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# Thermal Analysis of a Hybrid Rocket Propulsion System for Interplanetary CubeSats

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# Introduction (1/2)





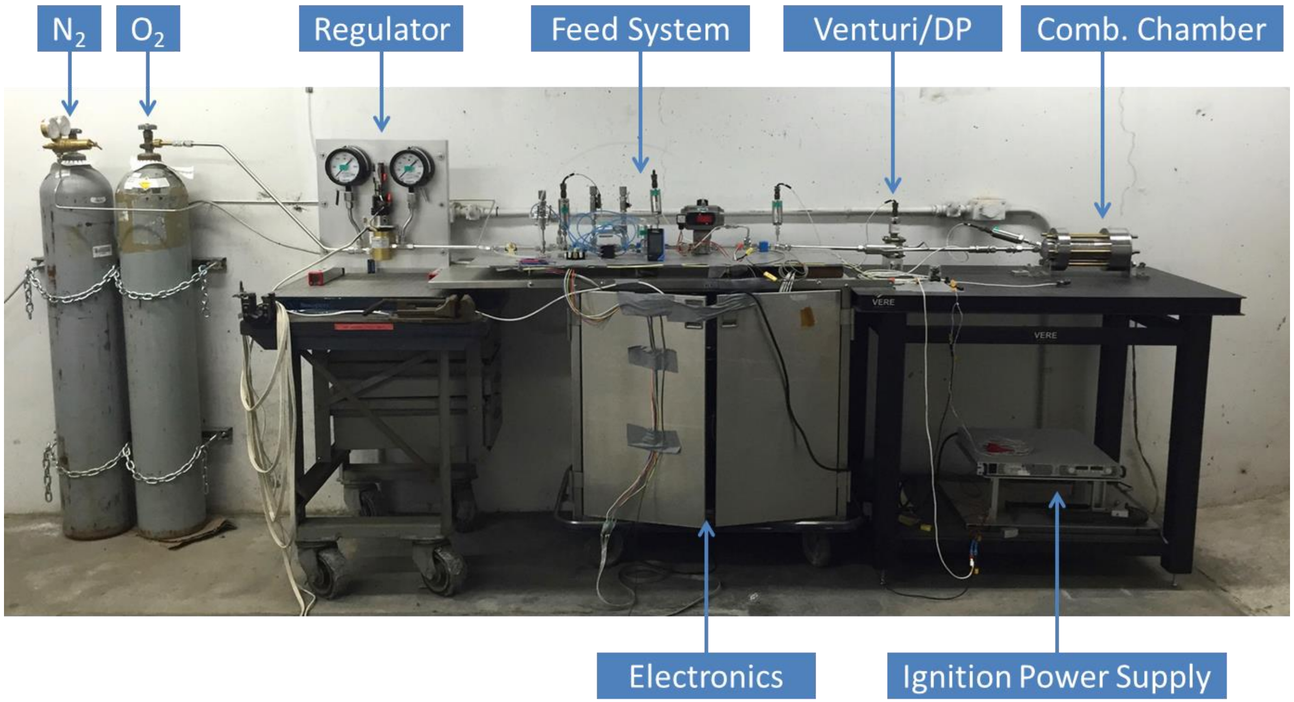
- Hybrid rocket motors represents a promising propulsion solution for future missions, since they have higher performance and are safer than conventional solid and liquid bi-propellant propulsion systems and therefore permit reduced cost.

- In 2013, NASA Jet Propulsion Laboratory started a research on this field. Current activity is focused on designing a hybrid motor that is capable of providing sufficient impulse to enable a stand-alone CubeSat/SmallSat interplanetary mission. As part of this work, a hybrid propulsion test facility was built.

- A thermal analysis was nedeed to understand the limits of safety for the motor design.

# Introduction (2/2)

## Test facility




## CubeSat mission requirements and system characteristics

| | |
|---|---|
| $\Delta V$ [m/s] | 1000 |
| Total mass [kg] | 25 |
| Max thrust [N] | 222 |
| Fuel outer diameter [m] | 0.05 |
| Maximum expected operating chamber pressure [MPa] | 2.41 |
| Maximum oxidizer upstream pressure [MPa] | 6.89 |

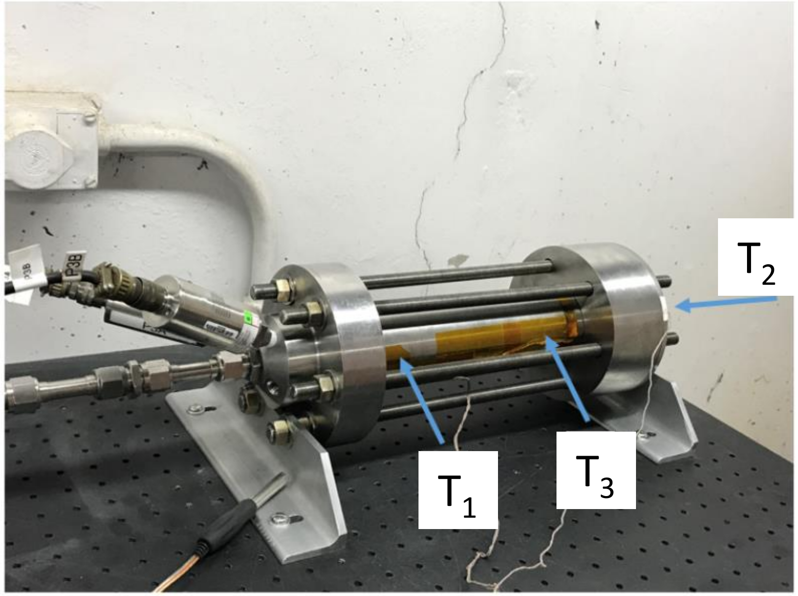
# Configurations (1/2)

Two different configurations have been analysed, with input data coming from two different tests: test 50 and test 59. Data from thermocouples have been used to verify the simulations results.

**Test data**

| Test # | Fuel | $t_b$ [sec] | $\bar{r}$ $[mm/s]$ | $\bar{r}_{lit}$ $[mm/s]$ | $\overline{p}_c$ [MPa] |
|---|---|---|---|---|---|
| 50 | clear PMMA | 20 | 0.48 | 0.26 | 1.38 |
| 59 | black PMMA | 20 | 0.44 | 0.28 | 1.42 |

**Thermocouples locations**



# Configurations (2/2)

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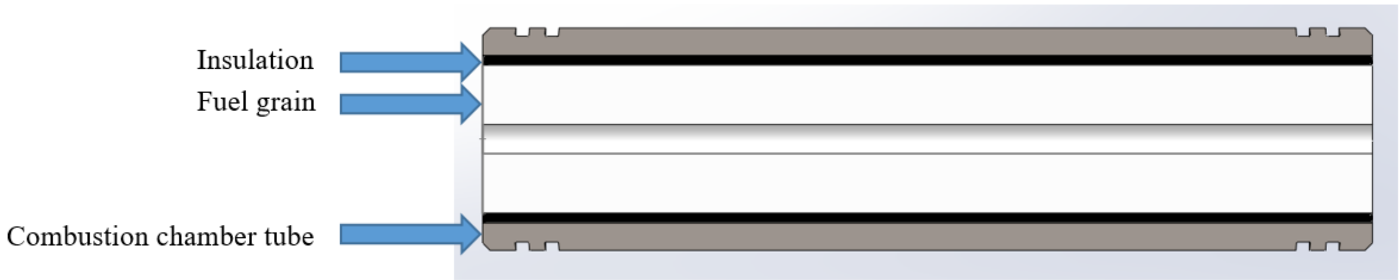
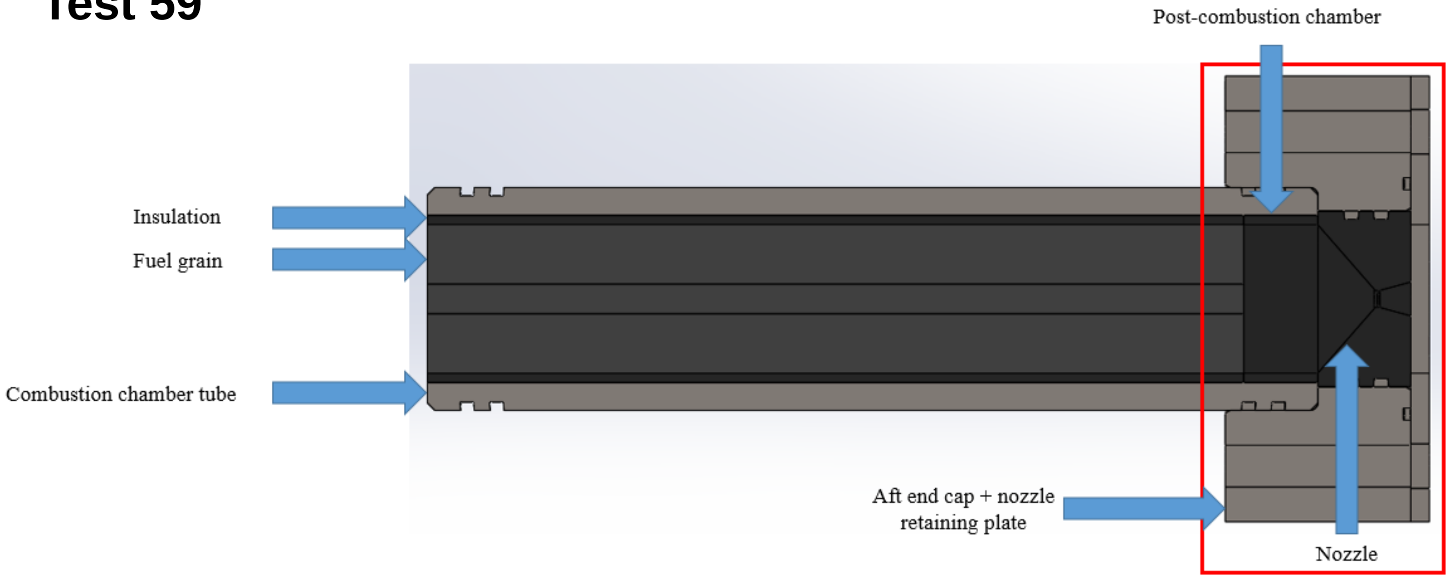
## Test 50




## Test 59



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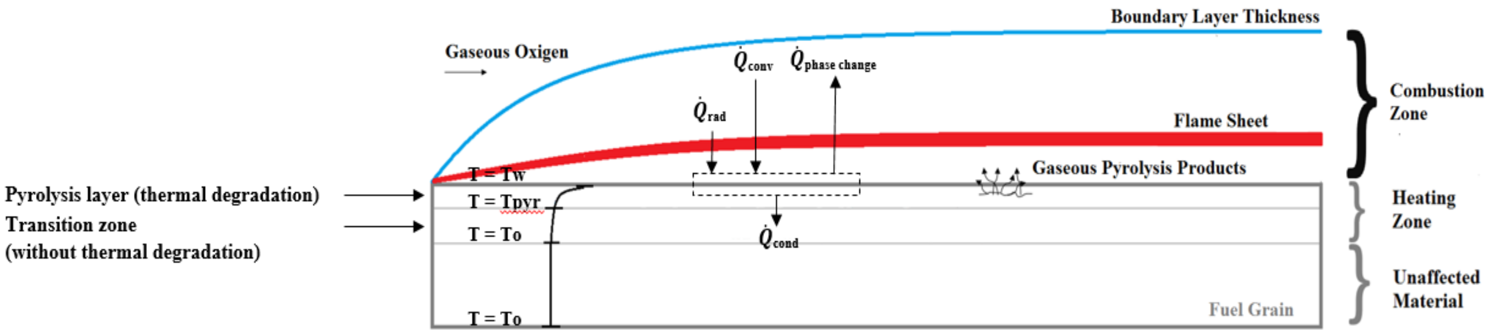
# Heat transfer theory for hybrid rockets

In the classical hybrid configuration using liquid or gaseous oxidizer, the combustion process occurs in a turbulent boundary layer through diffusive mixing between oxidizer flowing through the port and fuel evaporating from the solid surface. The flame sits within the boundary layer and is generally assumed to be a thin flame sheet.




**Total heat flux for steady state:** $\dot{Q} = \rho_f \dot{r} h_g$

**Radiative heat flux:** $\dot{Q}_r = \sigma \varepsilon_w (\varepsilon_g T_r^4 - T_w^4)$

**Total heat flux considering the coupling effect between convective and radiative heat flux:** $\dot{Q} = \dot{Q}_c \left[ \left( \frac{\dot{Q}_r}{\dot{Q}_c} \right) + e^{\left( -\frac{\dot{Q}_r}{\dot{Q}_c} \right)} \right]$

# Heat of gasification





The heat of gasification is defined as the amount of heat required to bring one kilogram of a polymer from the initial state, usually taken at room temperature, to the pyrolytic state at the final pyrolysis temperature.

The *effective* heat of gasification induces the transformation of the solid fuel into gaseous pyrolysis products at the surface temperature, and it is mathematically defined as:

$$h_g = \int_{T_0}^{T_{mel}} (c_p(T)_s) dT + H_{mel} + \int_{T_{mel}}^{T_{pyr}} (c_p(T))_l dT + \frac{1}{\sum_{i=1}^{n} m_i} \left\{ \sum_{i=1}^{n} \left[ \int_{T_{pyr}}^{T_{vap}} m_i \left( T_w \frac{dT}{dt} \right) (c_{pi}(T))_l dT + m_i \left( T_w \frac{dT}{dt} \right) H_{vapi} + m_i \left( T_w \frac{dT}{dt} \right) H_{pyr} + \int_{T_{vapi}}^{T_w} m_i \left( T_w \frac{dT}{dt} \right) (c_{pi}(T))_g dT \right] \right\}.$$

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# Assumptions

Some assumptions had to be made in order to analyze the heat transfer process using SolidWorks.

1. The polymeric fuel completely pyrolyzes into a gaseous monomer at the surface temperature $(700\ K \leq T_w \leq 850\ K)$
2. $T_{pyr} = T_{vap} = T_e = T_w$

$$h_g = \int_{T_0}^{T_w} (c_p(T)dT + H_{mel} + H_{vap} + H_{pyr}$$

3. $\dot{Q}_w = \rho_f \dot{r} h_g = \dot{Q}_c$
4. $\dot{Q}_r = 0.01\dot{Q}_c\ or\ 0.2\dot{Q}_c\ or\ 0.4\dot{Q}_c$
5. $\dot{Q}_c = \rho_f \left(\int_{T_0}^{T_w} c_p(T)dT\right) \dot{r}_{test50} + \rho_f (H_{mel} + H_{vap} + H_{pyr})\dot{r}_{lit}$
6. $\dot{Q}_{cSW} = \rho_f \left(\int_{T_0}^{T_w} c_p(T)dT\right) \dot{r}_{test50}$

# Total heat flux





Starting from this assumptions, the total heat flux transferred to the fuel surface during the ignition process has been calculated using a heat of gasification that brings the surface to a final pyrolysis temperature of 800 K and considering the 20% of radiation.

$$\dot{Q}_{test50} = 1.0175 \times 10^6 \, W/m^2$$

This value is consistent with the results of a concurrent CFD study.

# Thermal analysis (1/2)





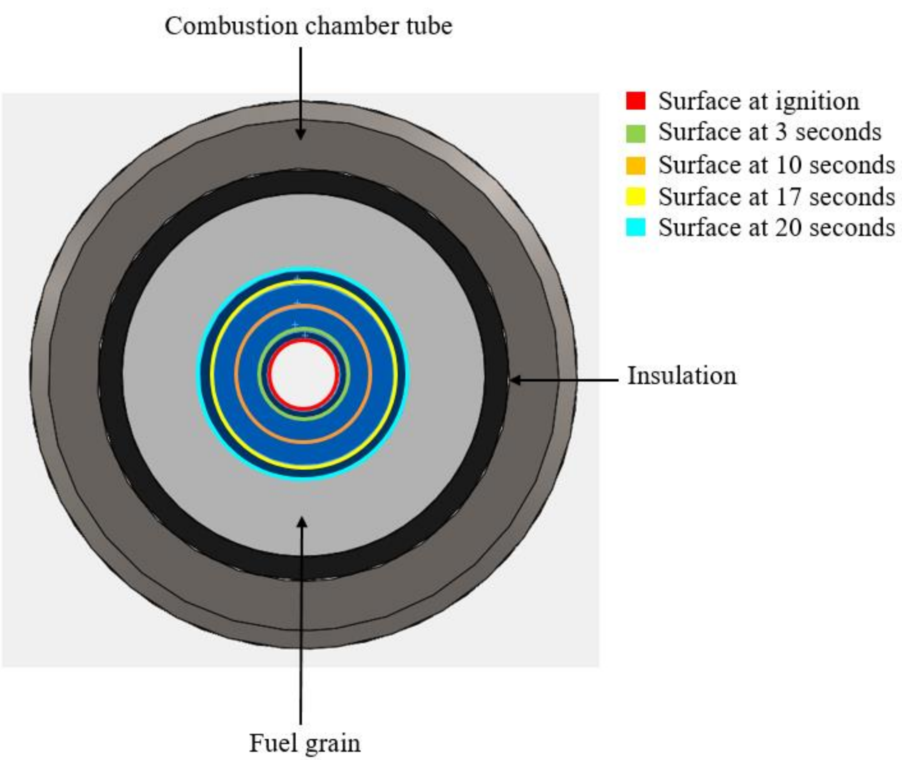
A curvature-based mesh has been selected for the entire model, applying different mesh controls to each component in the assembly. Different sizes of mesh were tested until convergent results were achieved.

- A first steady-state analysis has been performed, in which all the surfaces are initialized at the ambient temperature (300 K) and a bonded contact is used between the insulation and the combustion chamber tube, in order to permit conduction through contacting areas.

- The ignition process is reproduced by performing a transient thermal analysis with a very short time (~ 0.2 sec) and applying the total heat flux needed to rise the temperature from 300 K to 800 K to the inner fuel surface. Convection to the ambient temperature is set as boundary condition, with a heat transfer coefficient *h* of 100 $W/m^2\mathrm{K}$. A cylinder of 1 mm of thickness has been created in order to represent the pyrolysis layer that originates inside the material during this ignition process.

# Thermal analysis (2/2)

- For each step, initial and final surfaces have been calculated multiplying the regression rate value and the initial and final time of each analysis, creating a total of five concentric cylinders (including the fuel grain). A constant regression rate throughout the burn is then assumed. The heat flux to bring the surface at the final pyrolysis temperature has been applied to the inner surface of each cylinder.



# Stress evaluation

A stress analysis was performed in order to verify whether the fuel breaks during the combustion process and, if so, determine the thickness of the mechanically compromised region.

- **Von Mises stresses** have been calculated considering thermal loads and applying different amount of radiation to evaluate its influence on the stresses.

- **Directional stresses** have been evaluated to understand the behavior of the material in each direction.

- The **factor of safety** has been calculated to know where applied stresses exceed the yield strength of the material (52 MPa). The thickness in which the factor of safety is less than 1 is also calculated. It is assumed that this is where the material may break up during combustion.

**Note**: reference test for these analyses is test 50.

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Considering the configuration with a post-combustion chamber, a different total heat flux has been used. In fact, referring to test 59 that uses black PMMA, it is assumed that *all the fuel vaporizes completely and is burnt inside the combustion chamber*. This assumption is still being verified through testing, but appears accurate for tests ≤ 20 seconds.

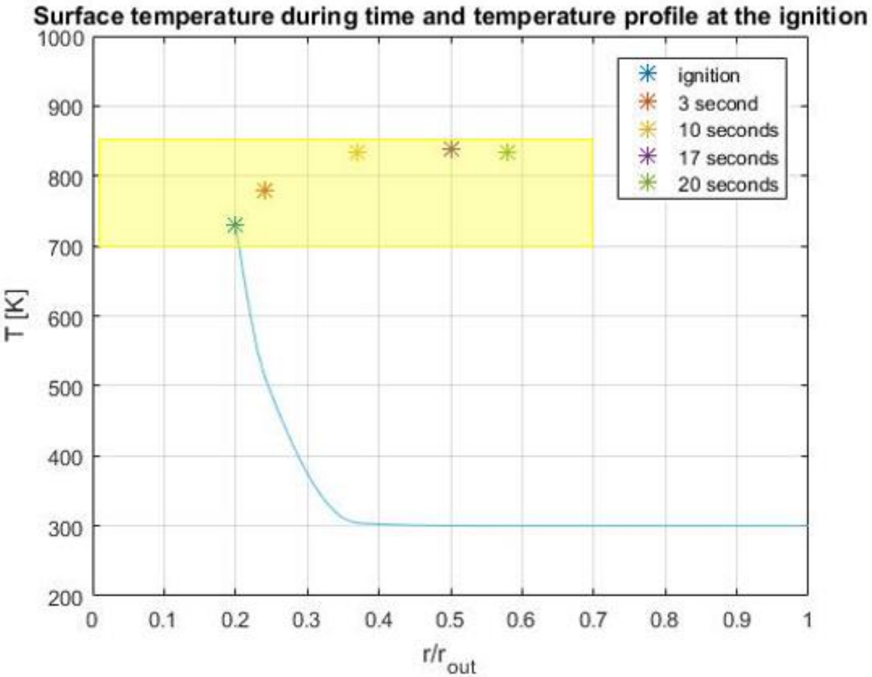
$$\dot{Q}_c = \rho_f \left( \int_{T_0}^{T_W} c_p(T)\,dT \right) \dot{r}_{test59} + \rho_f (H_{mel} + H_{vap} + H_{pyr}) \dot{r}_{test59}$$

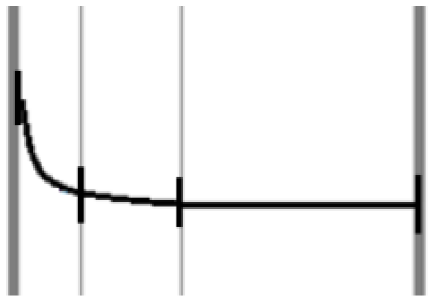
$$\dot{Q}_{test59} = 1.1971 \times 10^6 \; W/m^2$$

**Two long burn simulations** have been performed:

1. Total heat flux applied both in the post-combustion chamber and in the nozzle;
2. Total heat flux applied only to the nozzle → an ablative post-combustion chamber material is assumed.

# Thermal results (1/5)



$$700\ K \leq T_w \leq 850\ K$$

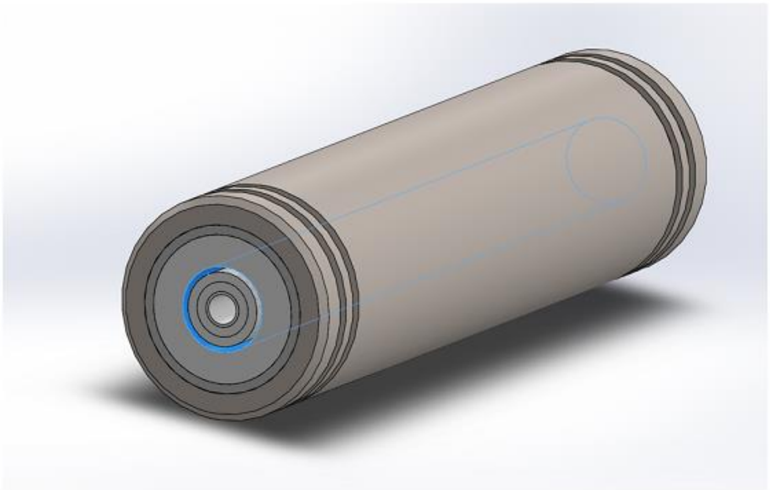
**Pyrolysis layer thickness during time**

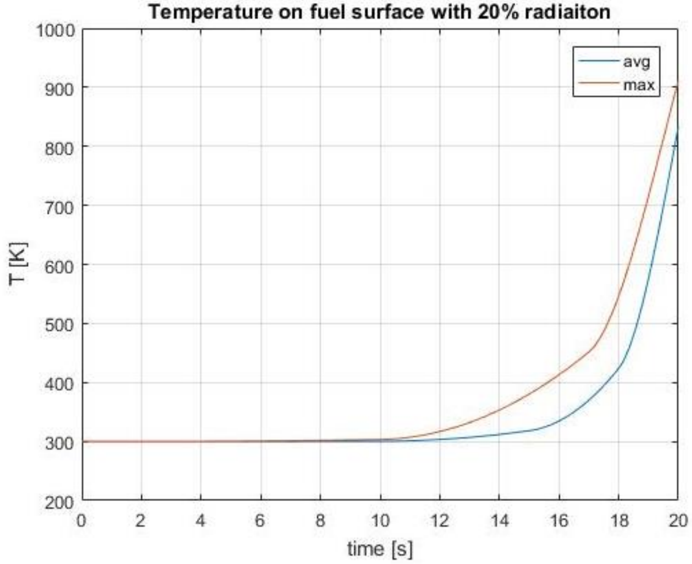
| Time | Thickness [mm] |
|---|---|
| Ignition | 0.593 |
| 3 seconds | 0.762 |
| 10 seconds | 1.016 |
| 17 seconds | 0.847 |
| 20 seconds | 0.508 |

# Thermal results (2/5)



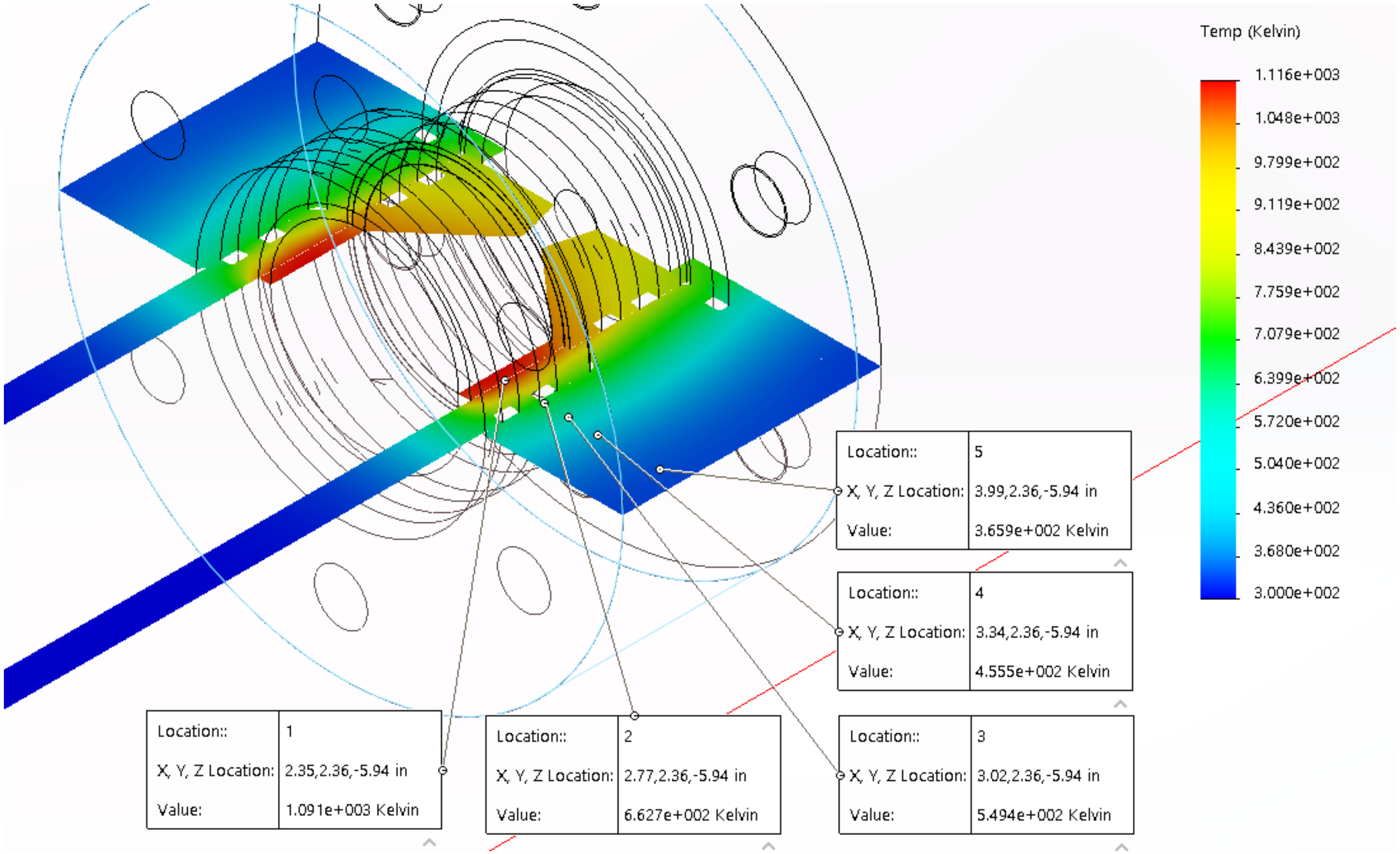
**Temperature trend on fuel surface during the burn time**





# Thermal results (3/5)

**Results applying the total heat flux both in the post-combustion chamber and in the nozzle**



# Thermal results (4/5)

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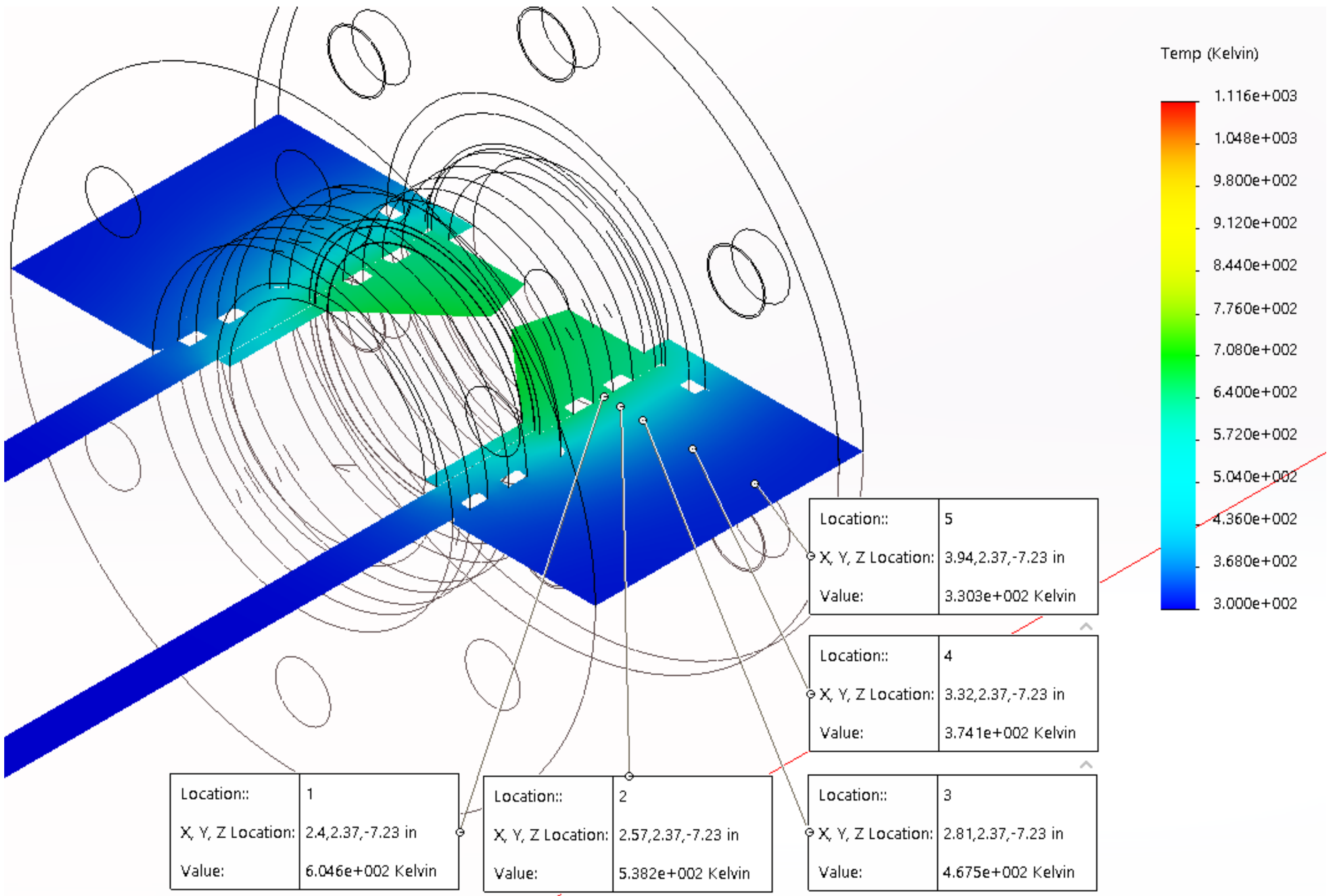
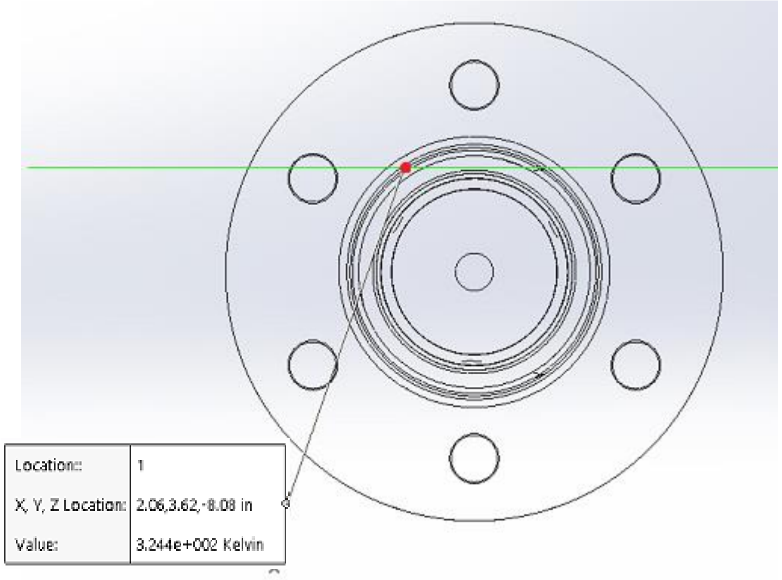
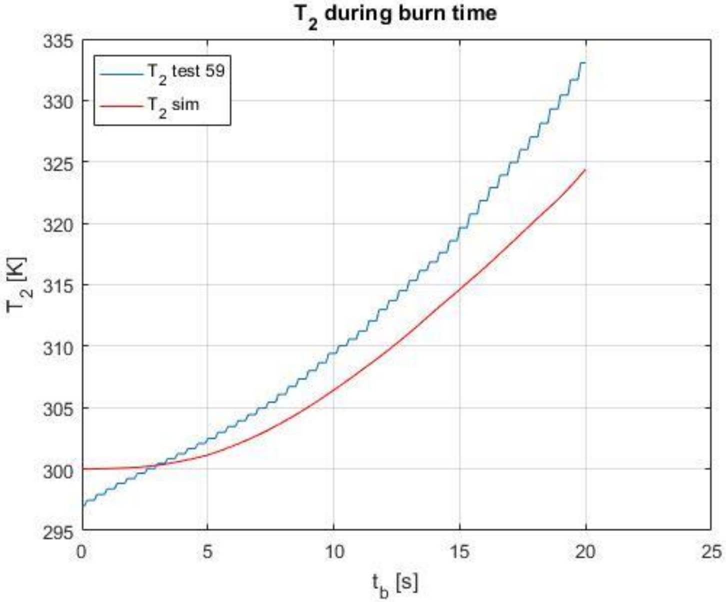
## Results applying the total heat flux in the nozzle



# Thermal results (5/5)

## Comparison between the SolidWorks simulation and test data from test 59



# Stress results (1/2)

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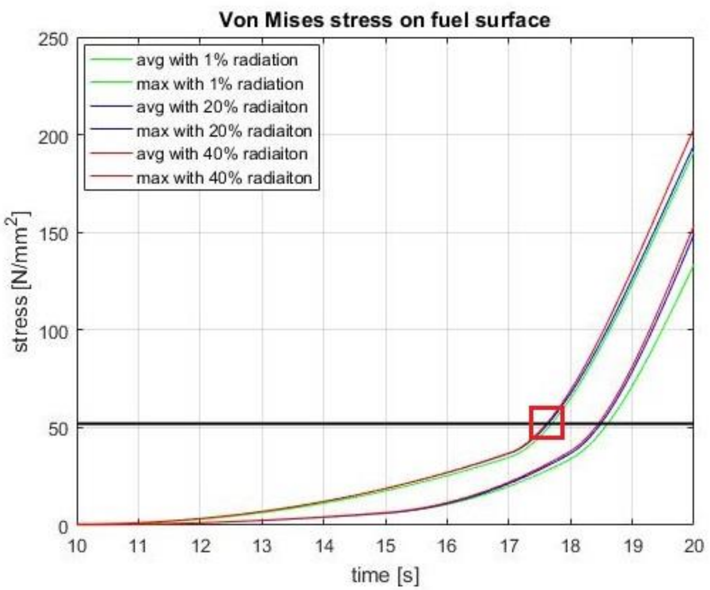
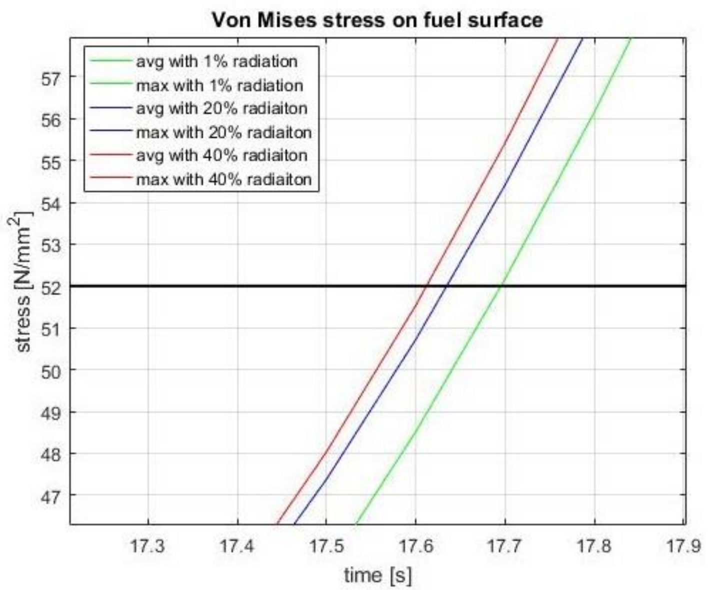
## Von Mises stresses with different amount of radiation



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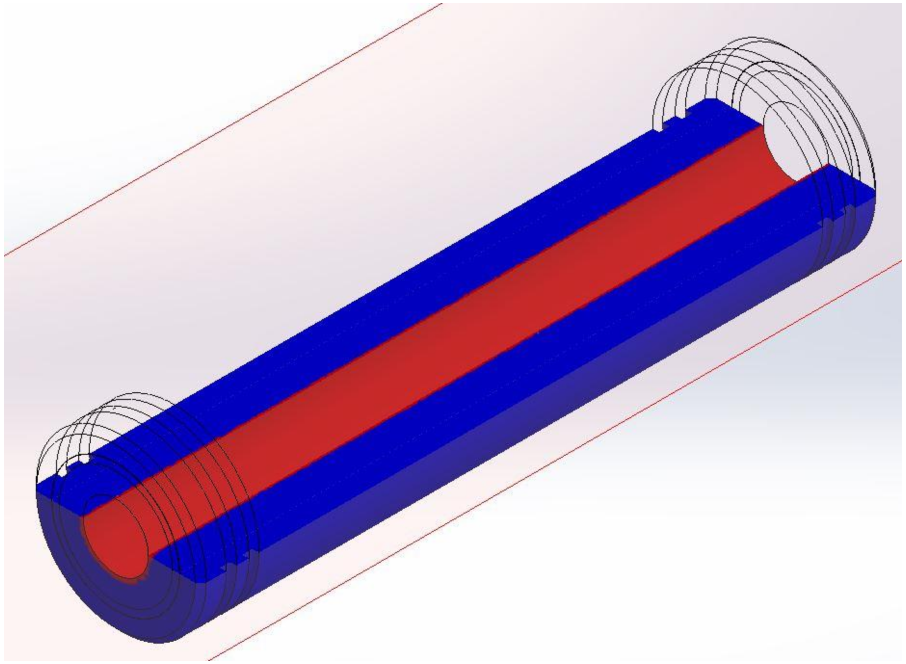
## Directional stresses after 20 seconds of combustion

| | **Radial stresses** [MPa] | **Tangential stresses** [MPa] | **Axial stresses** [MPa] |
|---|---|---|---|
| Thermal | -8.63 | -158.8 | -152.9 |
| Pressure | -1.35 | 0.9162 | -0.1343 |
| Superimposition (th+pr) | -9.98 | -157.88 | -153.03 |
| Solidworks | -9.99 | -157.9 | -153 |

## Factor of safety



**Thickness of broken fuel:**

Front face: ~ 1.3 – 2 mm
Aft face: ~ 0,5 – 1.3 mm
Inner surface: ~ 0.5 – 1.3 mm

# Conclusions



1. The areas with a factor of safety < 1 for a thickness greater than 1 mm (pyrolysis layer thickness ~ 0.5 – 1 mm) are potentially breaking up.

2. An ablative material is recommended for the post-combustion chamber during long duration burns (> 1 min), since the graphite adopted in the current configuration brings the stainless steel of the combustion chamber tube near its maximum service temperature.

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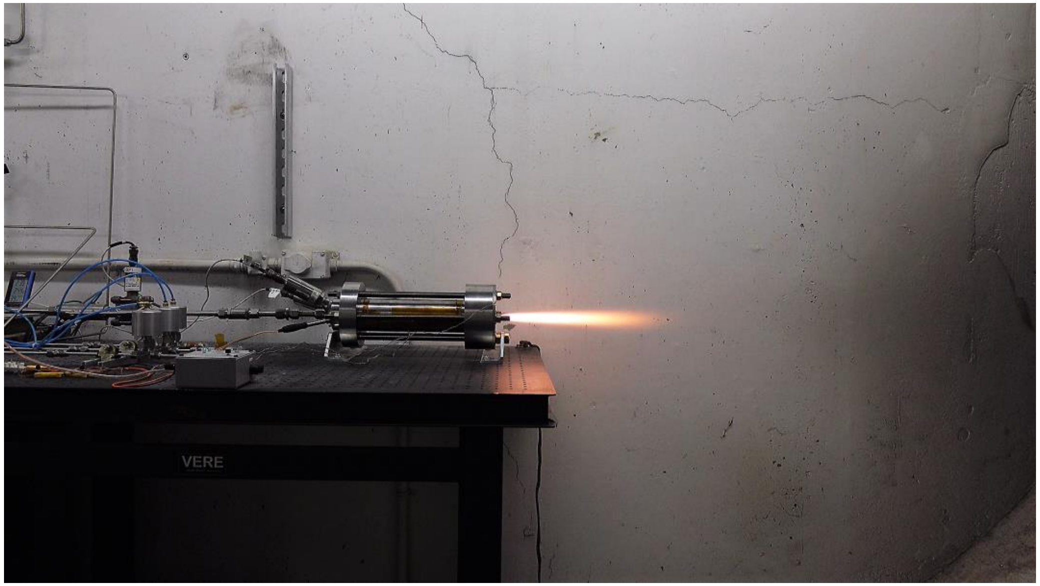
Thank you for your attention.
***Questions?***

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