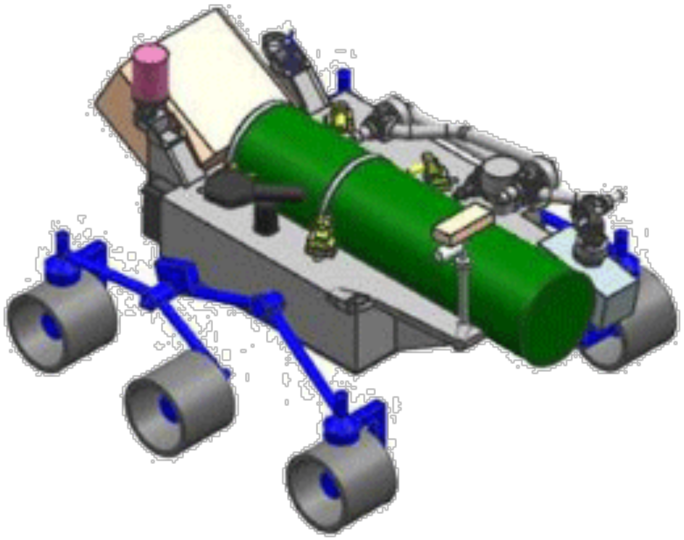
Mars Ascent Vehicle Hybrid Motor Structural Analysis

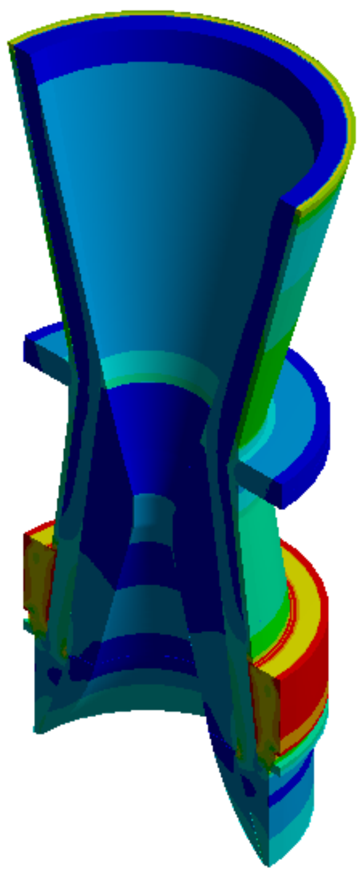
MSFC - James Luce ER41 (Summer intern program)

Background: the MAV

- MAV: Mars Ascent Vehicle (MAV) is a small rocket being designed to launch samples from the surface of Mars to orbit.
- The MAV would likely be launched from a rover similar to Mars Science Laboratory.
- The MAV would rendezvous with another spacecraft and return to earth.
- Three propulsion designs being considered, including hybrid fuel.

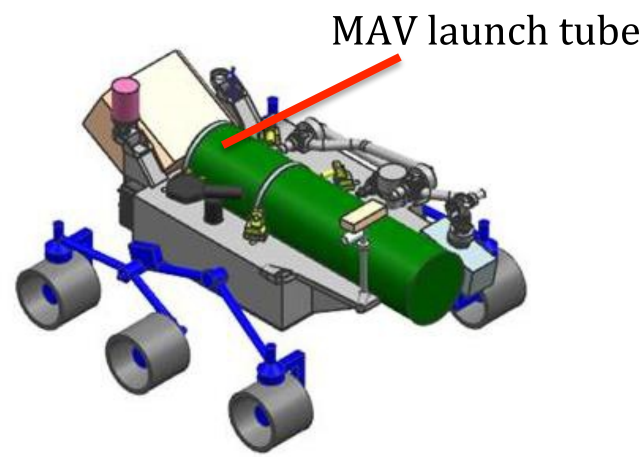


- Structural analysis looks at geometry, materials and loads and asks: will it break?
- Analysis was conducted by hand calculations and using finite element analysis (FEA) software (ANSYS).
- These were static analyses, i.e. not moving parts, fluids, or vibration simulations.
- Three different parts of the rocket were analyzed:
  - **Fuel**
  - **Motor casing**
  - **Nozzle**

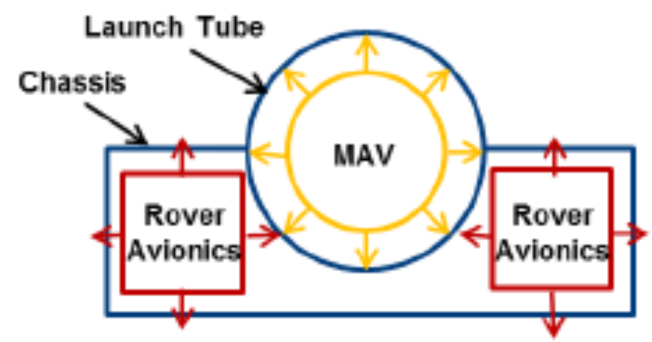


Background: MAV thermal issues.

- Mars gets very cold (~ -100C at night)
- Mars sees significant temperature fluctuations each sol.
- The MAV would have to spend a long time (~ 1 year) on the surface.
- This is not a nice environment to store a rocket in.
- A hybrid motor is an propulsion option to try to mitigate these problems.



Mission Concept for a Mobile MAV rover of a similar size and weight as MSL and Mars 2020.[1]



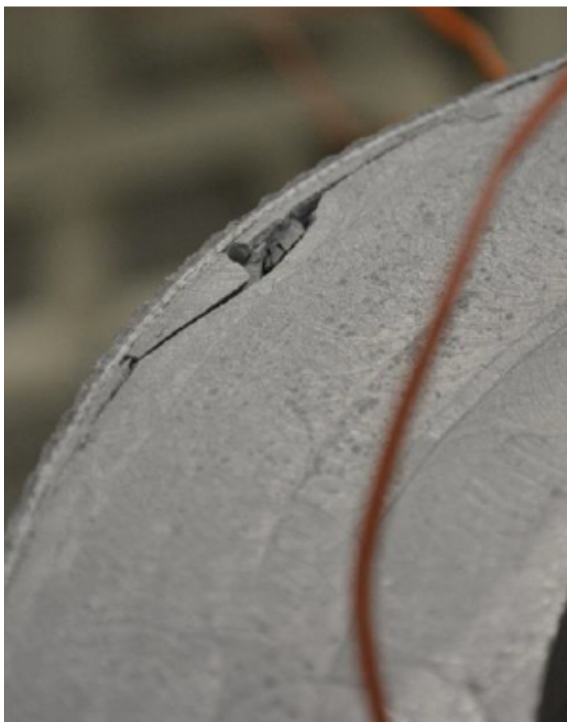
Notional dimensions, configuration, and heat loss diagram for a MAV thermal design concept.[1]

Analysis 1: Hybrid fuel grain

A new hybrid fuel was developed for the MAV. In environmental testing (thermal cycling at cold temperatures) the fuel grain experienced cracks.

The goals of conducting a structural analysis were:

- Understand why the samples cracked as they did.
- Investigate mitigation options to aid future design decisions.



Circumferential (debonding)

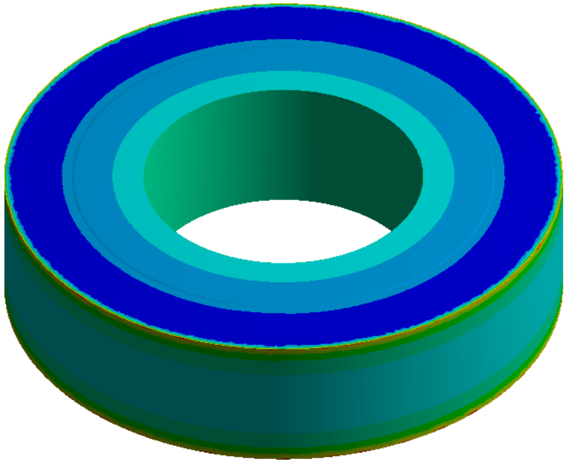
Circumferential (debonding) & radial

Radial

Analysis goals

- This analysis modeled the thermal stresses caused by the low temperatures seen in the environmental testing.
- This was a **comparative analysis.** Instead of saying "the fuel will crack at *this* temperature", it said "making these changes should help".

Fuel sample for thermal cycle testing.[1]



Fuel sample model showing strain effects.

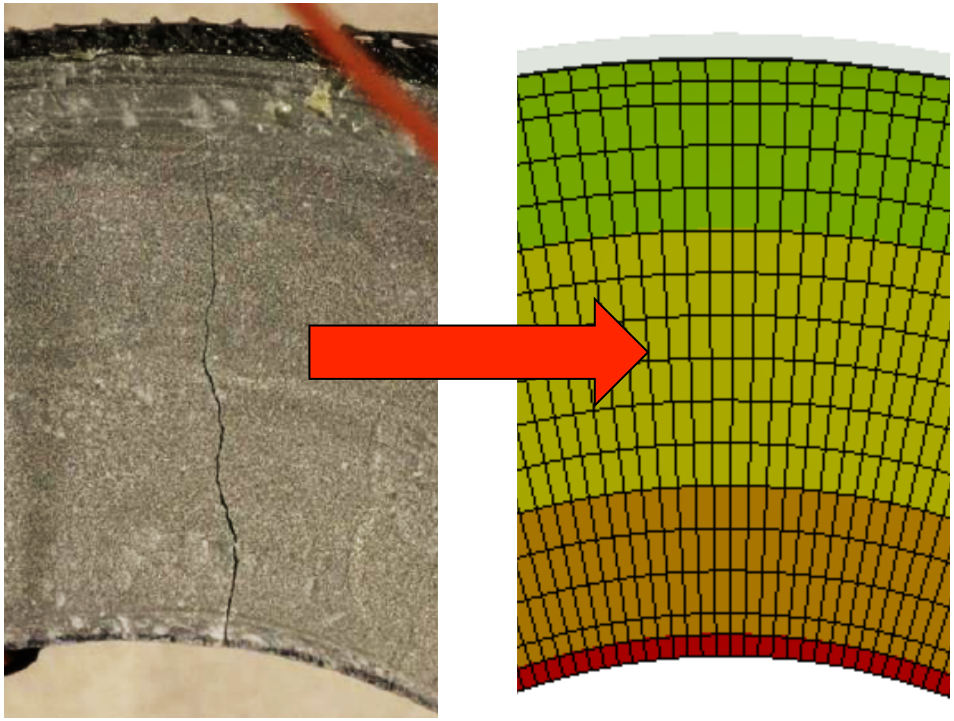
Bad input

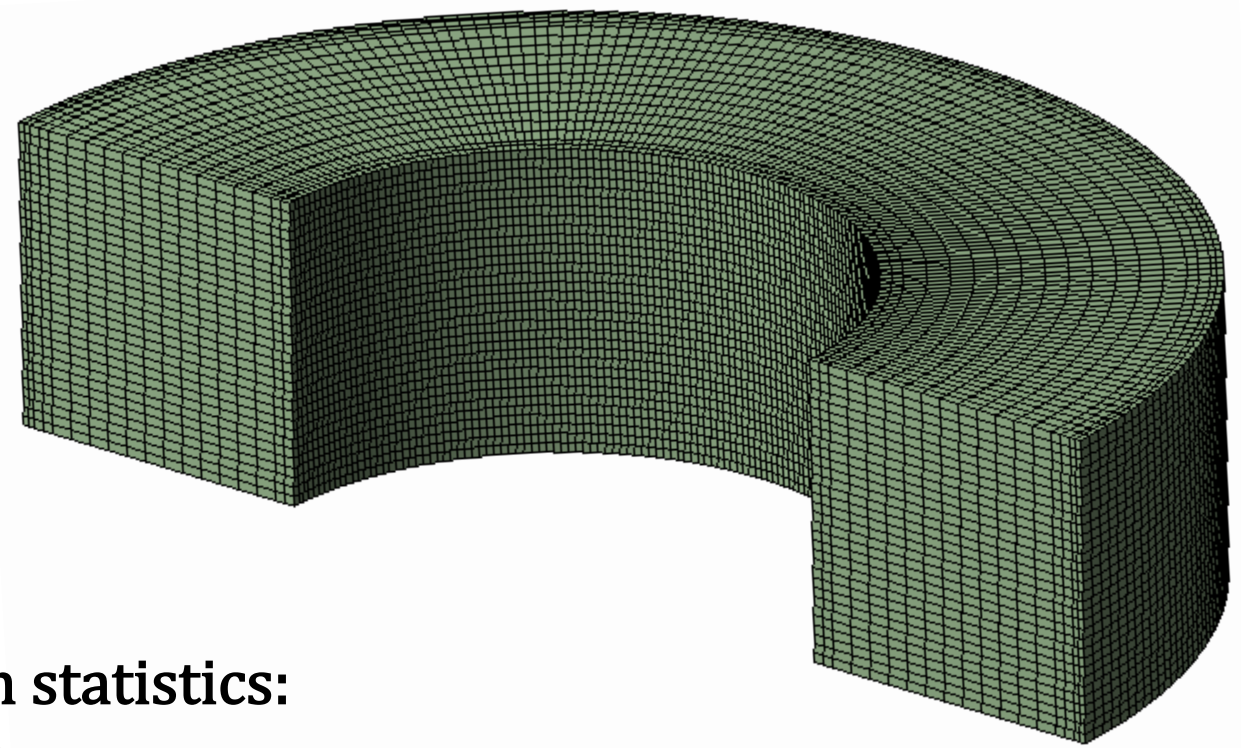
- **Most of the mechanical properties of the fuel were unknown.**
- The most important properties were:
  - The coefficient of thermal expansion.
  - It's strength (elasticity).
  - It's Poisson's ratio.
- The fuel is similar to paraffin wax, so those properties were substituted.
- Because we weren't sure of properties, we couldn't say "the fuel will crack at *this* temperature."
- This is why is was a comparative analysis: **Bad input = bad output.**

- Finite element analysis: Geometry is modeled as a mesh of small elements to find the distribution of stresses, strains, or other effects.

- FEA gives pretty output, but …

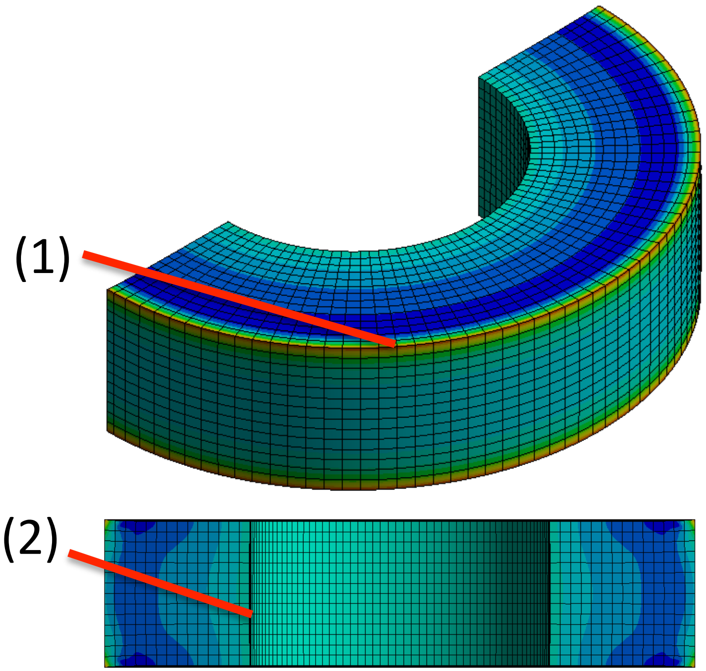
  bad input = bad output.



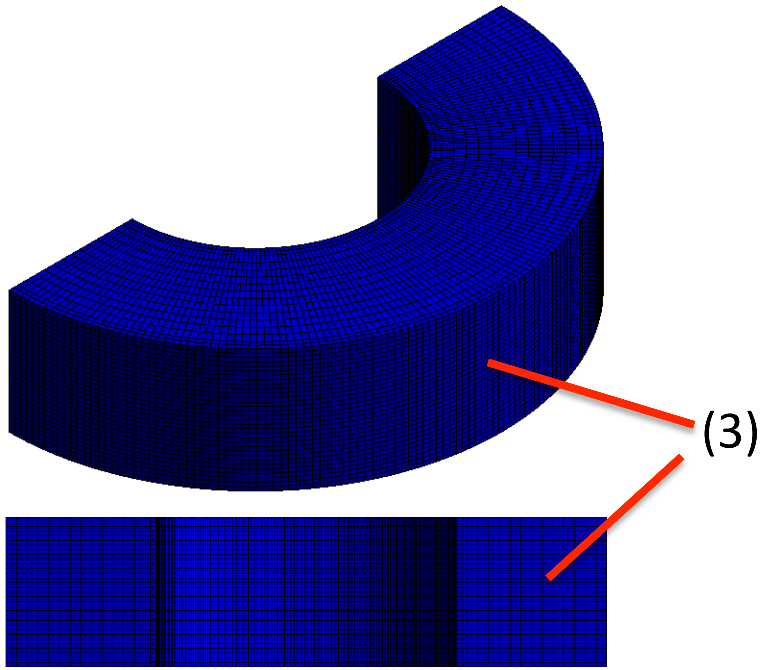


Example mesh statistics:
343213 nodes
80064 elements

Why did the samples crack?



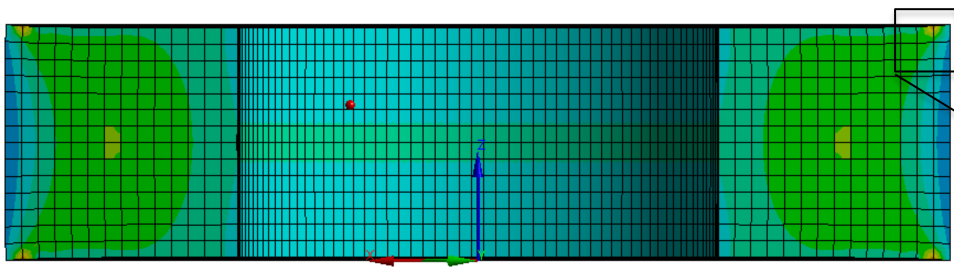
Von Mises stress in fuel grain with casing (casing not shown)

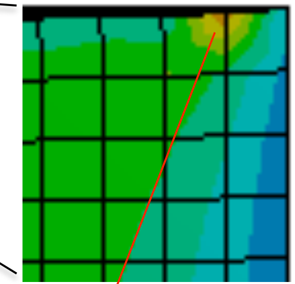


Von Mises stress in fuel grain without casing

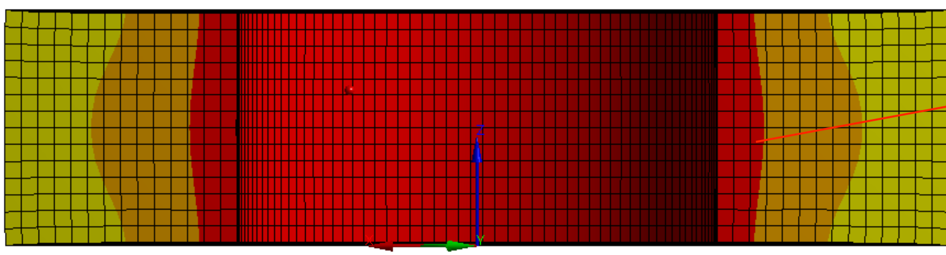
The SP7 fuel has a higher coefficient of thermal expansion (CTE) than case and insulation materials. Under cooling conditions, stress arises as the fuel wants to pull away from the case radially (1). When it cannot, the fuel pulls away from itself circumferentially at the bore (2). Without a case, no significant stresses arise (3).

Strain directions





Radial strain

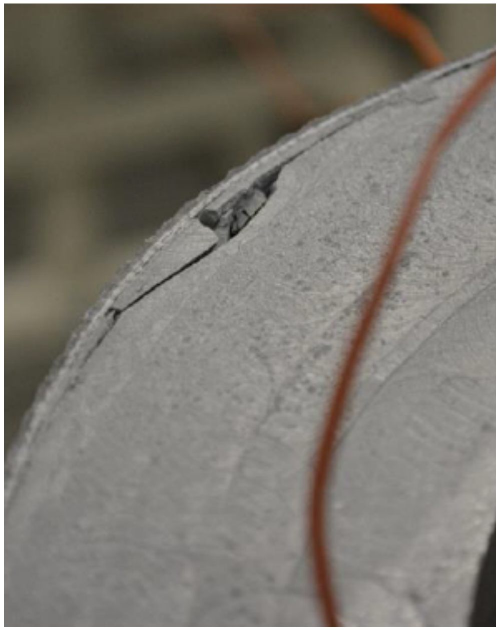


(1) (2)

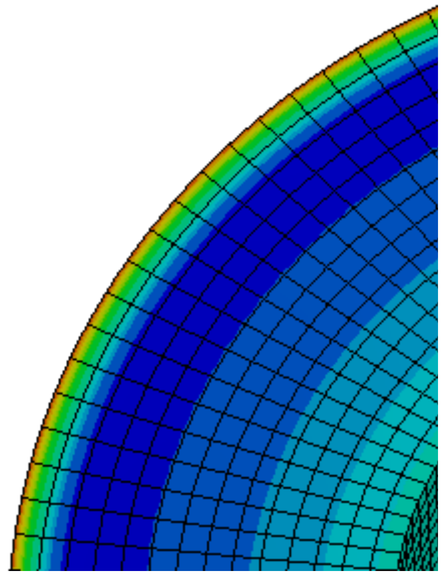
Circumferential strain

The highest strains in the model appear circumferentially at the inner bore (1) and radially just inside of the rim (2). (consistent color scale)

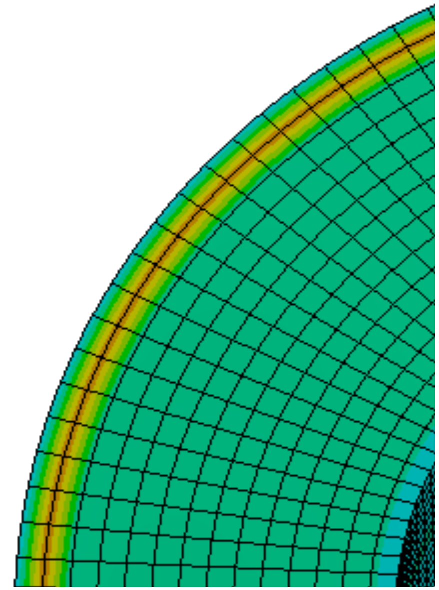
Debonding crack causes



Cracked sample



Radial stress

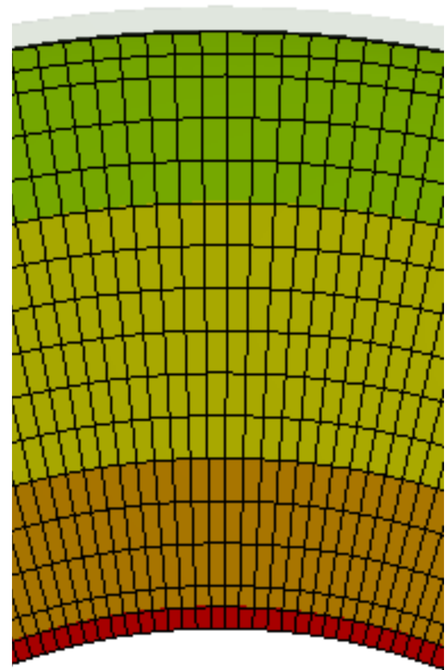


Radial strain

Strain at the outer edge of the fuel grain is tensile and acts to pull the fuel away from the case, causing the fuel to either debond from the case or fracture near the bonding surface.

Radial crack causes

Radial cracks



Circumferential strain

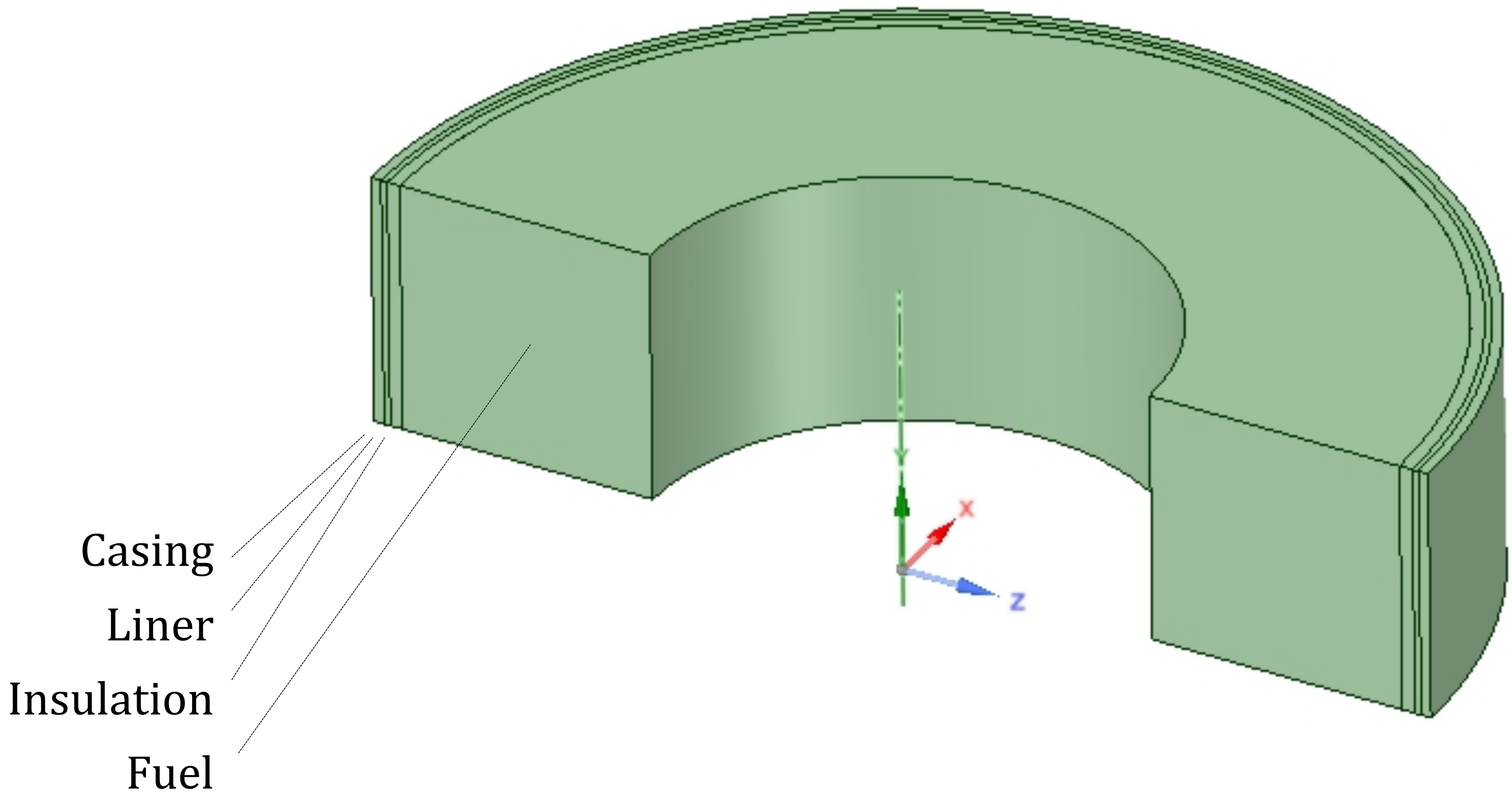
Circumferential strain at the inner bore is tensile and acts to pull the fuel away from itself, causing radial fractures.

Mitigation options

Fuel

Composite Casing

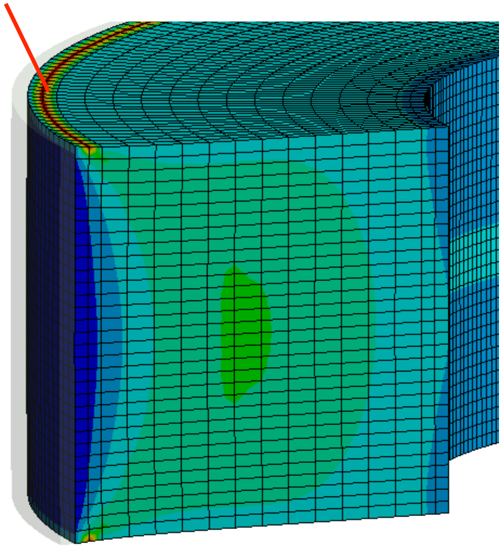
Mitigation options



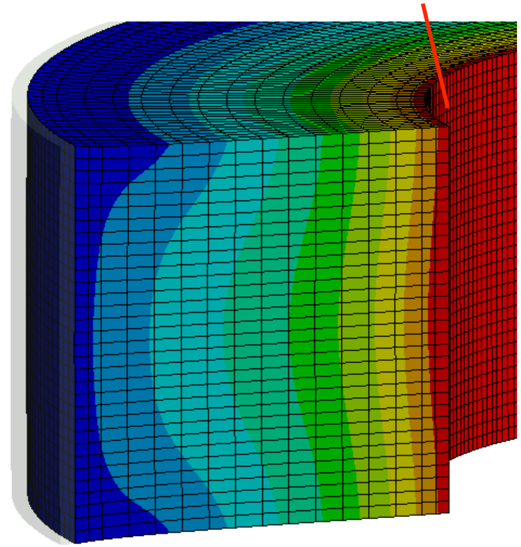
Effect of case material (no insulation)

Case material (0.1”)	“CF 230”	“CF 395”	Ti-6Al-4V	304 SS
CTE (/F) @ 68F	1.22E-6	1.39E-6	4.9E-6	8.44E-6
E (ksi) @ 68F	8900	13300	16300	28300
Radial strain at case	Reference	+23%	+42%	+56%
Circ. strain at bore	Reference	+5%	+2%	0%

Radial strain at case



Circumferential strain at bore



Effect of case material (with insulation)

Case material	Ti-6Al-4V	Ti-6Al-4V	“CF 230”	304 SS
Case CTE (/F) @ 68F	4.9E-6	4.9E-6	1.22E-6	8.44E-6
Case E (ksi) @ 68F	16300	16300	8900	28300
EDPM insulation	None	0.125”	0.125”	0.125”
Radial strain at case	Reference	-89%	-94%	-86%
Circ. strain at bore	Reference	+1%	0%	-1%

When a thin layer of insulation is used, there is a significant reduction in stress and case material becomes unimportant.

Effect of insulation thickness

Case	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
EDPM insulation	None	0.125”	0.25”
Radial strain at case	Reference	-89%	-102%
Circ. strain at bore	Reference	+1%	+5%

Doubling the thickness of the insulator only causes a slight reduction in debonding strain and a slight increase in radial crack strain.

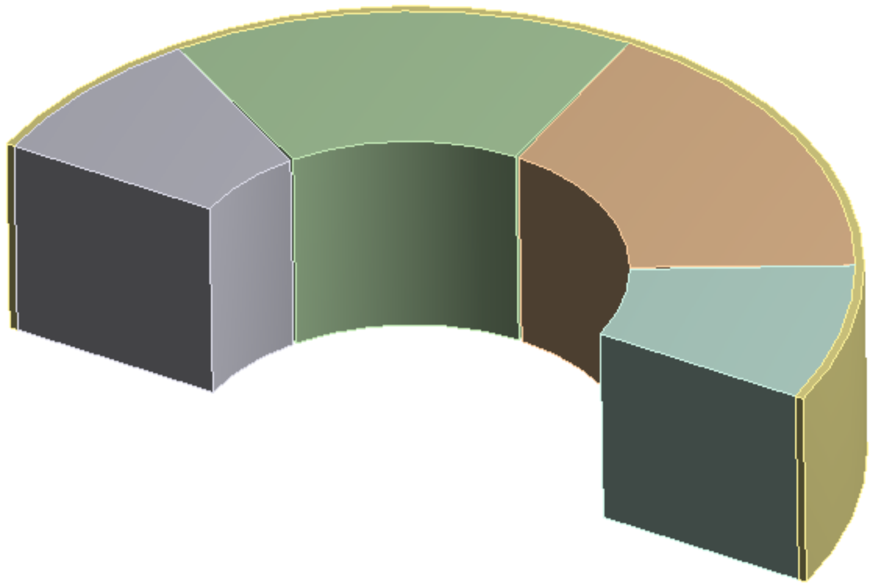
Effect of insulation type

Case	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Insulation type	None	EPDM	SCP	“Liner”
Insulation thickness		0.125”	0.125”	0.0625”
Insulation radial CTE (/F) @ 68F		4.2E-5	2.02E-5	7.6E-5
Insulation radial E (ksi) @ 68F		4.4	3400	0.4
Radial strain at case	Reference	-89%	-27%	-83%
Circ. strain at bore	Reference	+1%	-4%	-8%

A harder insulator (SCP) does not significantly reduce debonding strains like a softer insulator (EPDM) of the same thickness.

A very soft liner (“Liner”) can be very thin and reduce both radial debonding strains significantly.

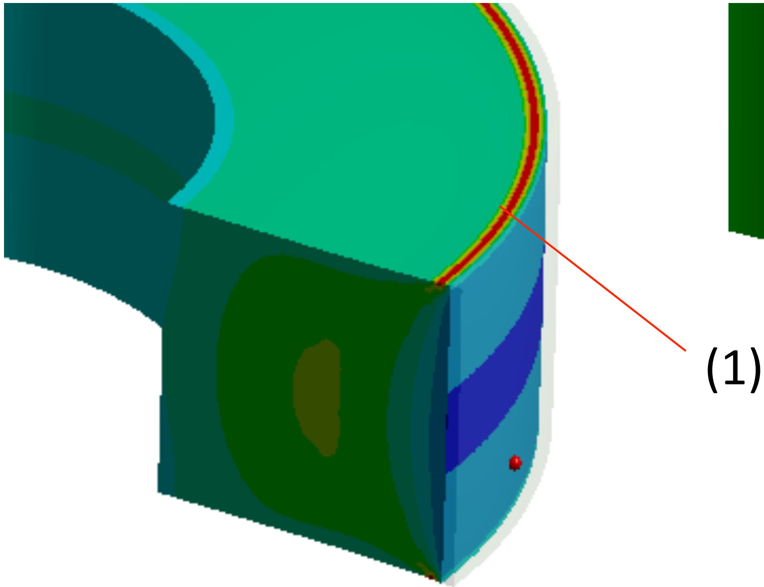
Design option: segmented grain



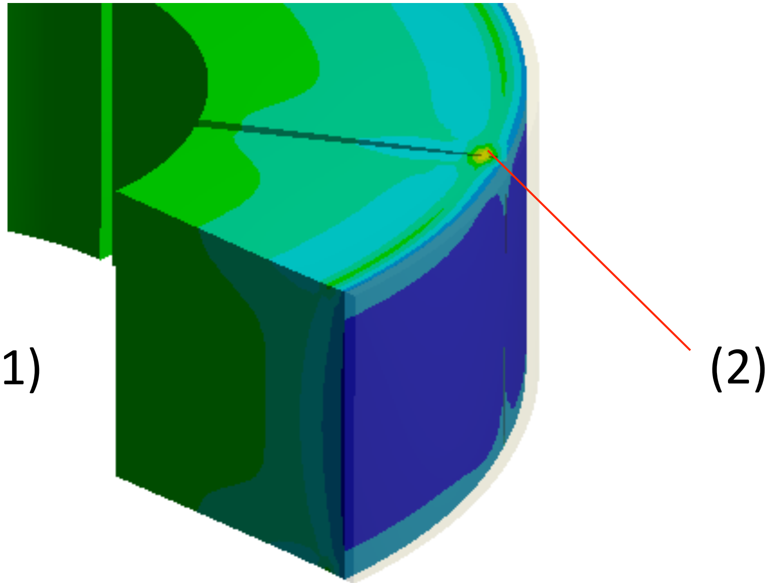
One design suggestion was to relieve stresses by designing the grain to have radial divides.

This idea is similar to seeing what stresses and strains might arise when radial cracks propagate from the bore through to the case.

Segmented grain (radial strain)



Radial strain,
normal grain geometry

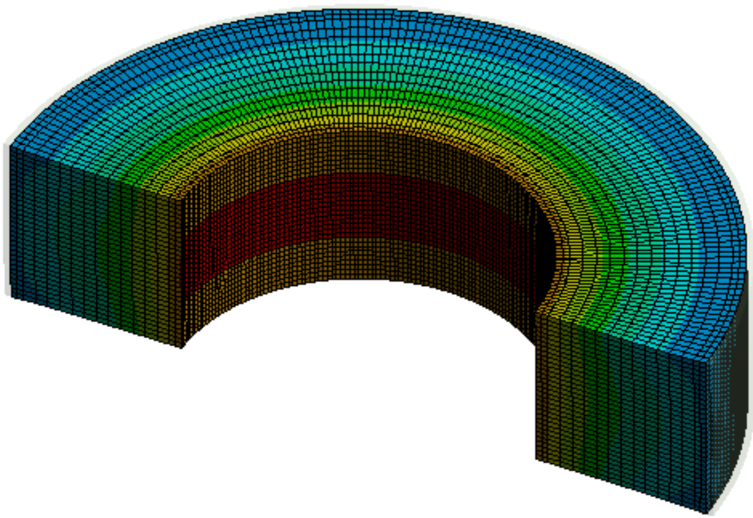


Radial strain,
segmented grain geometry

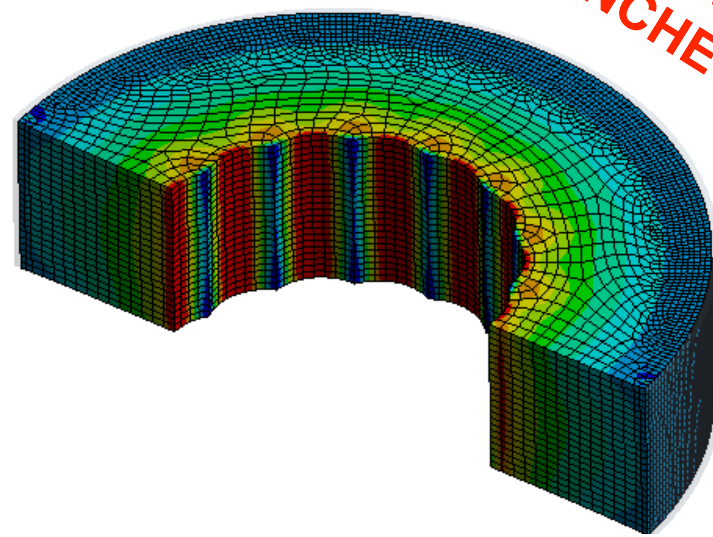
The segmented grain eliminates the zone of radial strain along the rim of the grain (1). However, a new strain zone appears, running axially where the segments meet and are bonded to the case (2).

Design option: bore shaping

PRELIMINARY UNCHECKED



Circumferential strain, simple bore



Circumferential strain, shaped bore

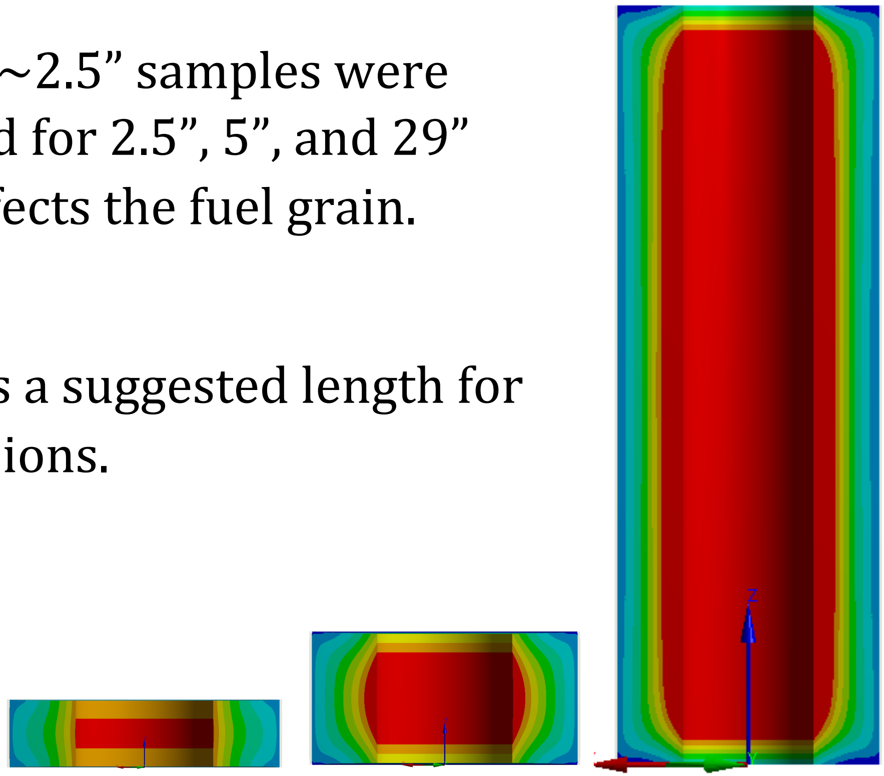
A suggested bore design was modeled as a possible way to help relieve strains, but the model did not see benefits.

Case	Ti-6Al-4V	Ti-6Al-4V
Bore	Simple	Shaped
Radial strain at case	Reference	+49%
Circ. strain at bore	Reference	+33%

Effect of axial length

In the thermal cyclic test, ~2.5” samples were used. Models were created for 2.5”, 5”, and 29” to examine how length affects the fuel grain.

29” was modeled as it was a suggested length for the motor in prior discussions.



Case	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Height	2.5”	5”	29”
Radial strain at case	Reference	+136%	+112%
Circ. strain at bore	Reference	+27%	+94%

Grid of models

Model	1	2	3	4	5	6	7A	7B	8	9	10	11	12	13	14	15	16	17	18
230 GPa CF case	x							x											x
395 GPa CF case		x															x	x	
304 SS case			x				x												
Ti-6Al-4V Ti case				x	x	x			x	x	x	x	x	x	x	x			
0.0625” Liner					x														
0.125” EPDM						x	x	x			x		x						
0.125” SCP									x										
0.25” EPDM										x									
Constant OD											x								
Segmented grain												x	x						
Bore shaping														x					
29” height															x				
5” height																x			
Comp. zone geom.																	x		
Comp. zone geom. low E																		x	
High CTE SP7	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
Low CTE SP7																			x

Analysis 1: Conclusion

- Model corroborates failures seen in testing
- The model suggests that CTE differences among case materials not significant
- The model suggests that a soft layer (liner, insulation) will reduce debonding risk but not radial crack risk
- Both debonding and radial crack strains increase significantly with axial length of motor

Analysis 1: Future work

- Additional fuel material property testing is needed.
- Low temperature (<80C) insulation properties are needed.

Analysis 2: Motor case thickness

The second analysis looked at the thickness of the motor casing considering the expected loads during launch.

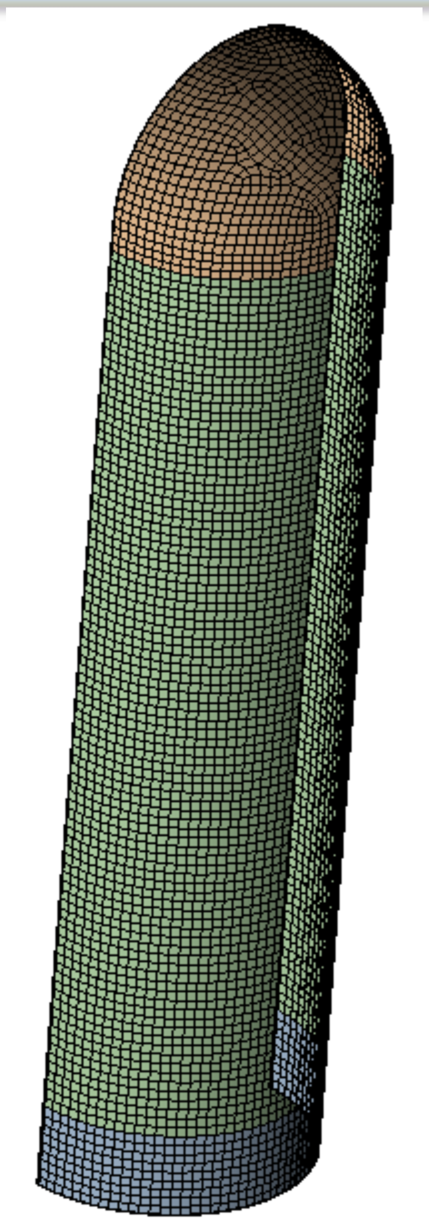
There were two approaches to this analysis:

- **Examine stresses based on minimum manufacturing thickness.**
- **Establish minimum design thickness.**

Mesh statistics:

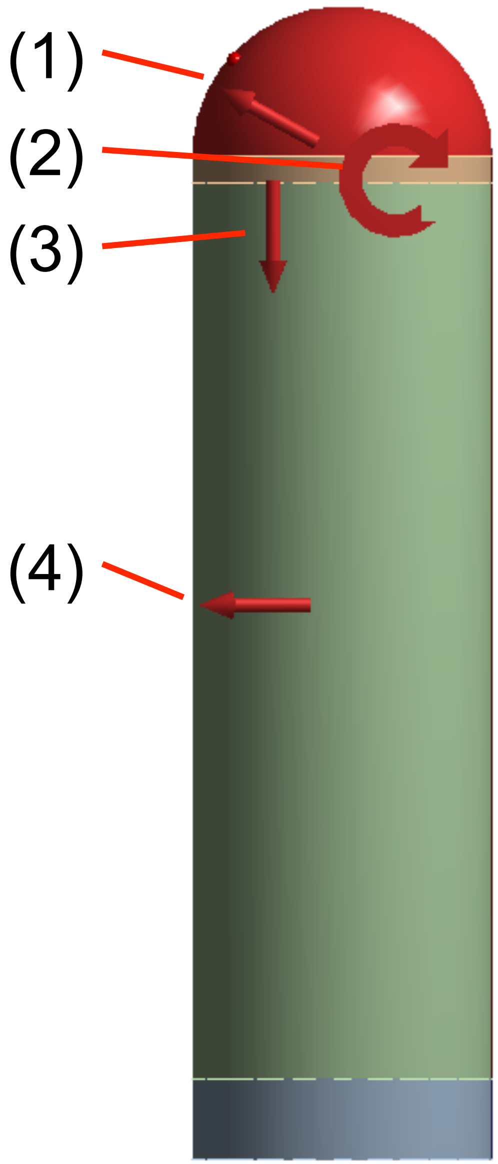
- 10593 nodes
- 10495 elements

Model is a cylindrical surface represented with shell elements.

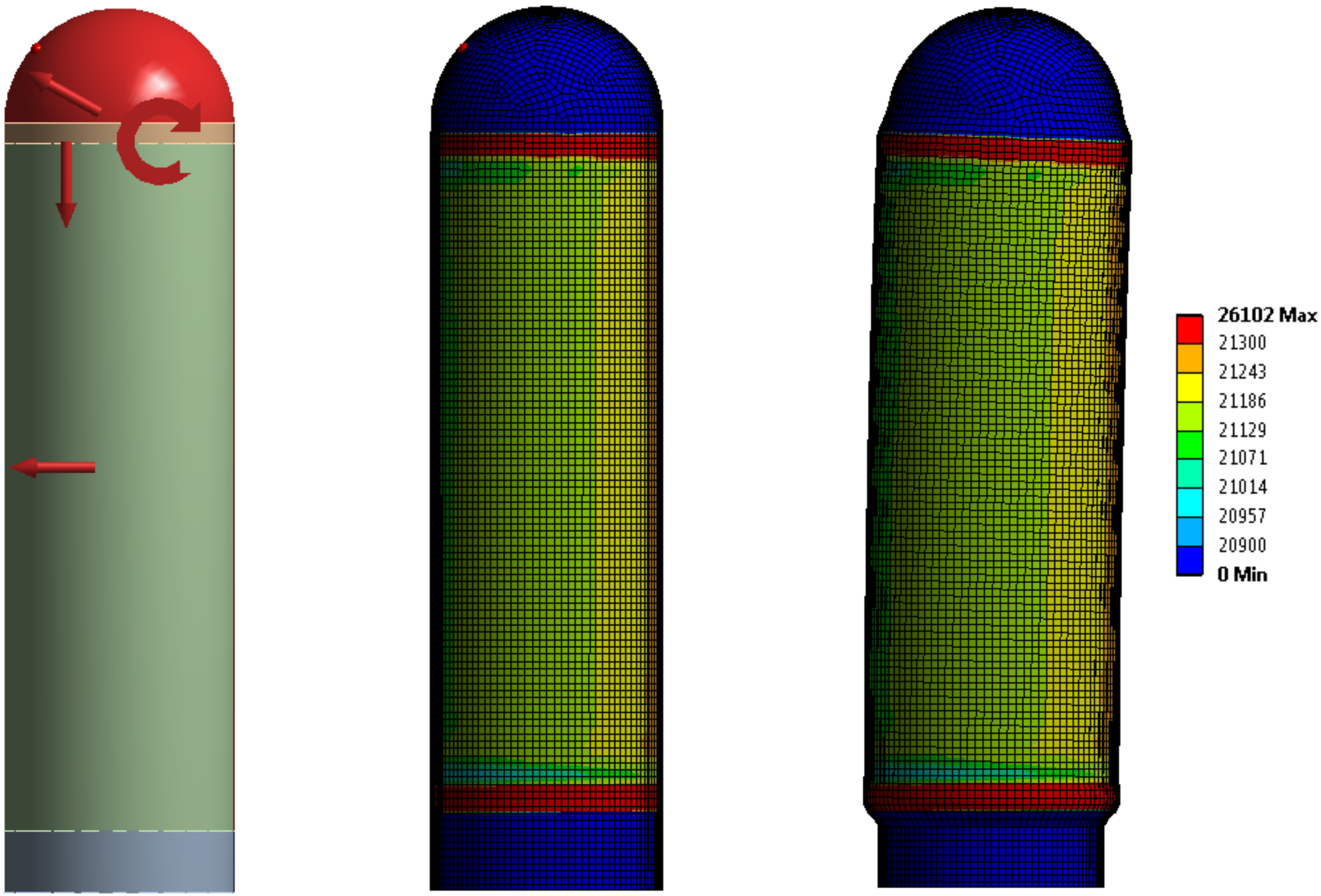


Loading:

1. Cap internal pressure.
2. Thrust vector control.
3. Axial launch load.
4. Inner surface pressure.



Stresses



Loads

True deflection

100x deflection

Minimum thickness FS

All loads: Pressure, LITVC moment, axial thrust			
	Max model stress (ksi)	Yield strength	Factor of safety
Hoop	26.8	126 ksi	4.7
Axial	29.2		4.3
von Mises	**26.1**		**4.8**

If we assume the minimum machinable wall thickness for a titanium casing, we end up with much higher factor of safety than is necessary (and extra mass!), so what if we *could* make it thinner?

Finding ideal thickness

Given a lower factor of safety (1.4), how thin could the wall be?

$$\sigma_{z.\,bending} = M*c/I = F_{litvc}*CG_z*\frac{d_i+2t}{2} \Big/ \frac{\pi}{64}\left((d_i+2t)^4-(d_i)^4\right)$$

$$\sigma_{z,\;launch} = F/A = -m*a/A = -GLOM*6.67*g \Big/ \frac{\pi}{4}\left((d_i+2t)^2-(d_i)^2\right)$$

$$\sigma_{z,\;pressure} = P*r/2*t = P*d_i/4*t$$

$$\sigma_z = \sigma_{z.\,bending} + \sigma_{z,\;launch} + \sigma_{z,\;pressure}$$

$$\sigma_\theta = P*r/t = P*d_i/2*t$$

$$F_{ty} \geq FoS\sqrt{\sigma_z^2+\sigma_\theta^2-\sigma_z\sigma_\theta}$$

Finding ideal thickness

$$m*a = GLOM*6.67*g$$

$$F_{crit} = \pi^2 * E*I/(K*L)^2 = \pi^2 * E*\pi/64\,((d_i + 2t)^4 - (d_i)^4)/(K*L)^2$$

$$FoS = F_{crit} / F_{launch}$$

$$F = P*A = P*\pi/4*(d_i)^2$$

$$CG_z = \sum m*C_z / \sum m$$

(Etc. etc.)

Analysis 2 conclusion

The outcome of determining thickness based on desired FS is that the vast majority of weight in this design, as limited by manufacturing technique, is unnecessary, suggesting that a **different material may be appropriate.**

	FS	Weight (lbs)	Mass (kg)
t=min	4.8	6.93	3.15
t=ideal	1.4	1.73	0.78

Analysis 2 future work

- More detailed loading and vibration data needed to refine FS.
- More detailed design needed to examine stress concentrations.
- Other materials or manufacturing techniques should be considered if design mass is unacceptable.

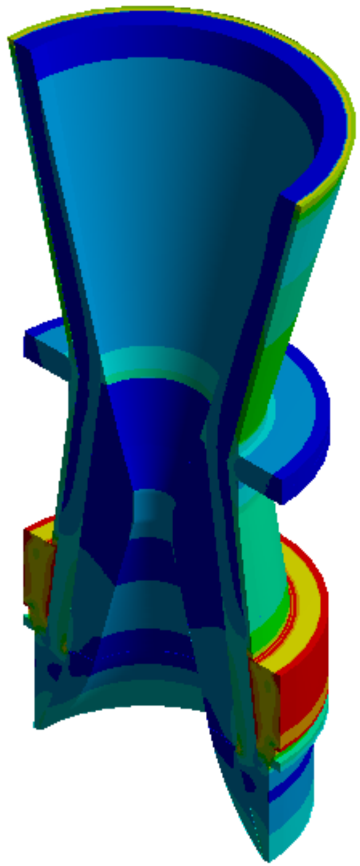
Analysis 3: Nozzle casing.

A third analysis looked into the stresses expected in the motor's nozzle.

This analysis was done as part of an iterative design loop with other teams:

- Performance (pressure, thrust, dimensions)
- Thermal (will it melt?)
- Design engineering (can it be manufactured?)

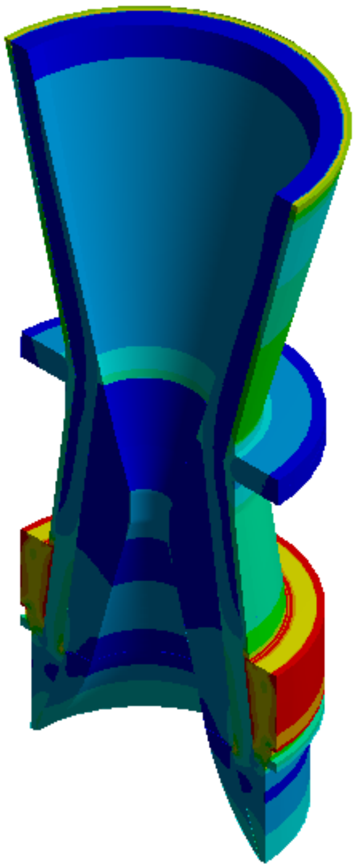
After these teams incorporated their needs into the design, it was handed to structural analysis: will it break?



Loading

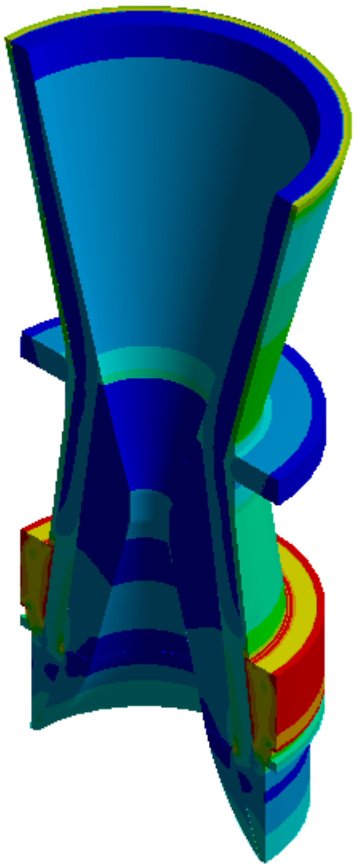
This was a much more complex analysis than the first two:

- True 3D FEA model with multiple components required.
- Launch pressure gradients incorporated into loading.
- Thermal gradients incorporated into model.
- 3D thrust vector effects considered, which required determining the center of gravity of the entire rocket.



First iteration conclusions:

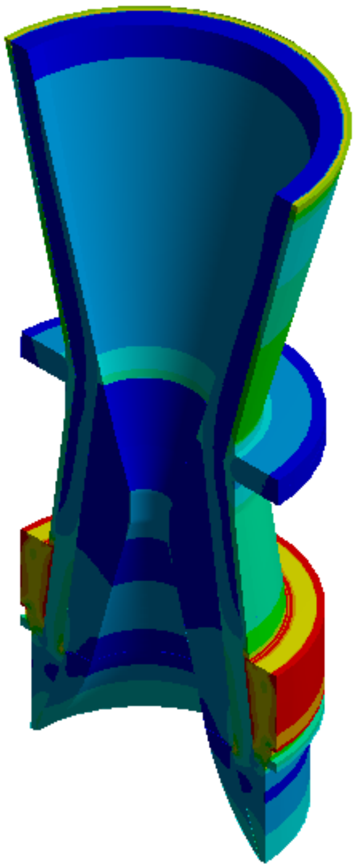
- The dominant stresses were caused by thermal gradients, not launch loads.
- The titanium casing was far thicker and heavier than it needed to be (factor of safety 16.8!).



This analysis was passed back into the loop of team members, who returned a second design.

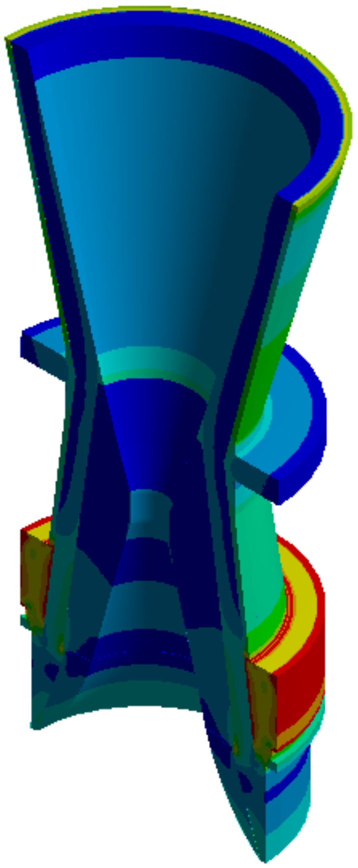
Second iteration conclusions:

- A significant amount of mass could be shed from the first design without reducing the factor of safety (29% reduction in mass, 0.1 reduction in FS).
- The design was still far heavier than necessary.



Future work

The ongoing refinement of iterations this design and model will continue, but not for this intern!



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Patrick Rogers (MSFC)

Tina Atchley (MSFC)

Catherine Lanier (OSGC)

Material properties: SP7 hybrid fuel grain

PRELIMINARY
UNCHECKED

Assumptions:

- Isotropic.
- Stress free temperature: 22 C.
- Pure paraffin properties are substituted where SP7 properties are unknown.
- Room temperature values were used where temperature dependent properties are unknown.
- Properties changes below glass transition temperature unknown.

CTE: ~8.3E-5 ft/ft*F

- Tabular CTE values for SP7 at temperatures ranging from -80 C to 60 C were derived from a plot of SP7 data.[1] The highest measured CTE value at any given temperature was used, creating a worst-case scenario for the model, as the fuel grain's CTE drives the stresses and strains.
- Source: AIAA Thermal Cycling for Development of Hybrid Fuel for a Notional Mars Ascent Vehicle

Tensile Young's modulus: 200 MPa, 29 ksi

- Value is for pure paraffin
- It is noted that the modulus of elasticity of wax rises dramatically as temperature lowers away from the melting temperature.
- Source: Tensile Tests of Paraffin Wax for Hybrid Rocket Fuel Grains, Table 2, low pull rate values averaged.

Poisson's ratio: .499

- Value is for pure paraffin
- 0.499 is an approximation of .5 for Ansys use.
- Source: Mechanics of Materials with Programs in C, section 2.8

Material properties: Insulations

EPDM insulation

	Circumferential	Axial	Radial
α (/F)	1.39E-05	4.22E-05	0.000242
E (MPa)	8500	3300	4400
v	xy : 0.3159	yz: 0.1763	xz: 0.6741

Assumptions: Properties are not temperature dependent, zero strain reference temperature: 22 C.
Source: Doc No, TWR – 17057, Revision A, Table 4: Storage conditions

SCP insulation

	Circumferential	Axial	Radial
α (/F), below 350F	9.78E-06	9.78E-06	2.02036E-05
E (MPa), below 70 F	23442	23442	17540
v	xy : 0.09	yz: 0.09	xz: 0.09

Assumptions: CTE and E known as a function of temperature at temperatures higher than this application. CTE value is applied as a constant below 350F, E applied as constant below 70F, zero strain reference temperature: 22 C.
Source: Internally provided ANSYS material file.

Liner

α (/F)	7.96E-05
E	400 psi, 2.76 MPa.
v	.4995

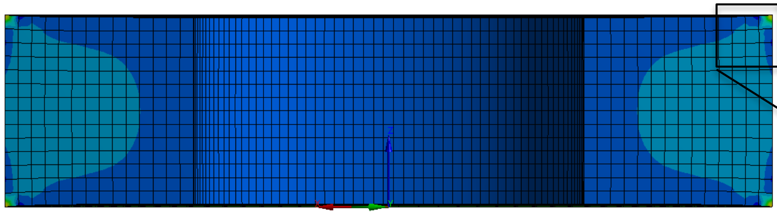
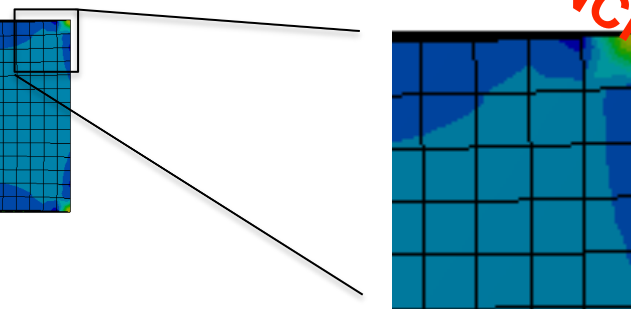
Assumptions: Isotropic, properties are not temperature dependent, zero strain reference temperature: 22 C.
Source: Doc No, TWR – 17057, Revision A, Table 4: Storage conditions

Grid of results

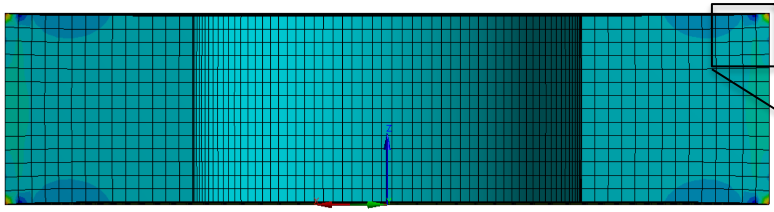
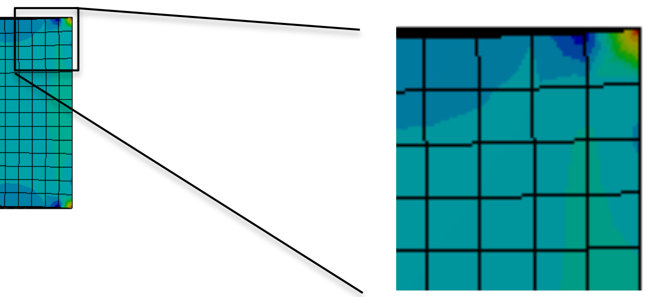
PRELIMINARY UNCHECKED

Model #	Description	Debonding strain	Radial crack strain
1	CF 230 Case	Reference	Reference
2	CF 395 Case	+23%	+5%
3	SS case	+56%	+0%
4	Ti Case	+42%	+2%
5	0.0625" liner, Ti case	-76%	-7%
6	0.125" EPDM, Ti case	-84%	+3%
7A	0.125" EPDM, SS case	-81%	+1%
7B	0.125" EPDM, CF230	-91%	+1%
8	0.125" SCP, Ti case	+4%	-2%
9	0.25" EPDM, Ti case	-104%	+7%
10	0.125" EPDM , Ti, constant OD	-86%	+2%
11	Segmented grain, Ti	-4%	-120%
12	Segmented grain, 0.125" EPDM, Ti	-7%	-116%
13	Shaped bore, Ti	+49%	+33%
14	29" tall, Ti	+112%	+94%
15	5“ tall, Ti	+136%	+27%
16	CF 395, normal E comp zones (unique mesh)	+12%	+5%
17	CF 395, low E comp. zones (unique mesh)	+13%	+5%
18	CF 230, low SP7 CTE	-15%	-15%

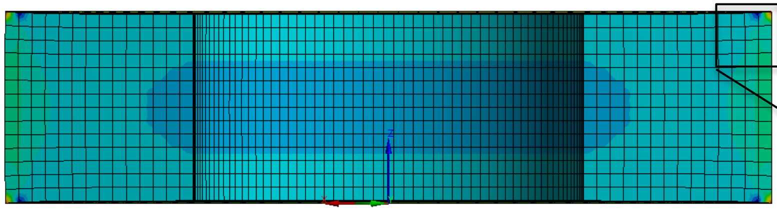
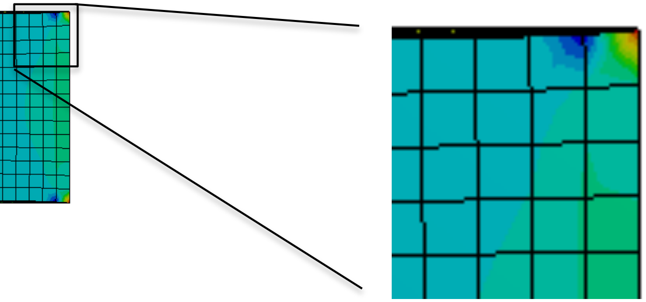
Stress directions

Radial stress

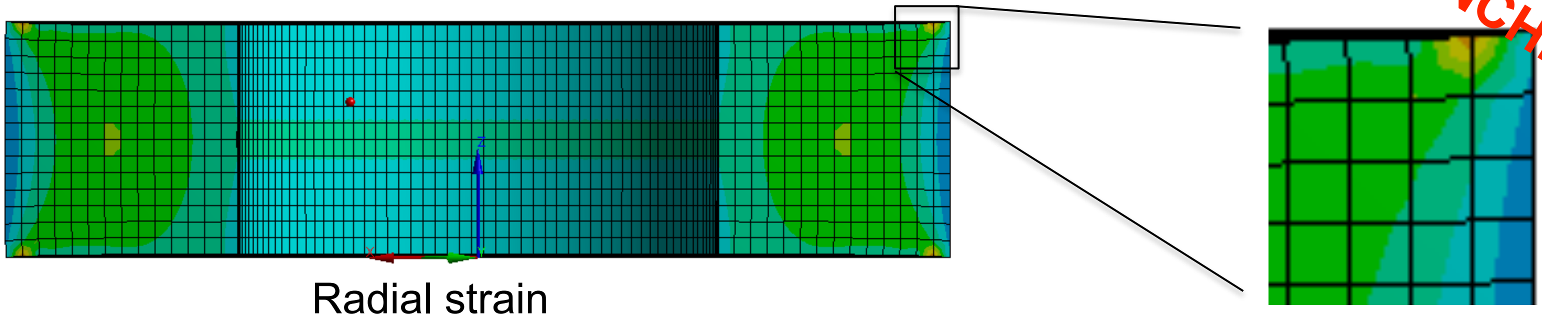
Circumferential stress

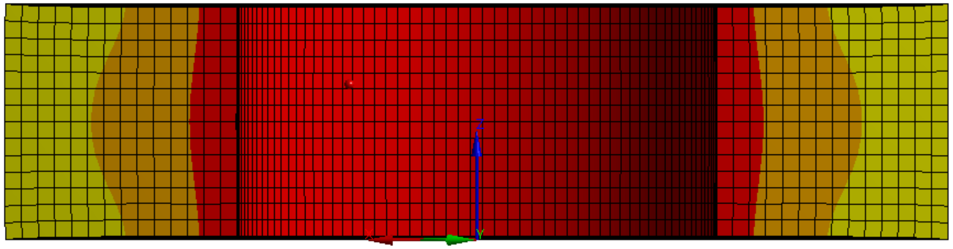
Axial stress

Observation: Stresses accumulate at outer bonded edge.

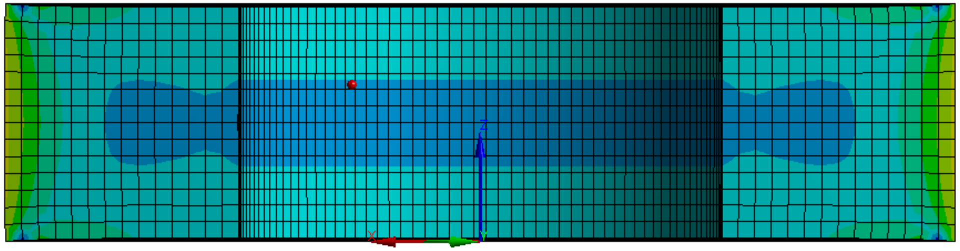
Strain directions



Radial strain



Circumferential strain



Axial strain

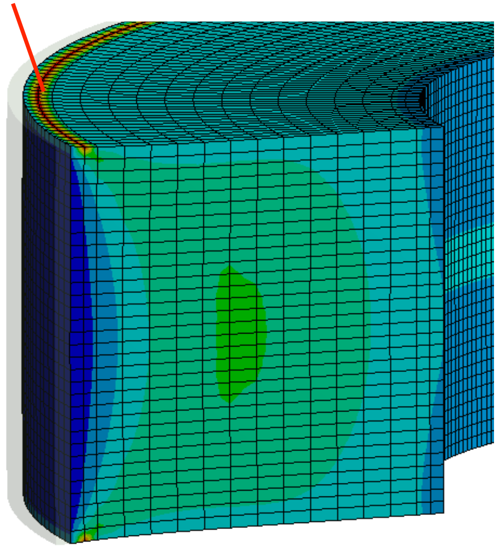
Observation: High strains appear circumferentially at the inner bore and radially just inside of the rim. (consistent color scale)

Effect of case material (no insulation)

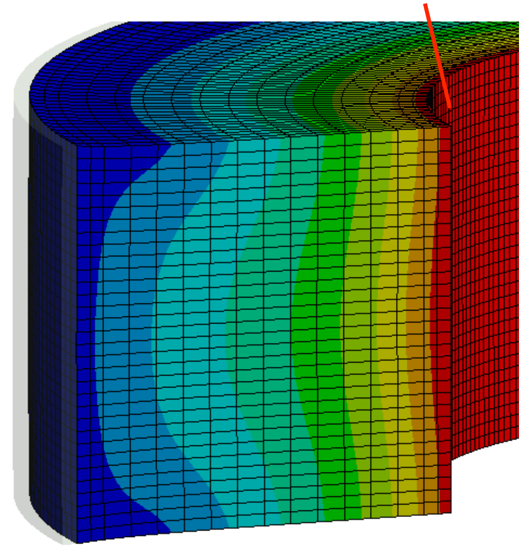
PRELIMINARY UNCHECKED

Case material	"CF 230"	"CF 395"	Ti-6Al-4V	304 SS
CTE (/F) @ 68F	1.22E-6	1.39E-6	4.9E-6	8.44E-6
E (ksi) @ 68F	8900	13300	16300	28300
Radial strain at case	Reference	**+23%**	**+42%**	**+56%**
Circ. strain at bore	Reference	**+5%**	**+2%**	**0%**

Radial strain at case

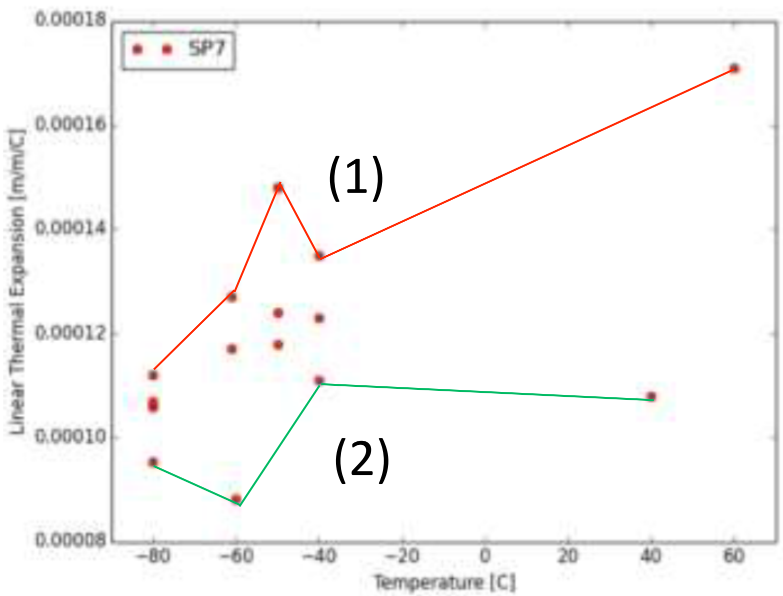


Circumferential strain at bore



Model check: Range of CTE of fuel

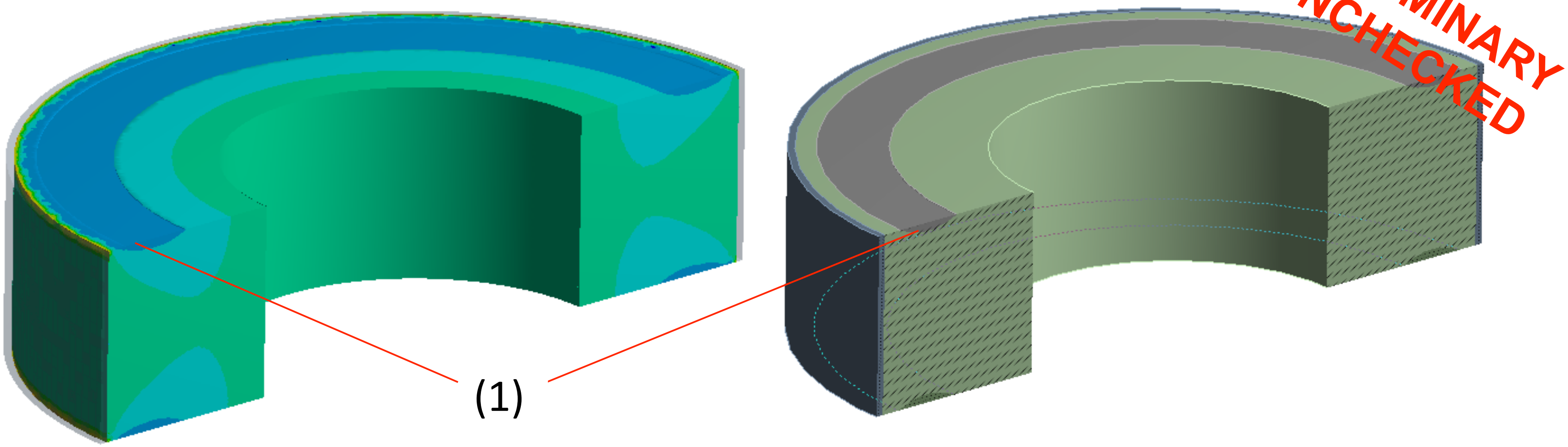
PRELIMINARY UNCHECKED



For all models, the highest available CTE values for the SP7 fuel were used (1). An additional model was created using the lowest CTE readings (2) for comparison. (diagram from *Thermal Cycling for Development of Hybrid Fuel for a Notional Mars Ascent Vehicle)*

Case	Ti-6Al-4V	Ti-6Al-4V
Fuel CTE	Highest	Lowest
Fuel CTE @ -100C (/C)	1.1E-4	9.5E-5 (-15%)
Radial strain at case	Reference	**-15%**
Circ. strain at bore	Reference	**-15%**

Model check: Compression areas



Because SP7 mechanical properties are unknown, a case was considered where the fuel has a significantly lower elastic modulus in compression than in tension. Some paraffin properties found suggested that this was a possibility.

A model was created where the zones in the fuel grain that experience compression (1) were given a lower modulus (8 ksi vs 29 ksi). This did not create a significant change in the peak strains in the regions of concern (changes in peak strains were < 1%).

Model check: Effect of diameter

PRELIMINARY UNCHECKED

All models assume a fuel grain OD of 10”, with the introduction of insulation and liners causing an increase in the case OD instead of decrease in the fuel grain OD.

A model was made to examine the effect of holding the case OD constant when adding a layer of insulation, allowing the fuel grain OD to decrease.

Case	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Insulation	None	0.125” EPDM	0.125” EPDM
Fuel OD (in)	10	10	9.75
Case OD (in)	10.2	10.45	10.2
Radial strain at case	Reference	**-89%**	**-86%**
Circ. strain at bore	Reference	**+1%**	**+2%**

References

1. *Thermal Cycling for Development of Hybrid Fuel for a Notional Mars Ascent Vehicle*, AIAA, Farias, E, et al.