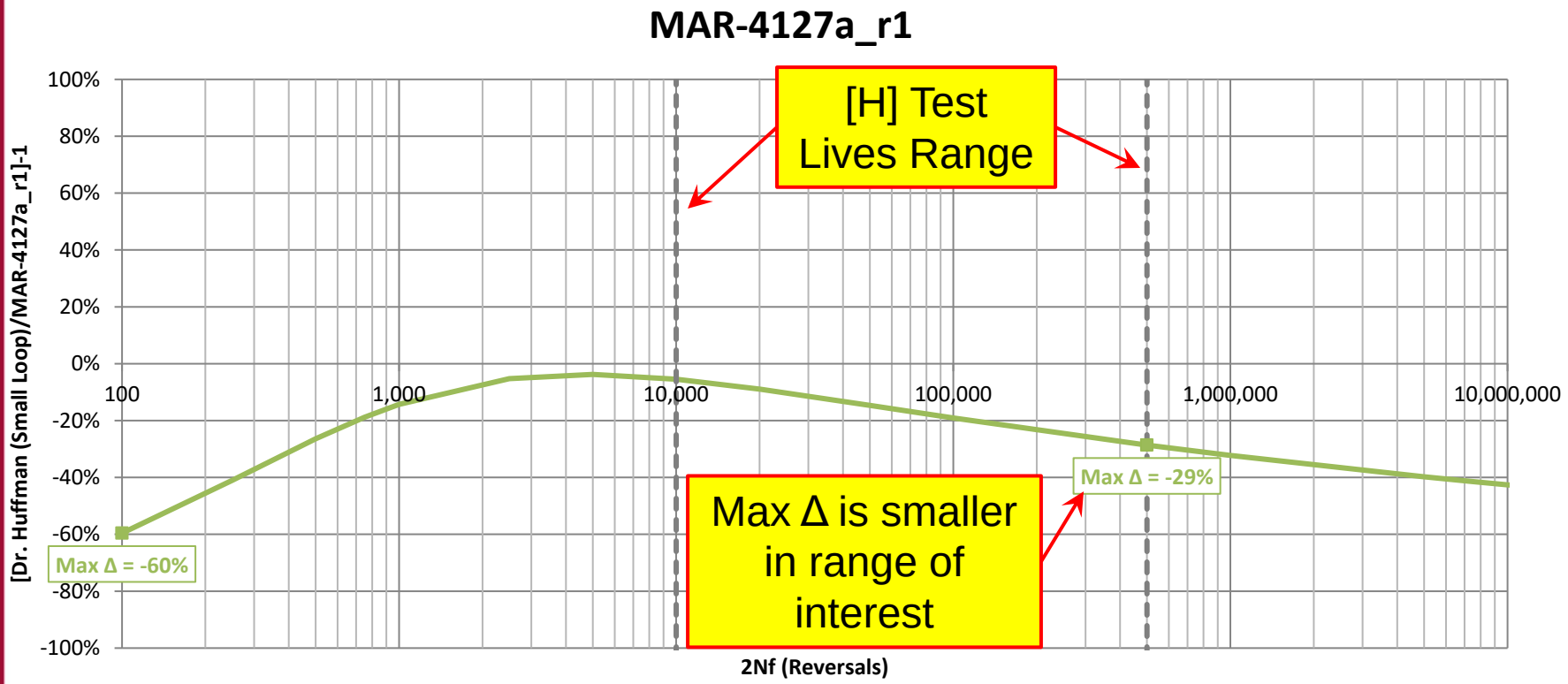
ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



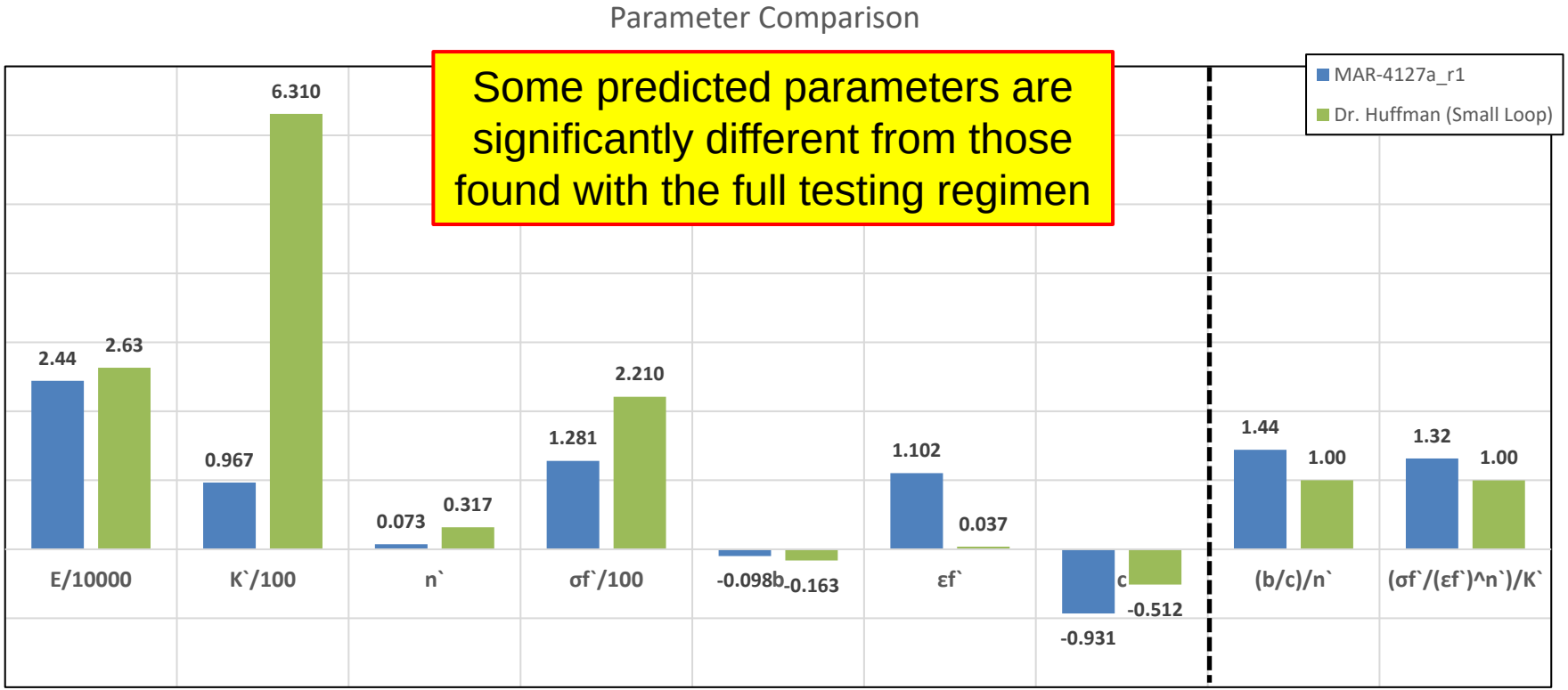
ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



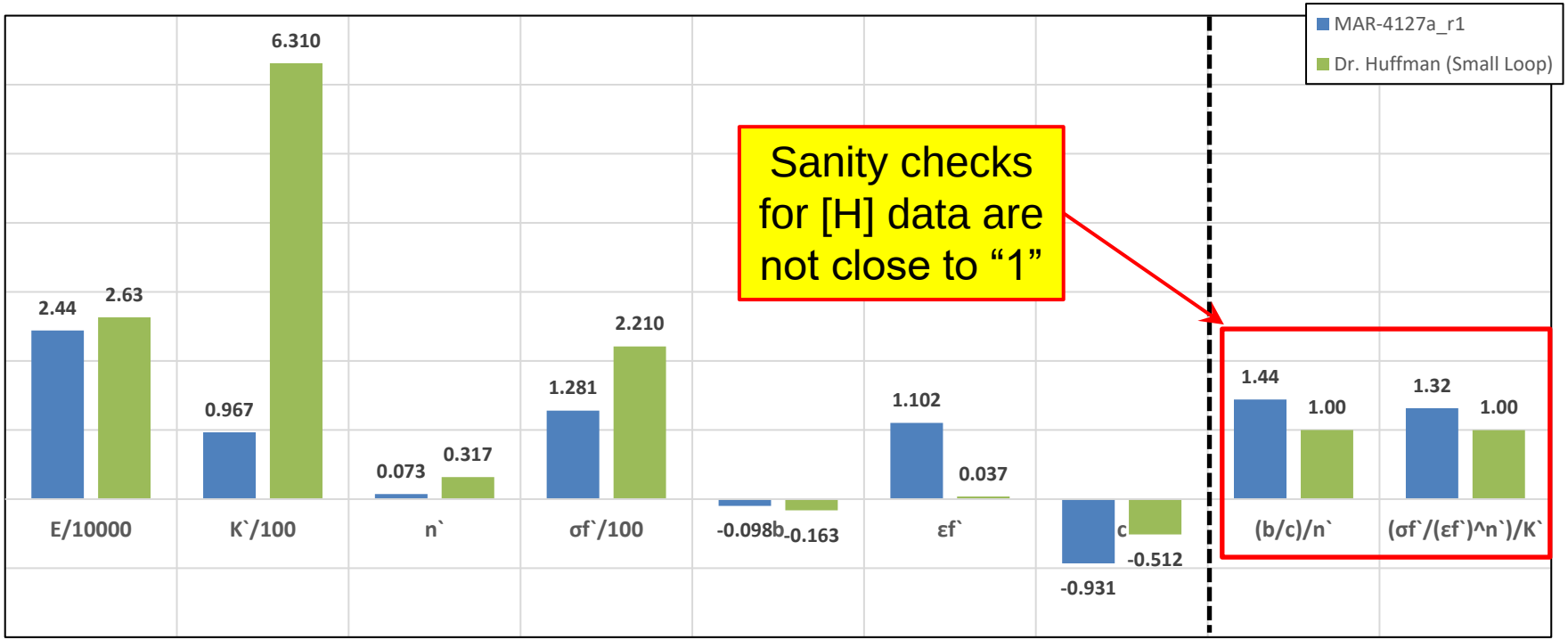
ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



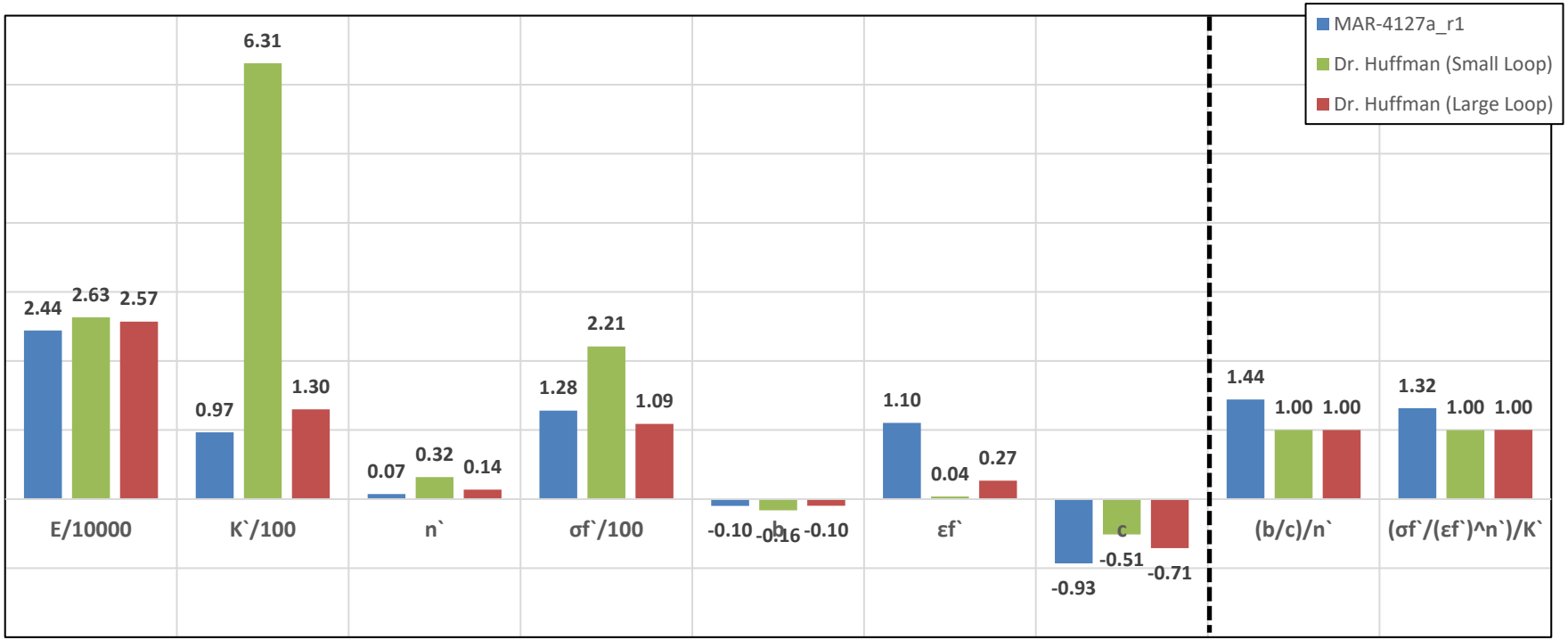
ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Both Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…



ε-N Curve Prediction (Small Hyst. Loop): Dr. H MAR-4127aR1 – D65-45-12…

- **Conclusions…**
  - **To test the method, MAR data was provided to Dr. Huffman…**
    - **MAR-4127a r1 – D65-45-12**
    - **Small hysteresis loop and corresponding $2N_f$.**
  - **The predicted curve…**
    - **Was a poor match (~61%) over parts of the strain range.**
    - **Matched reasonably (~31%) within the normal range of [H] testing.**
    - **Was not within the 95% Confidence Interval over parts of the strain range.**
  - **The Predicted Parameters…**
    - **Showed significant variation.**
    - **The [H] data sanity checks were not close to one.**

ε-N Curve Prediction (Hyst. Loops): Dr. Peter Huffman - Conclusions…

- The predicted curves, generated from a single high strain test, matched the final [H] test data very well over the range of interest…
  - Within ~30% while the 95% Confidence Interval was much larger.
- The Predicted Parameters…
  - The [H] data sanity checks were sometimes close to one.
  - [H] fitting method?
- Overall, the results look promising.

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