Engineered Porosity for Space Applications

A research thesis on 3D-printed porous ceramic thruster for clean in-space propulsion

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Water electrolysis propulsion is a clean alternative to hydrazine, but it imposes severe thermo-mechanical loads

Why water-based propulsion?

- Water **avoids** hydrazine toxicity and simplifies ground handling
- Hydrazine faces long-term **regulatory pressure** under the EU REACH framework
- Water Electrolysis Propulsion (WEP) stores water and **splits** it in **orbit** into H_2 and O_2, which are then **combusted** for thrust

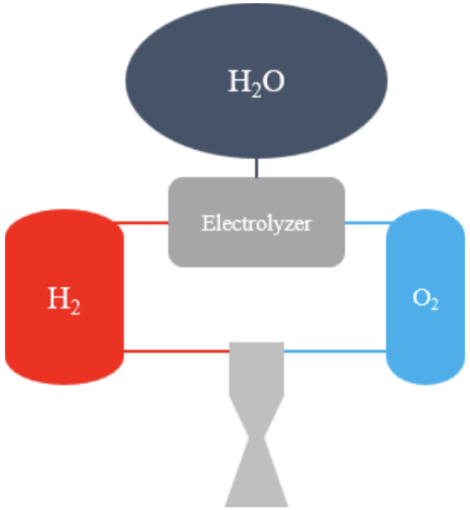


Figure: J. Hildebrandt et al. (2019)

WEP uses water as a safe, storable feedstock and converts it in orbit into combustible gases for propulsion

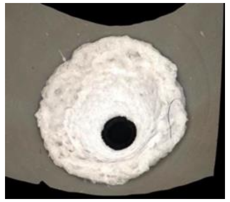
What makes the thruster difficult?

Challenge **Operational loads** & **Printability**:

Images courtesy of: J. Hildebrandt et al. (2019) & Dr. Wadih Yared IKMT

High temperatures

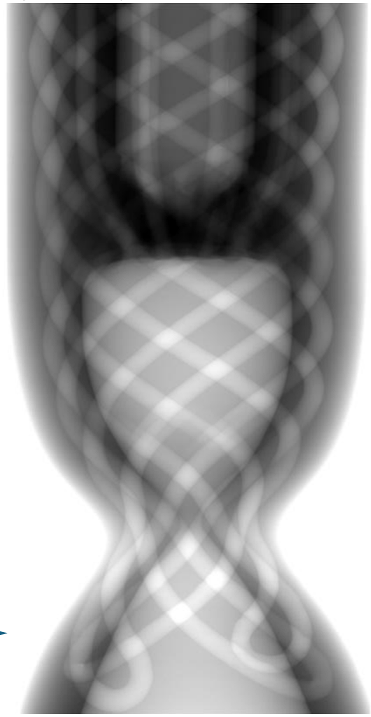
small features



oxidation

X-Ray of the desired thruster

Image courtesy of Dr. Wadih Yared - IKMT



- **~3000 – 3500 K combustion environment** under **oxidizing** H_2/O_2 conditions
- Extreme **wall heat flux** causes steep thermal gradients
- **Repeated** ignition**, pressure cycling and sub-mm features** demand high thermal-shock robustness and manufacturing precision

These loads define the need for an oxidation-stable, thermally robust, geometrically precise and printable ceramic solution

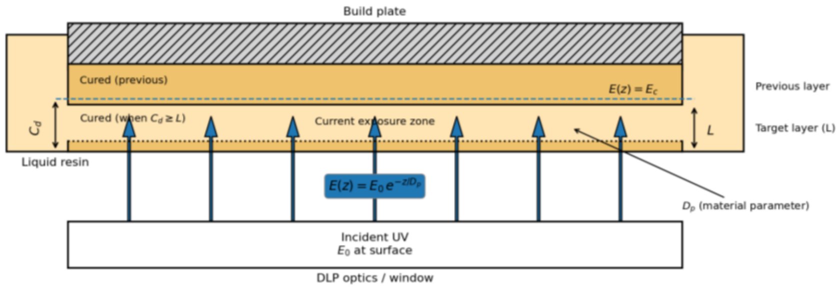
→ The only viable path: 3D-printing the thruster from ceramic slurries — combining geometric freedom with thermo-chemical resilience.

DLP 3D-printing enables complex thruster geometries with engineered porosity for thermal-shock resistance

Material Choice:

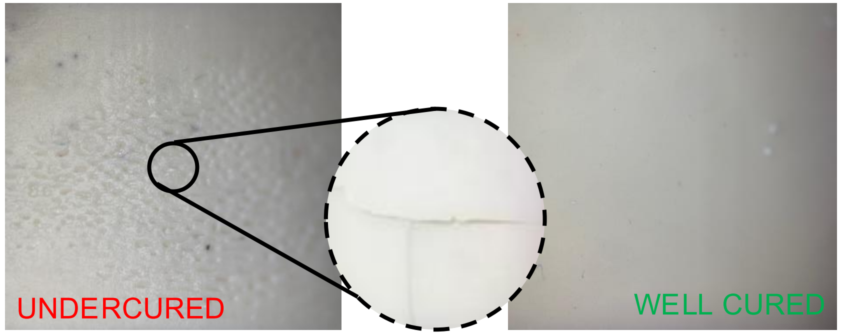
Challenges in Manufacturing:

A **ceramic-loaded photopolymer slurry** is cured **layer by layer** via UV light projection — enabling **sub-mm features** and **complex internal channels** that conventional methods cannot produce

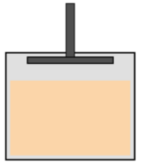


- **Exposure energy** varied (5–900 mJ/cm²) to control cure depth & crack risk
- **Layer thickness & solids loading** tuned for sub-mm feature resolution

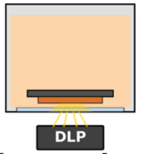
50 mJ/cm² *125 mJ/cm²*



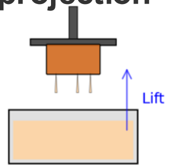
results in crack



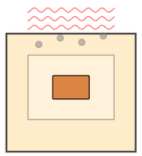
Ceramic slurry in vat



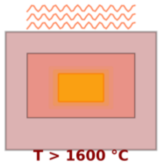
Layer-wise curing with **UV projection**



Green body removal and cleaning



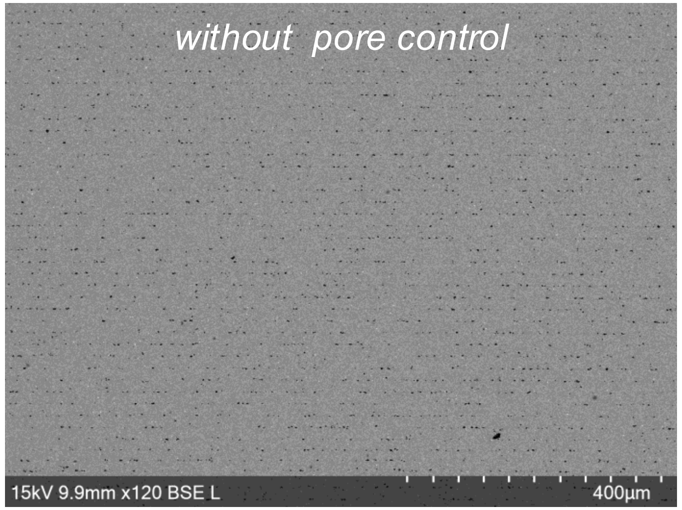
Thermal debinding to remove organics

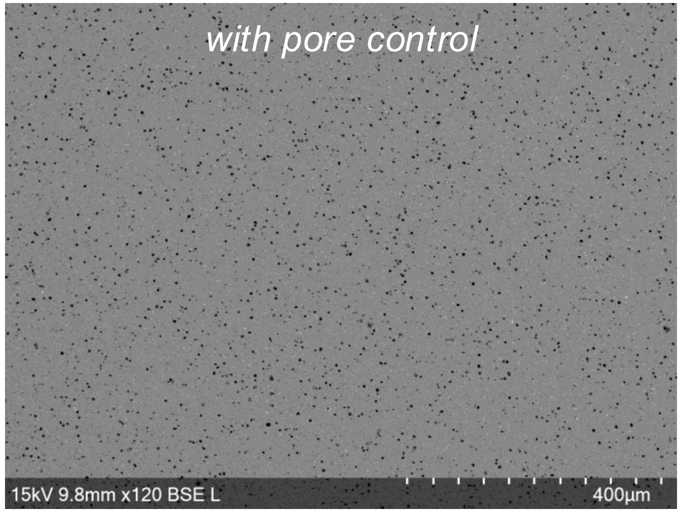


Sintering to dense ceramic (**T > 1600 °C**)

Porosity reduces density by ~2% while retaining >85% of flexural strength and comparable toughness

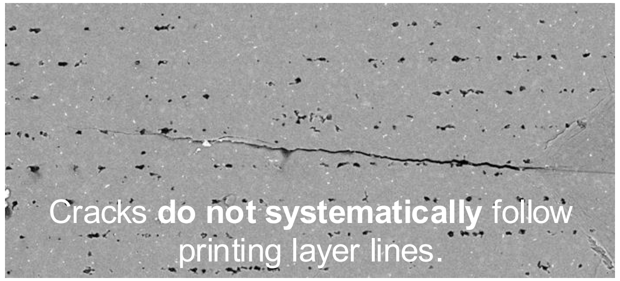
Microstructure SEM cross-section:



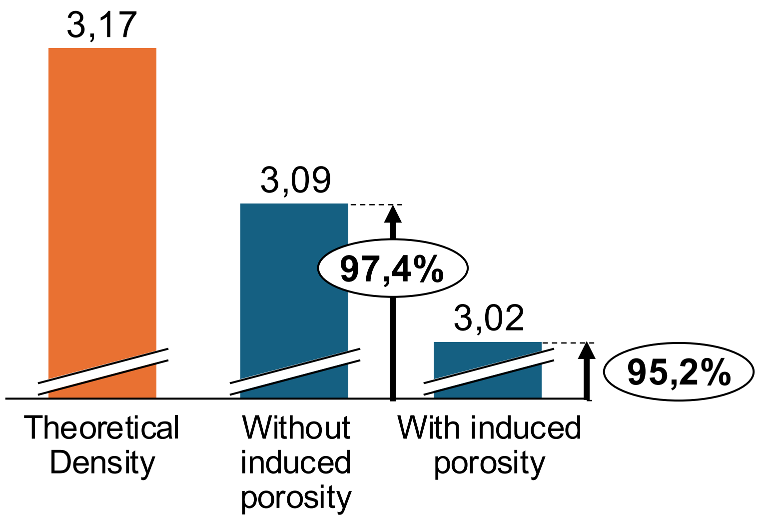


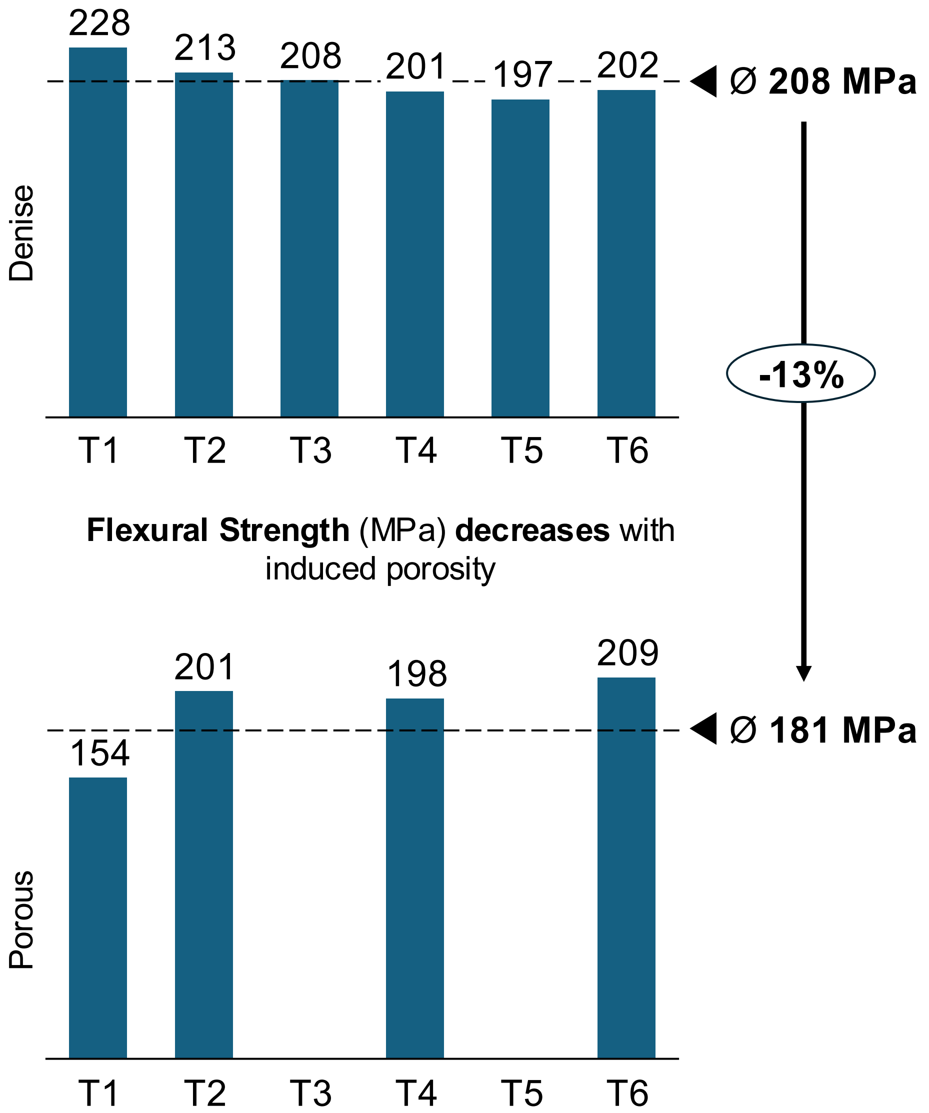
Key mechanical results:

→ The **mechanical trade-off** from induced porosity is **marginal** — an acceptable cost for creating the **connected pore network** needed for thermal management



Density [g/cm³] breakdown of **PMMA-templated mullite** (Archimedes-based)





Flexural Strength (MPa) **decreases** with induced porosity

A printable, porous thruster is a credible path toward hydrazine-free satellite propulsion, potentially enabling transpiration cooling

Conclusion:

- **Successfully** introduced porosity
- Engineered the **shape and size** of the porosity
- Quantified **trade-offs** in mechanical properties

→ Thruster survived pre-combustion chamber test at 1200 °C

Next Steps:

- **Hot-fire testing** of the printed thruster under real H_2/O_2 combustion conditions
- **Thermal cycling endurance** — validate performance over >100 burn cycles
- **Explore transpiration cooling** — validate porous wall as active coolant barrier under real firing conditions

Flight on IRS ROMEO mission —
the WEP thruster is planned to fly on the University of Stuttgart's 60 kg satellite to raise its orbit from LEO into MEO

What is Transpiration Cooling?

A **coolant** (e.g. H_2/O_2 bleed) is forced through the **porous ceramic wall** into the combustion chamber, forming a **protective film** that absorbs heat and shields the structure

- **Engineered porosity** controls coolant flow rate and distribution
- **Dense outer shell** (DLP-printed) provides structural integrity

Subject to ongoing research