# Carbide Coated Carbon-Carbon Heat Exchange Tube for Nuclear Thermal Propulsion Fuel Assembly


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Nuclear Emerging Technologies for Space Conference
Idaho Falls, ID | 8-11 May 2023

# Carbon-carbon tube development team

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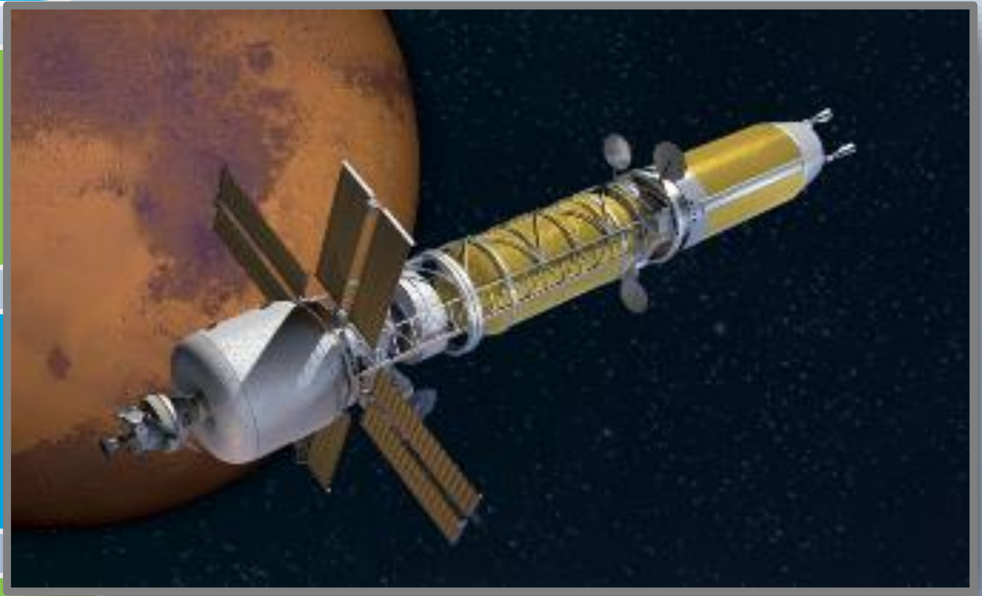
*This work is supported by the NASA Space Technology Mission Directorate through the Space Nuclear Propulsion (SNP) project*

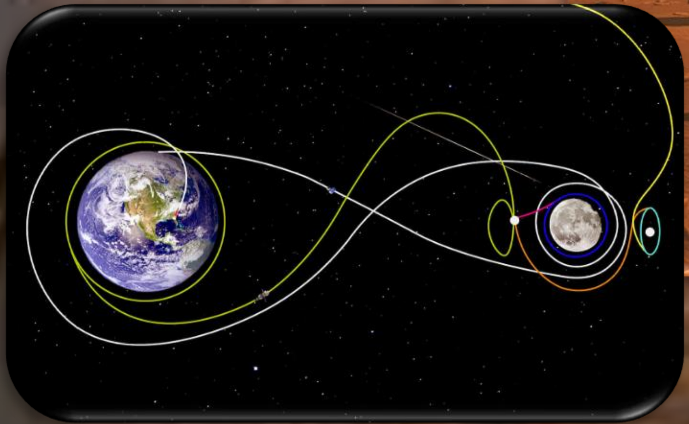
# Presentation Agenda

1. Motivation and Specific Challenge
2. Carbon-Carbon (C/C) Tube Project Overview
3. Project Status Update
4. Questions/Discussion



# Nuclear Thermal Propulsion (NTP) enables a host of missions beyond achieving the first crewed mission to Mars in 2039

Sustained human Mars presence



Expanded cis-lunar mobility

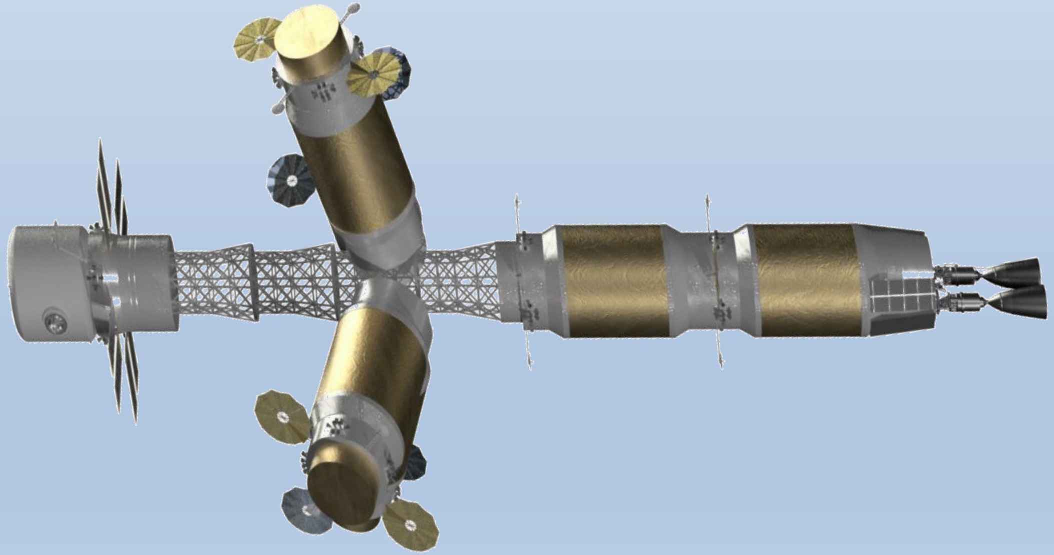
Deep space exploration

# NTP reactors must operate at very high temperatures to meet propulsion performance goals


Round trip mission duration:

**> 900 days** → **< 600 days**

Chemical propulsion → Nuclear thermal propulsion

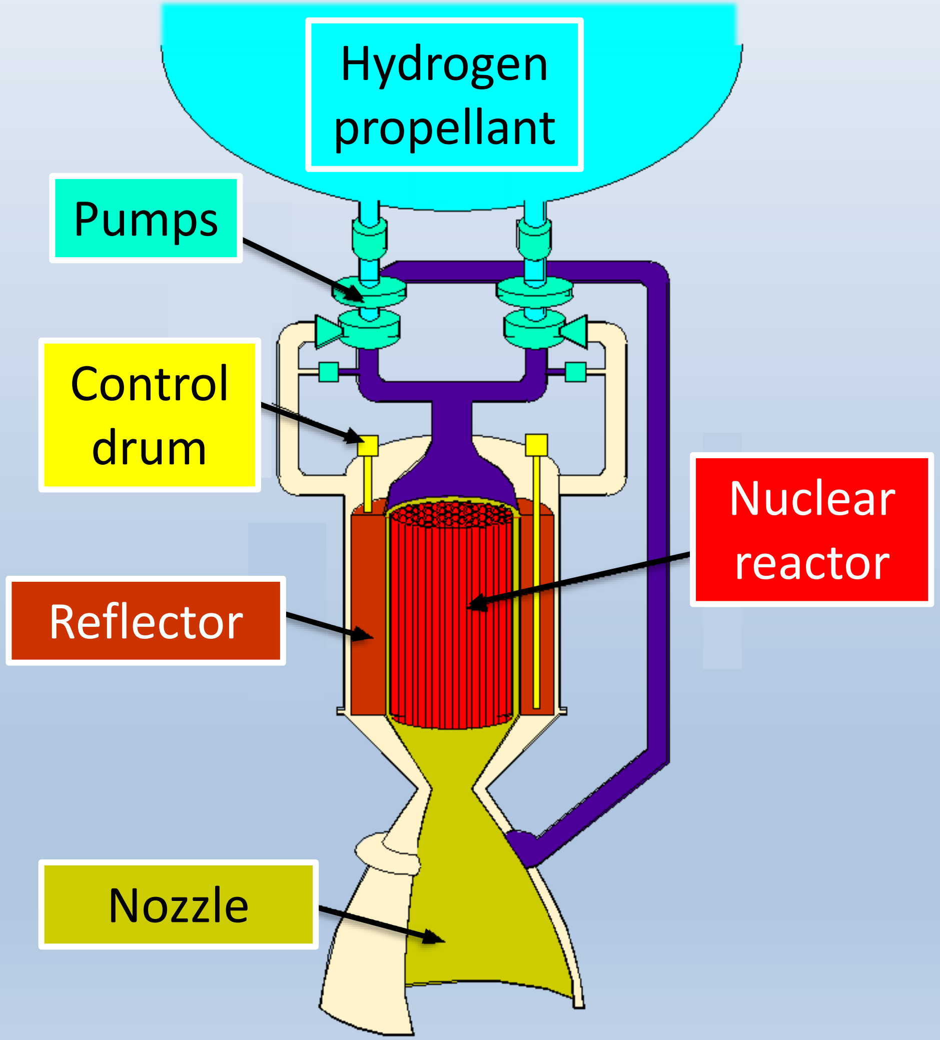


NTP spacecraft are high thrust, high specific impulse (Isp) systems

- Thrust directly related to thermal power of reactor
  - 100,000 N ≈ 450 $MW_{th}$ at 900 sec Isp
- Isp directly related to exhaust temperature:
  - Goal: 900 sec Isp → **~2900 K (2627°C)**

**= a materials problem!**

# How a typical NTP system works



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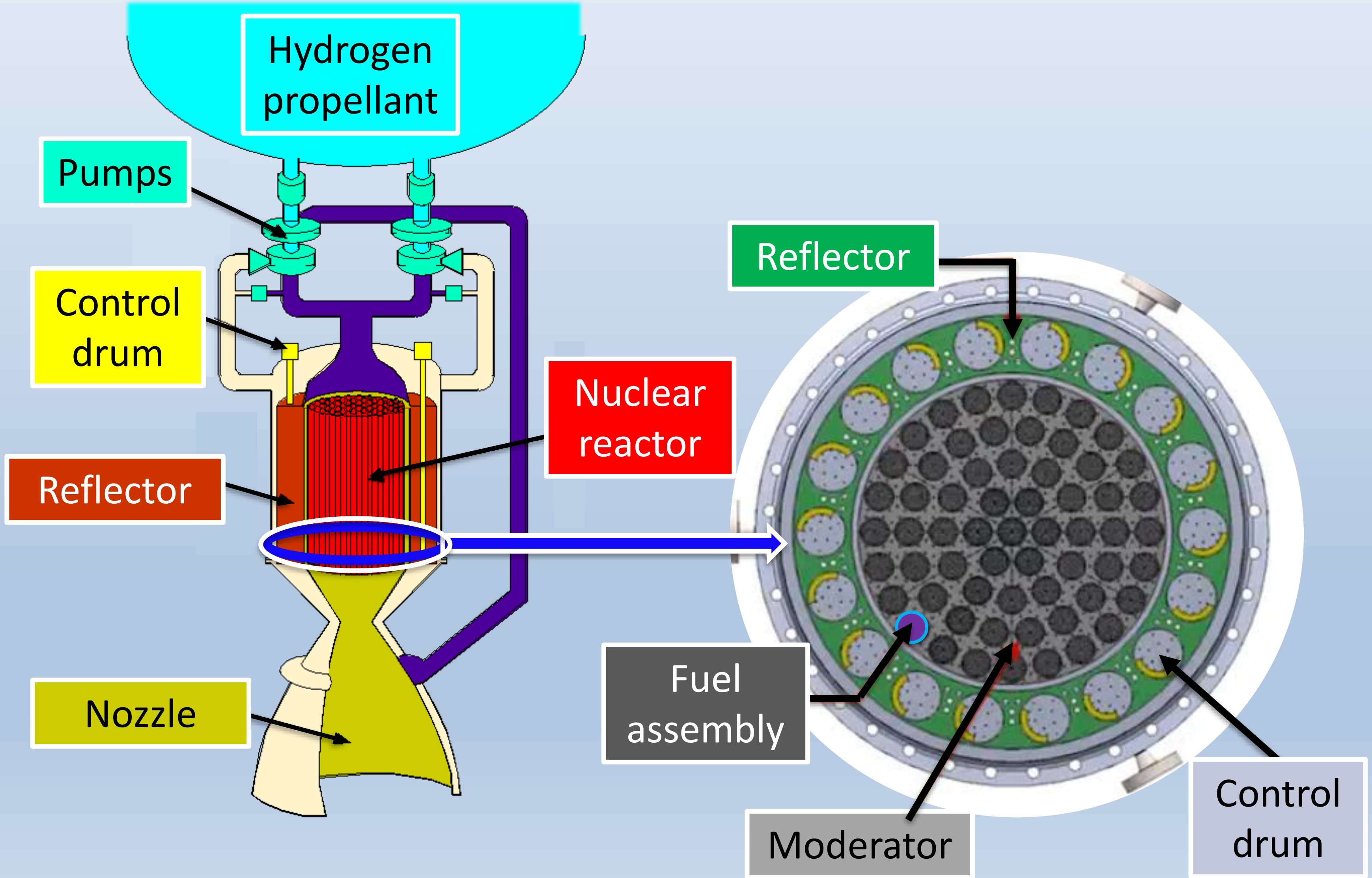

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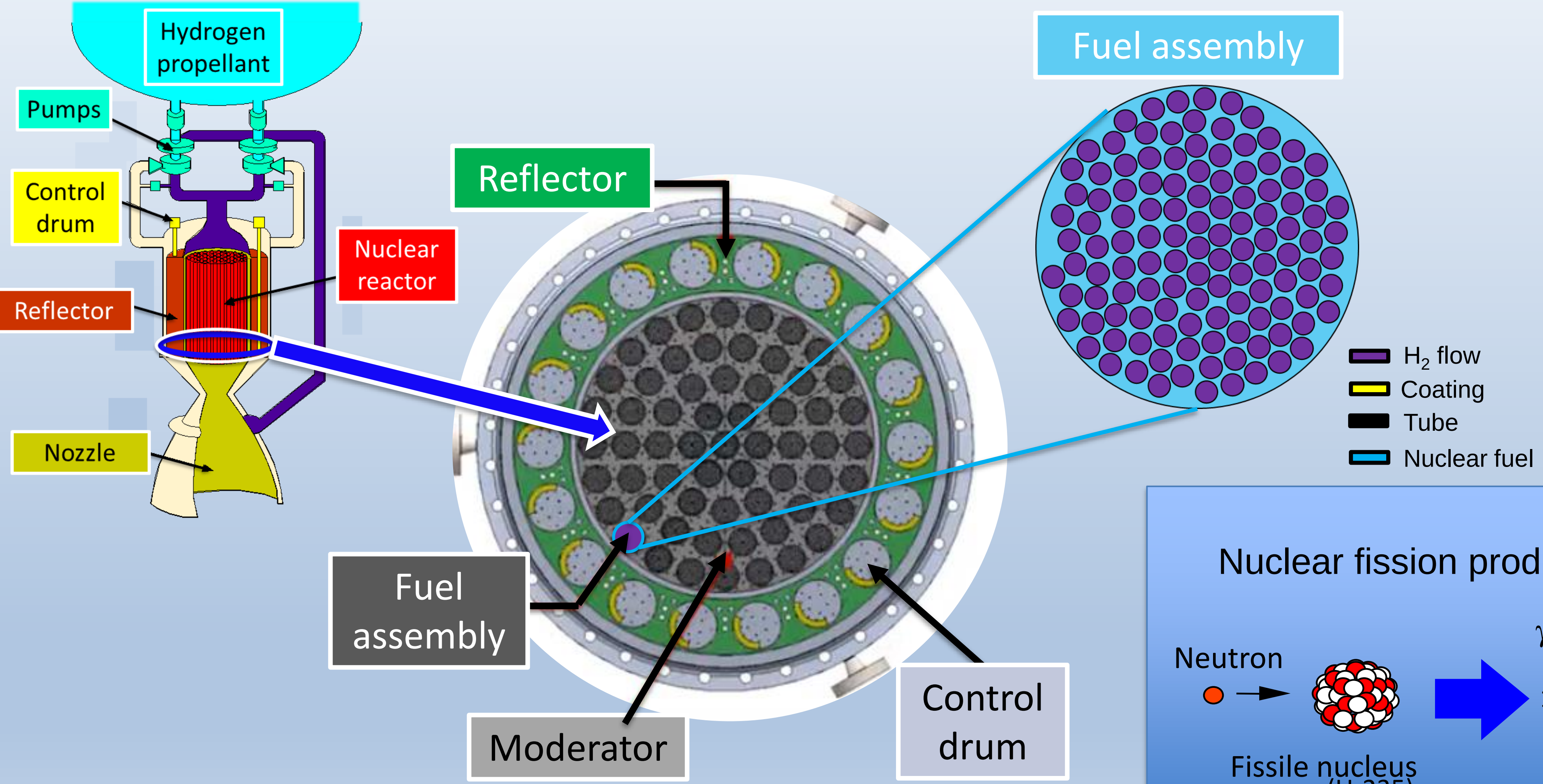


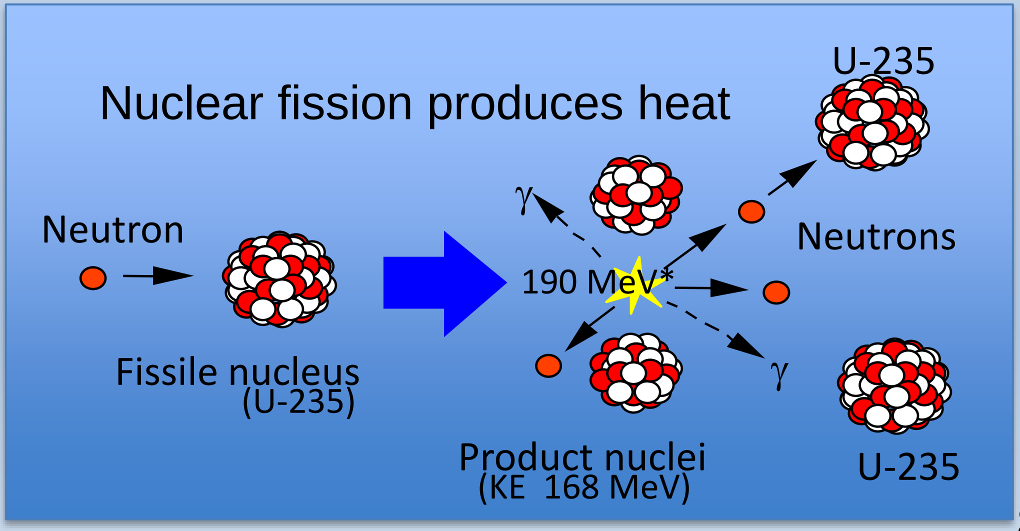

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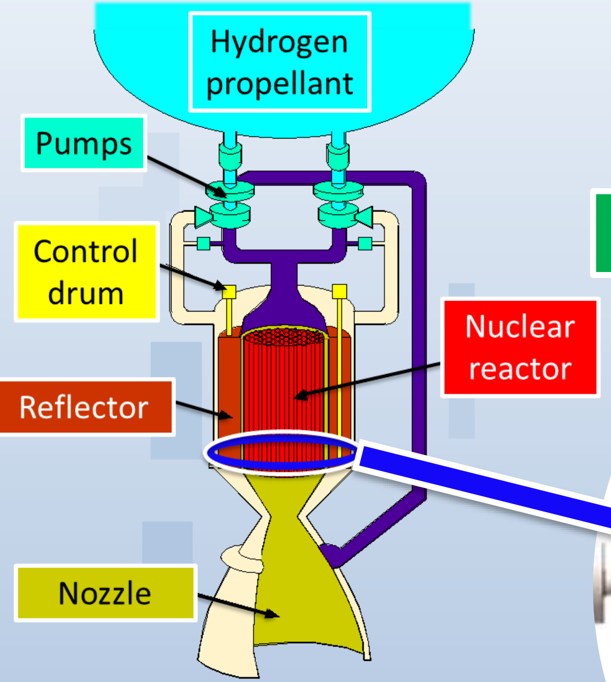
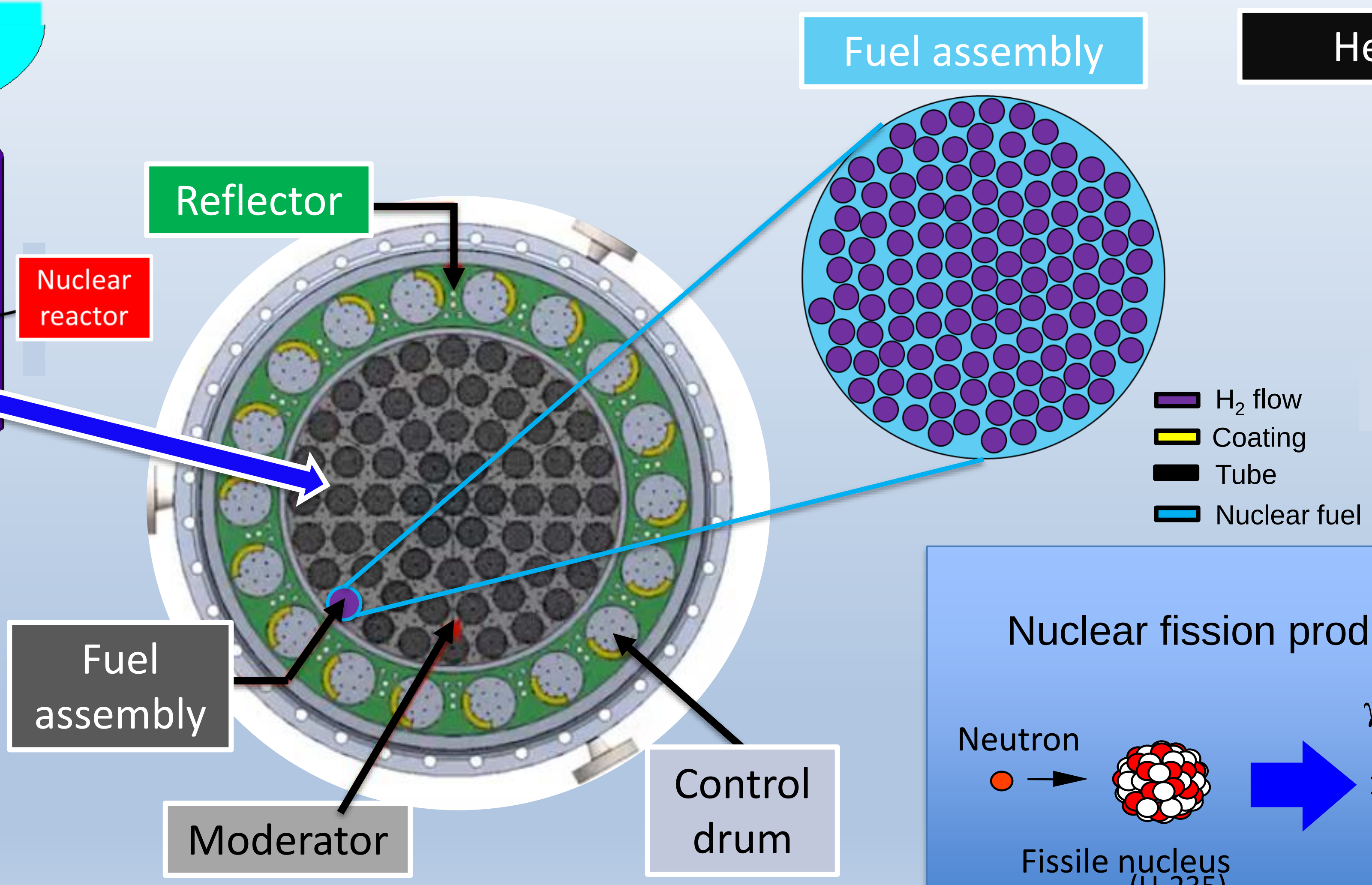
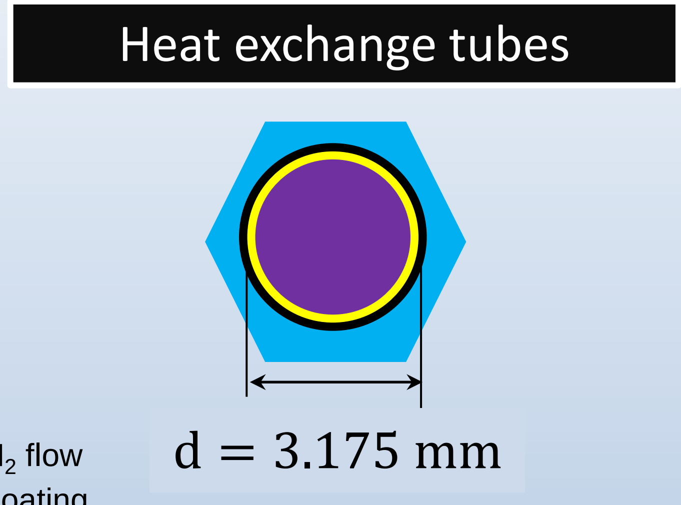
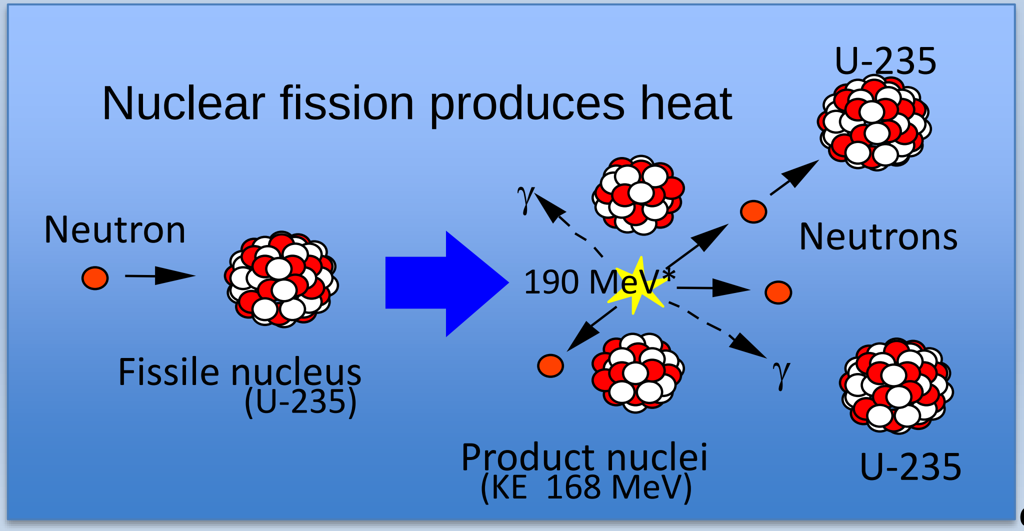


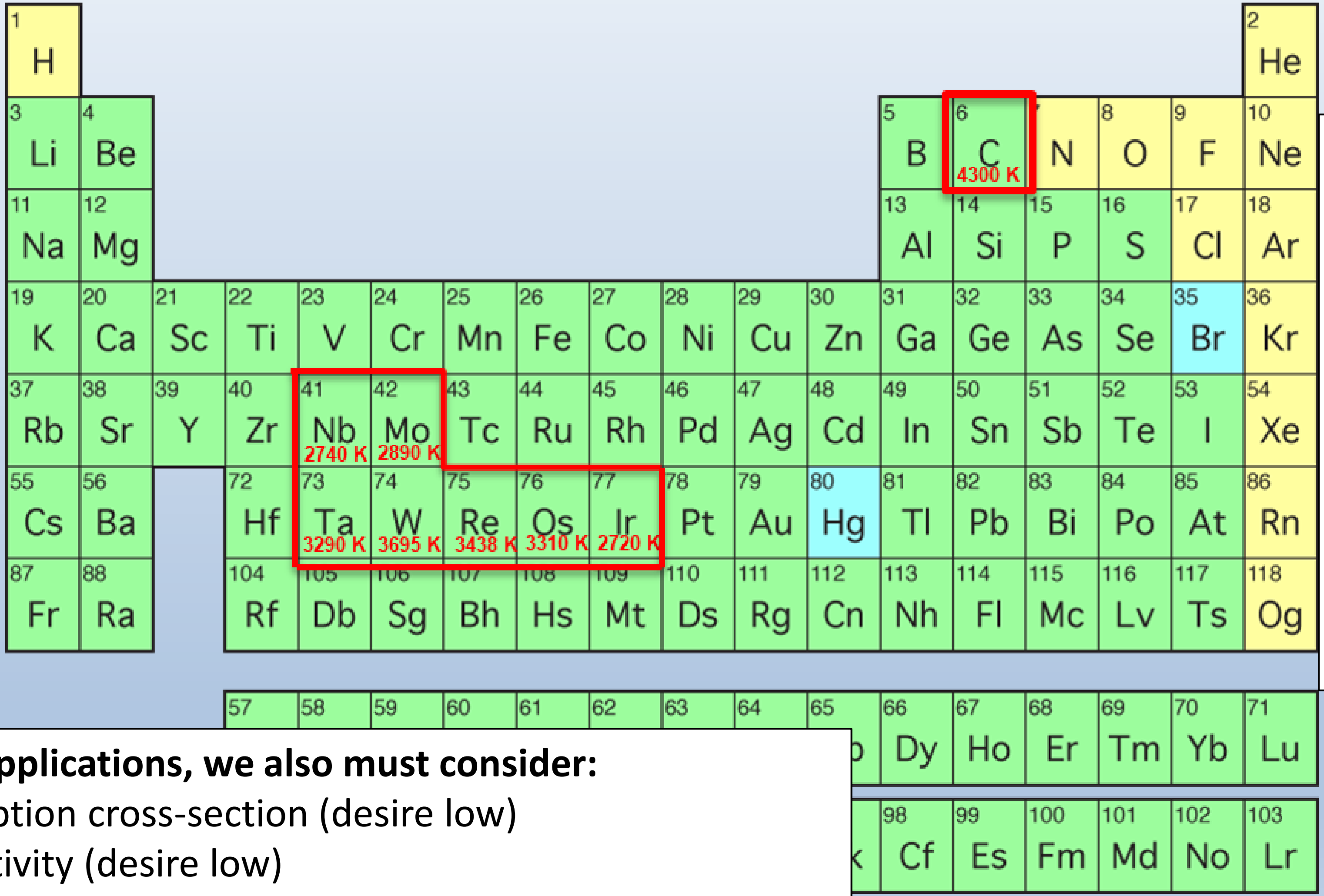



# Limited material options in 2900 K temperature range

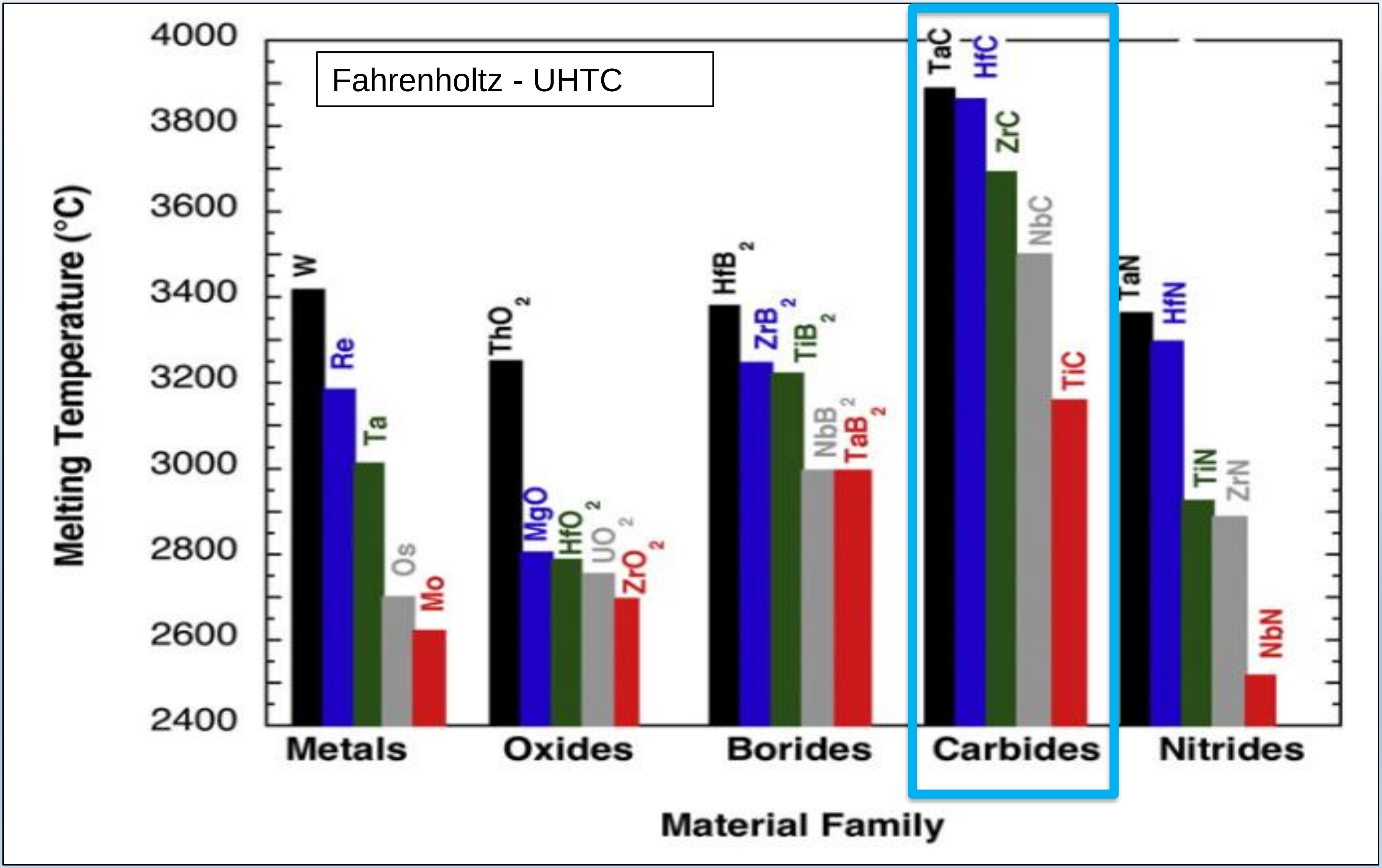
**Refractory Metals**
- Historically used in nuclear applications
- High-temperature capable
- Manufacturability issues
- $H_2$ embrittlement issues




**C/C**
- Typically used in hypersonics
- High-temperature capable
- Low coefficient of thermal expansion (CTE)
- $H_2$ corrosion without protective coating

**For NTP specific applications, we also must consider:**
- Neutron absorption cross-section (desire low)
- Hydrogen reactivity (desire low)
- Manufacturing complex geometry (small diameter tube)

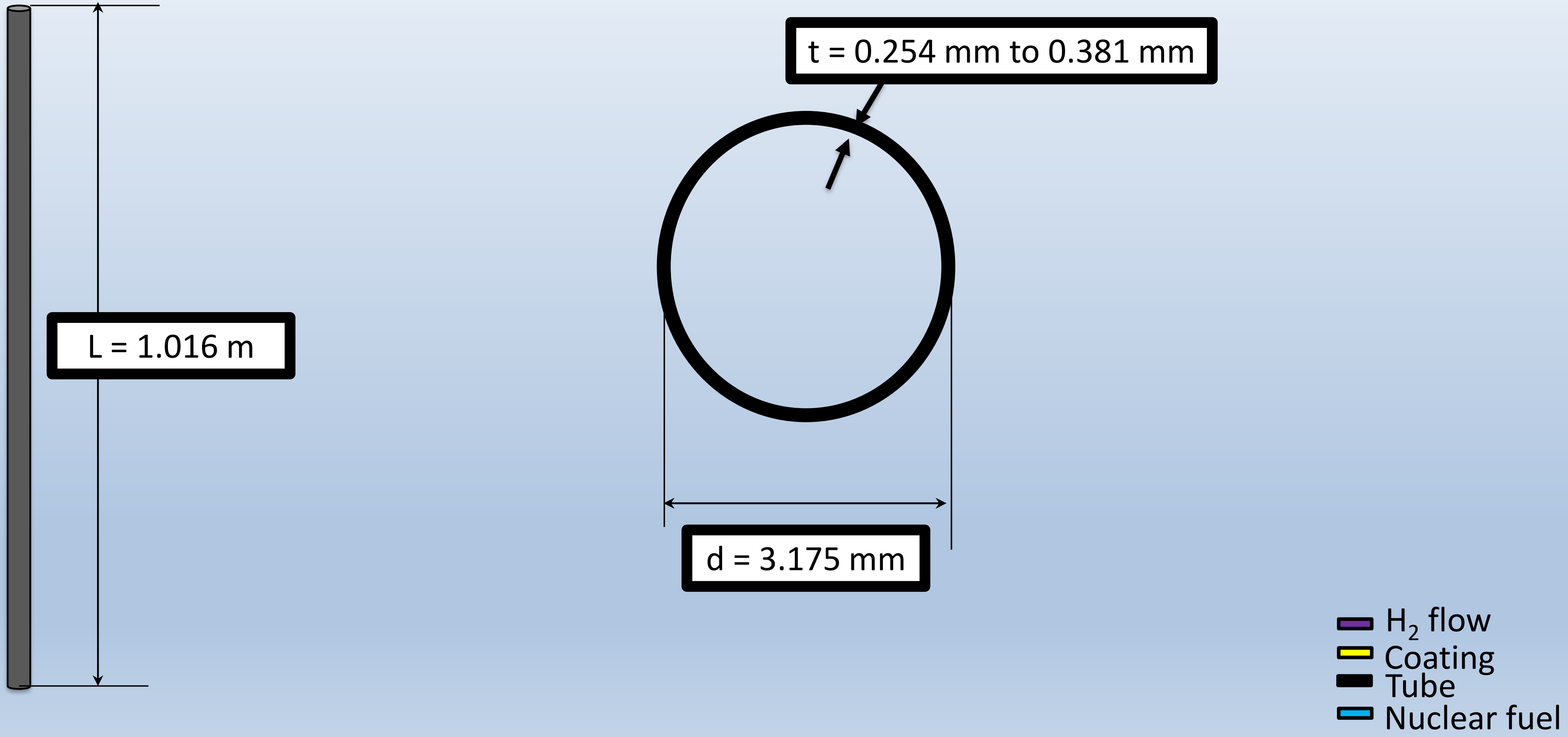
# Carbides provide another option for lining flow channels in NTP fuel element




Brittleness of carbides on their own may influence performance as a flow channel liner on their own due to damage caused by temperature cycling and high pressures

Carbide coated C/C heat exchange tube

# C/C heat exchange tubes must meet specific requirements to be successful



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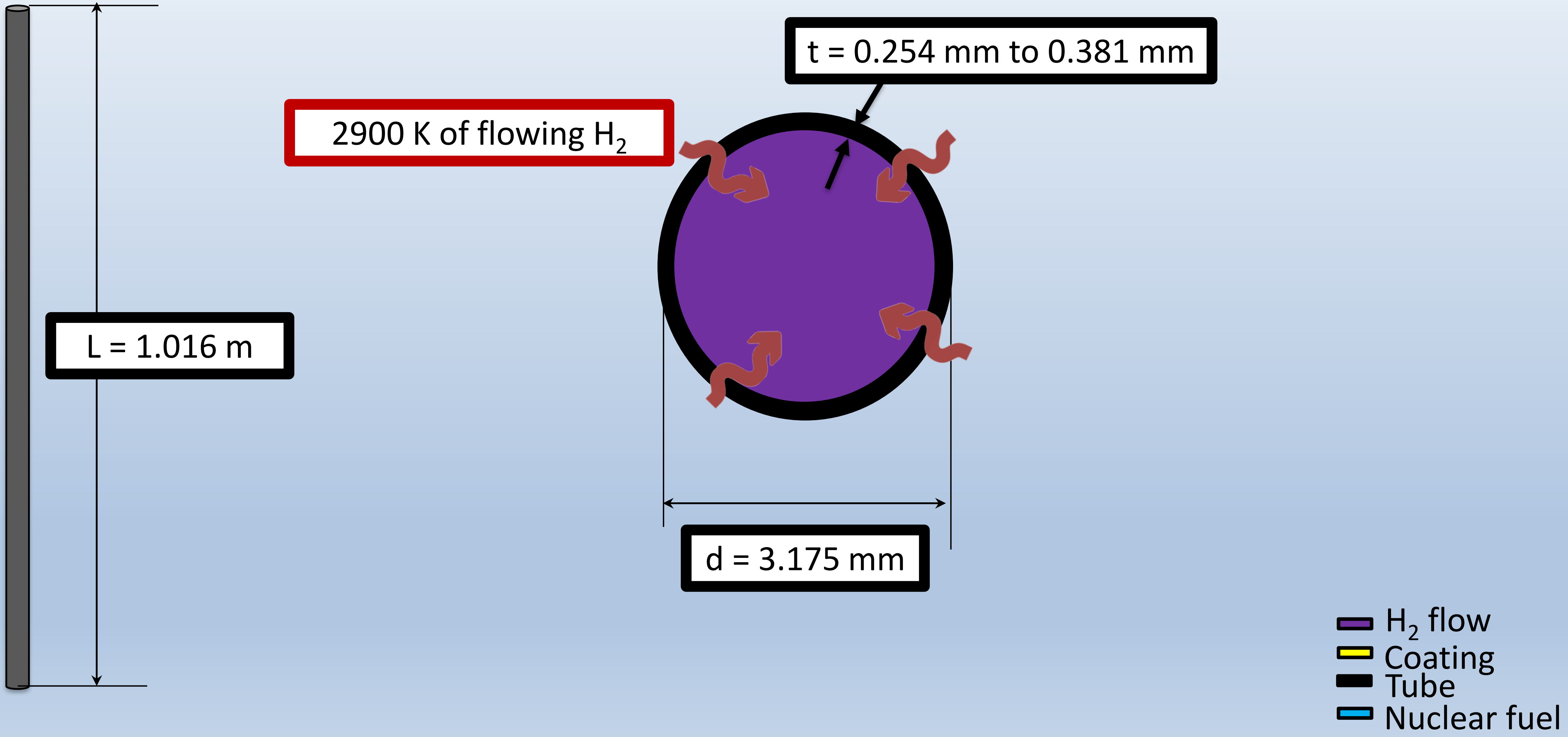

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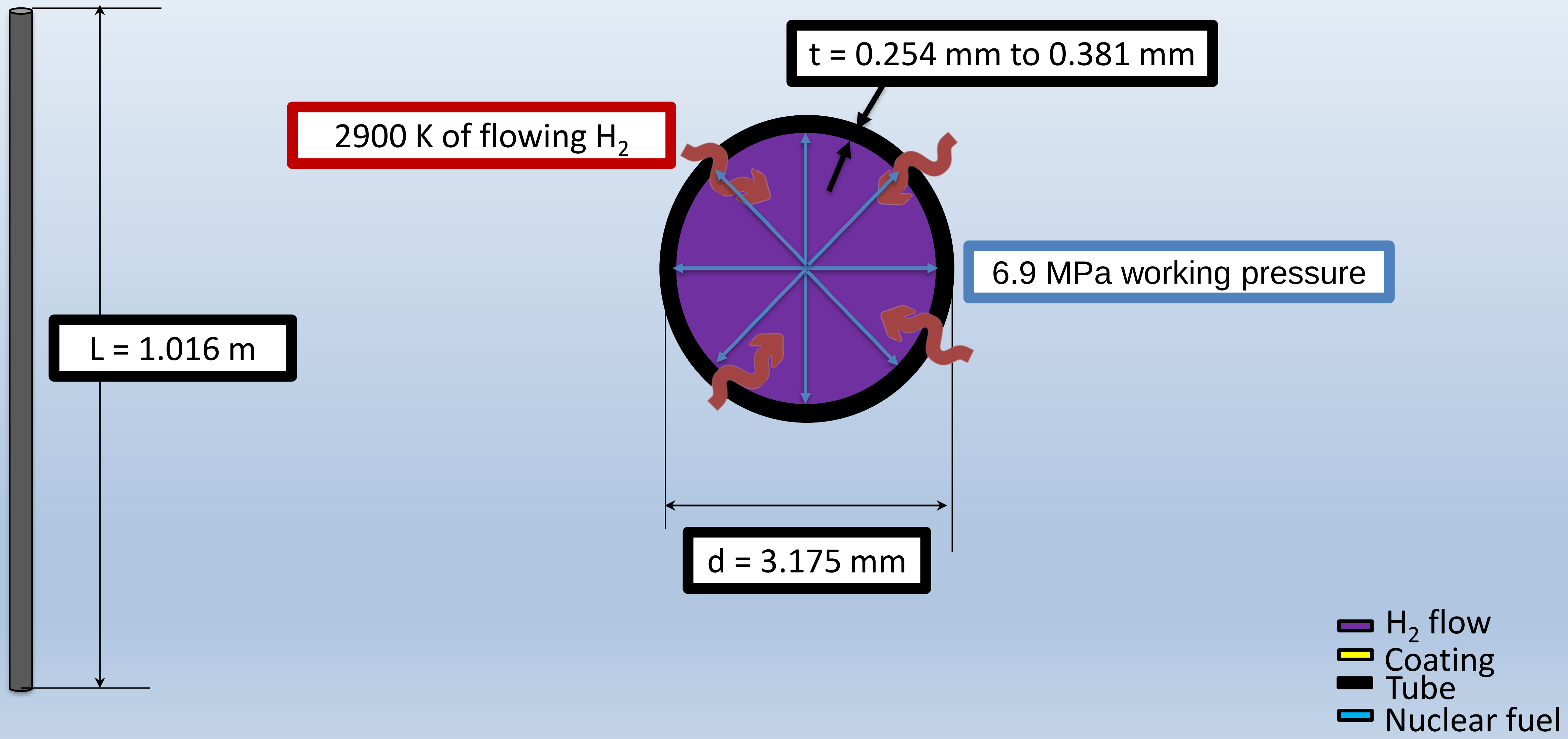

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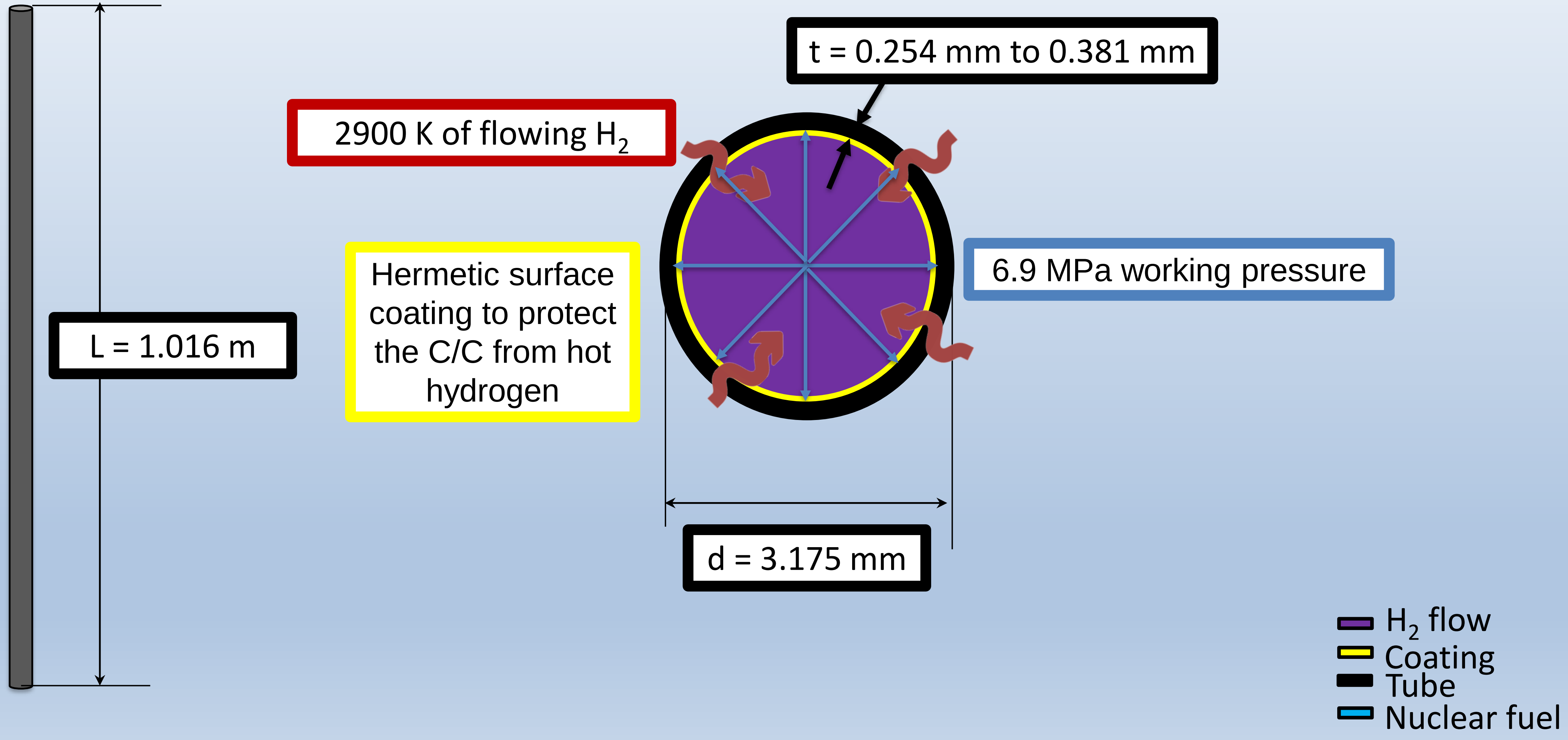

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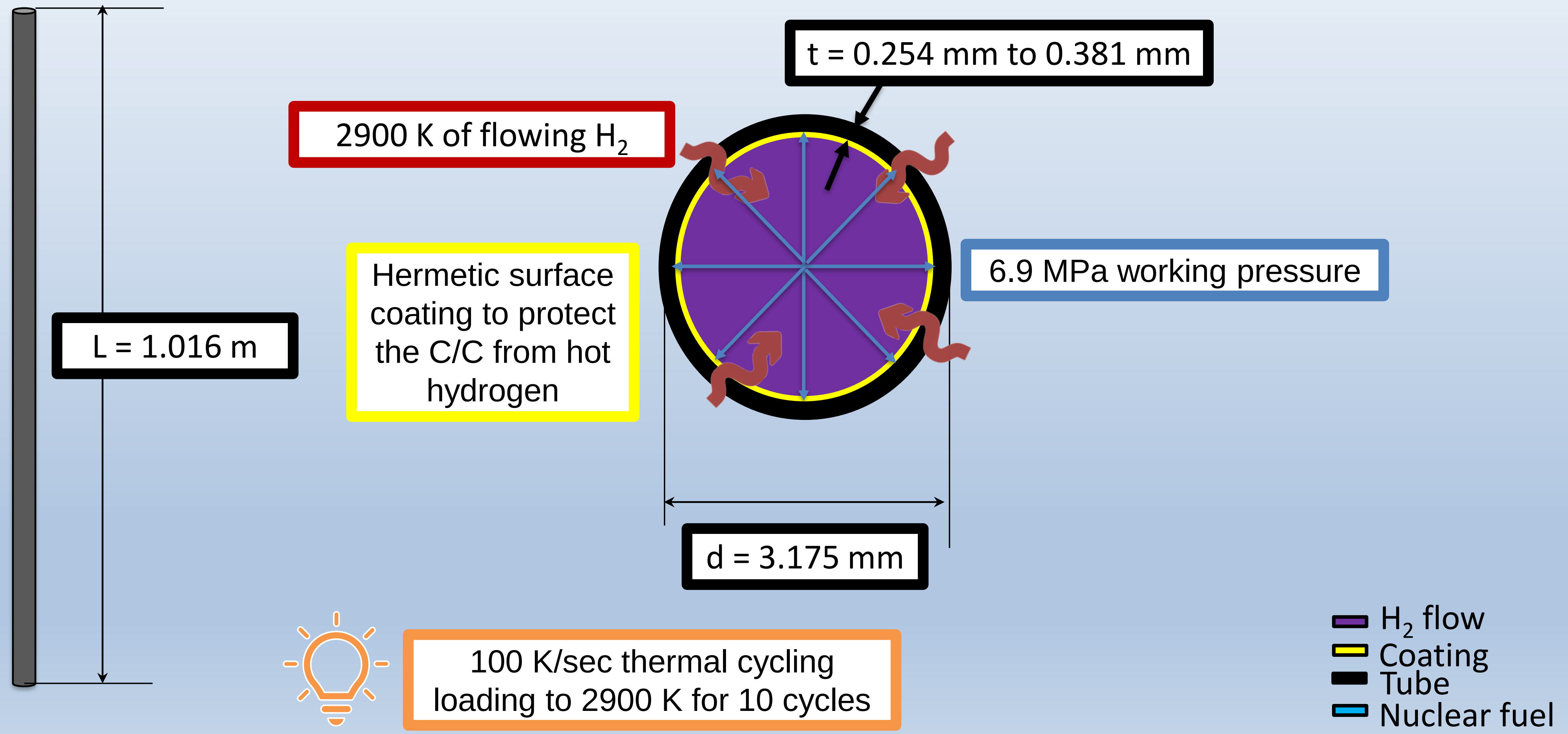

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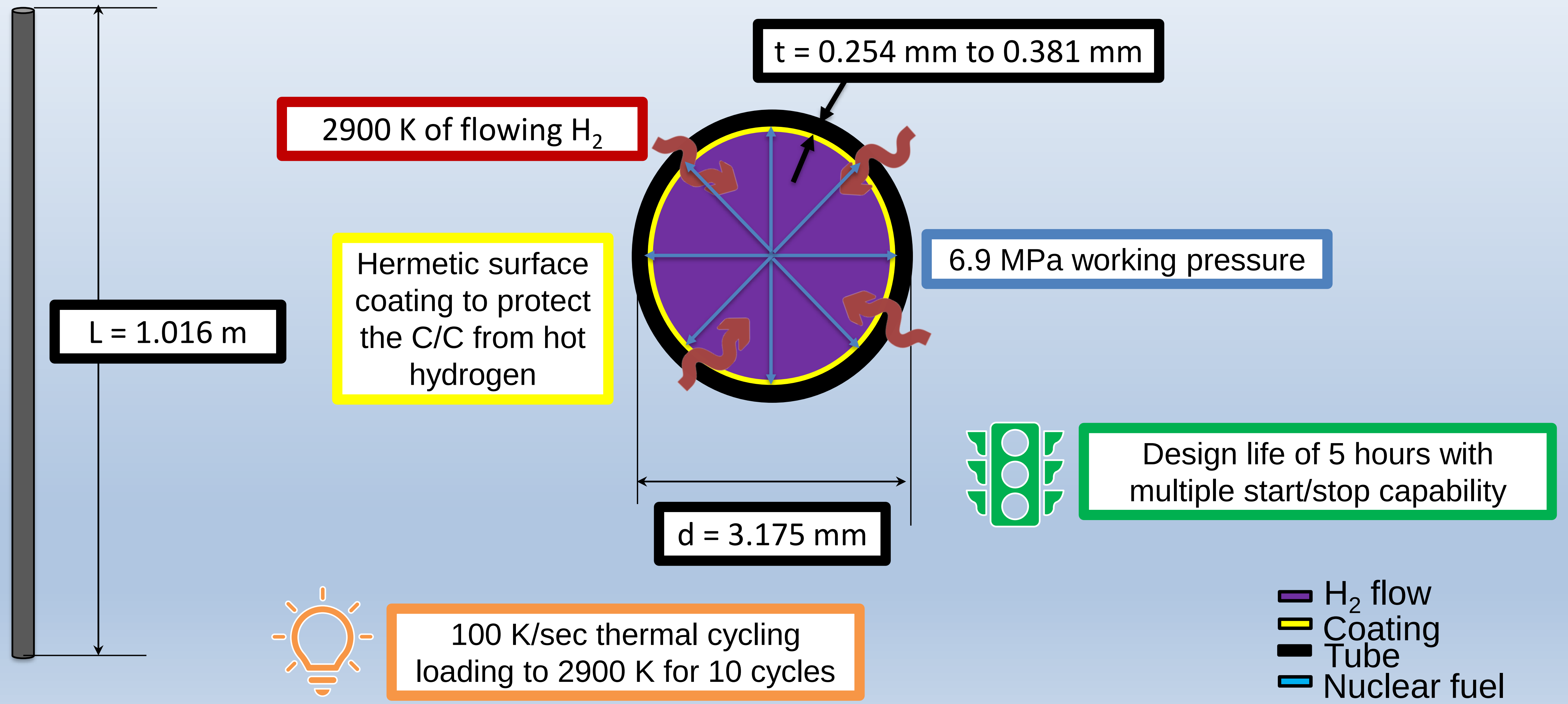


# Challenge: Develop a hermetic C/C tube with sufficient high-temperature strength and structural integrity for the NTP fuel element

Manufacturing C/C heat exchange tubes

CVDTEK

Hermetic coating on the tube interior surface to prevent $H_2$ corrosion


CVDTEK

Ames Research Center

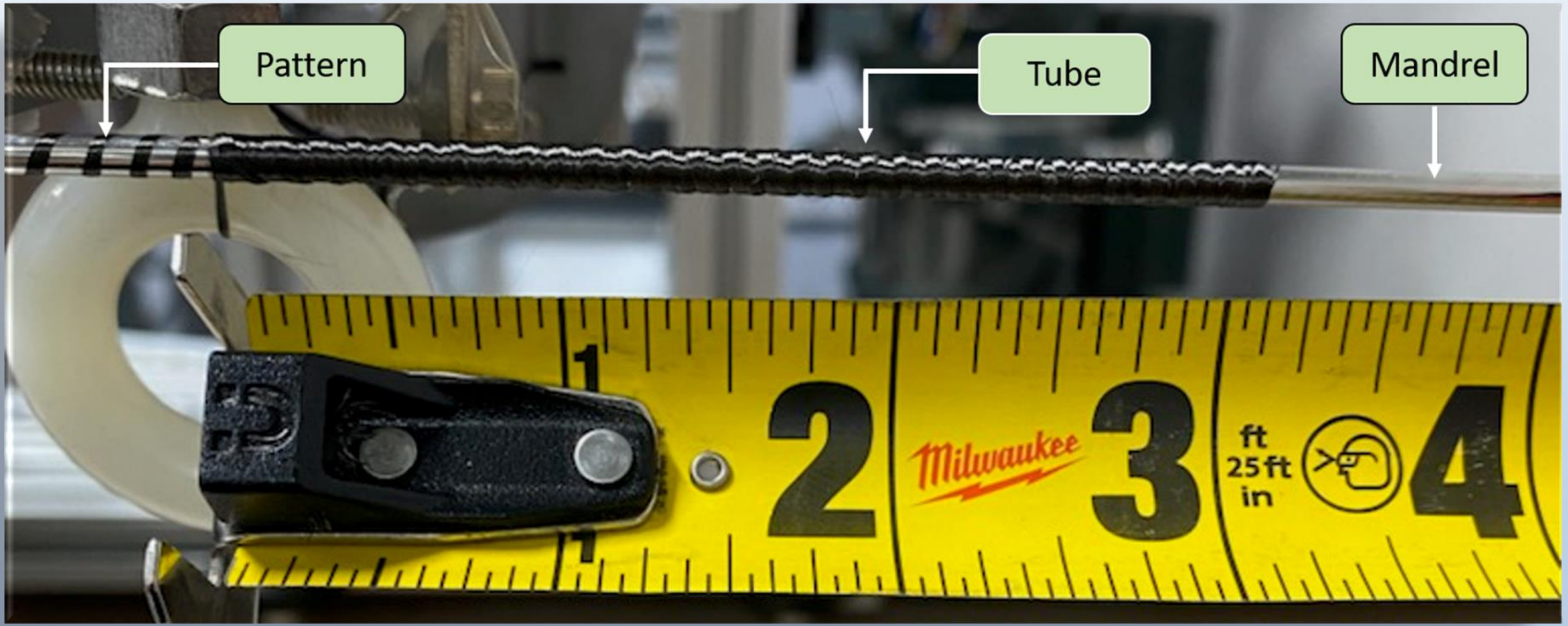
Experimental testing to understand structural behavior

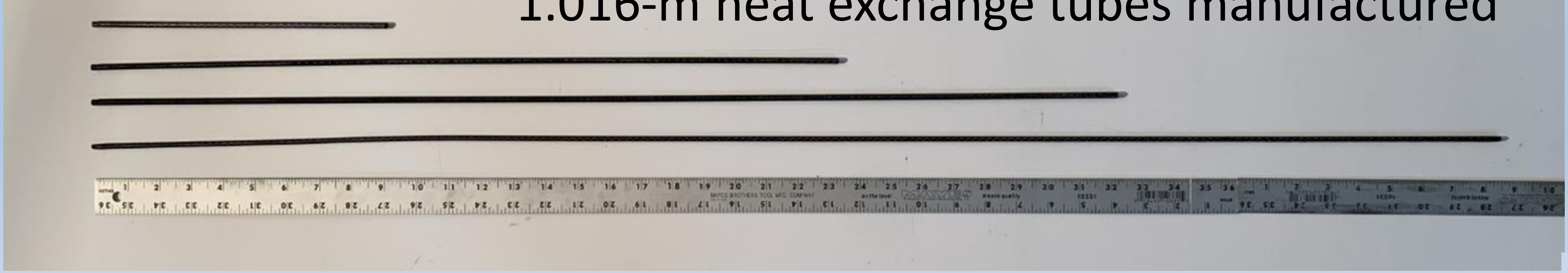
KRATOS

CVDTEK

Computational modeling of thermal and structural behavior

# Iterative "build-test-repeat" tube development cycle

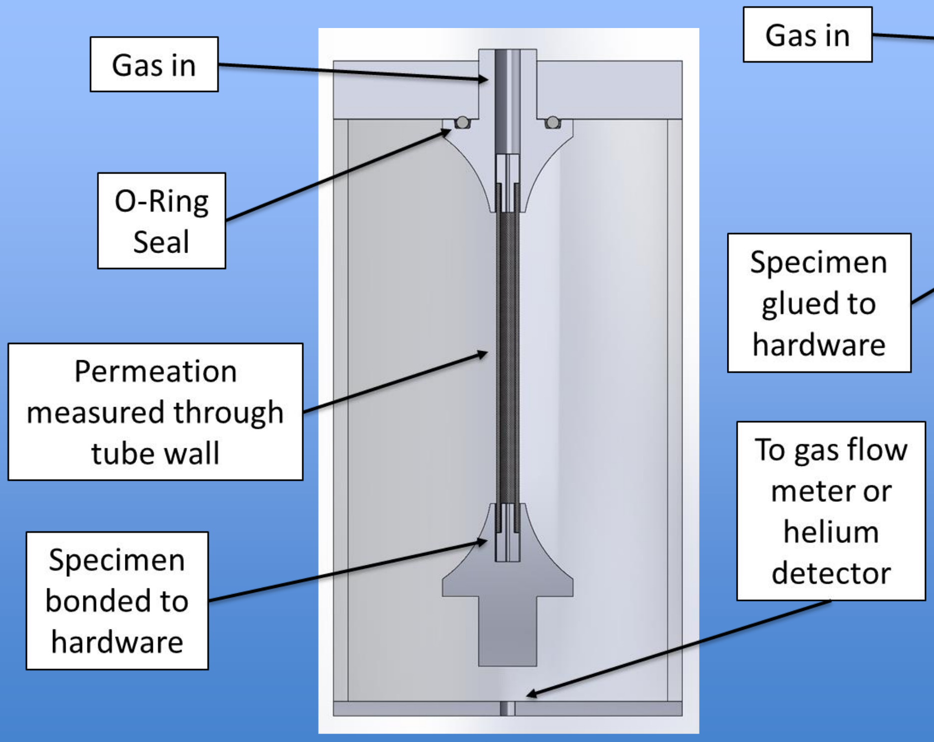


1.016-m heat exchange tubes manufactured

# Established a method to characterize tube permeability and axial tension

## Permeability Test Fixture

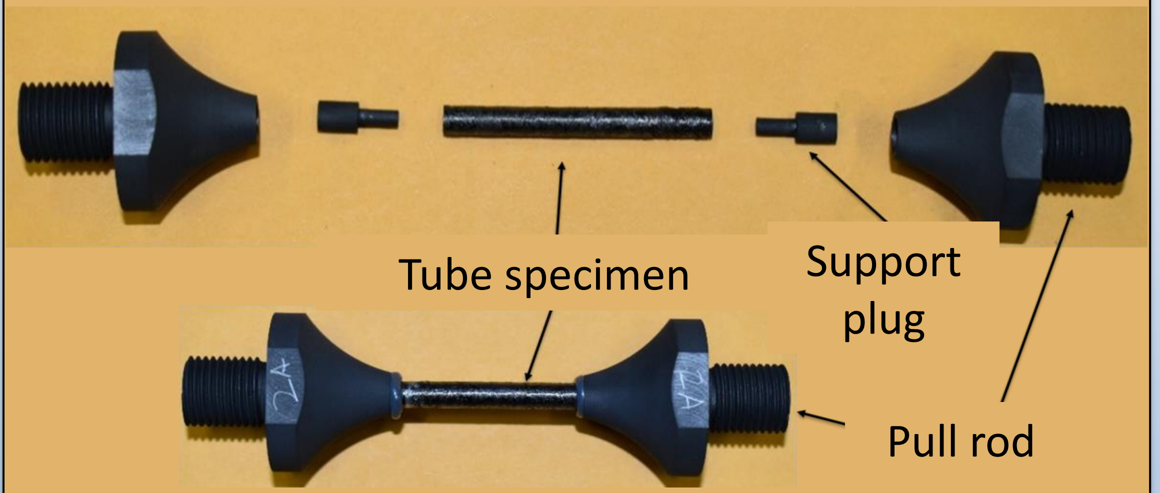



Section view

Design

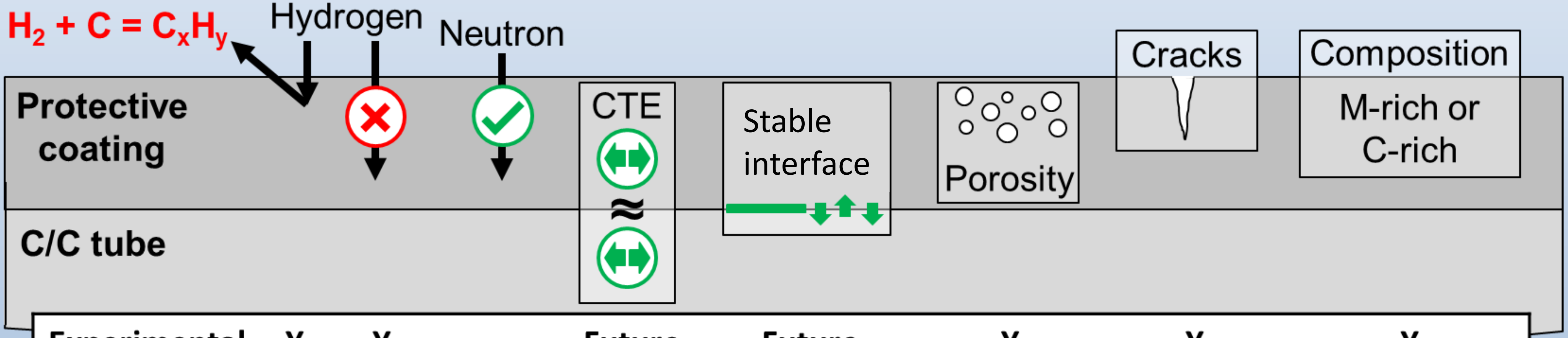

Test fixture

## Axial Tension Test Fixture



# Identified carbides as the candidate coating materials

- Carbides selected as best candidate materials
- Demonstrated preferential carbon volatilization in carbides



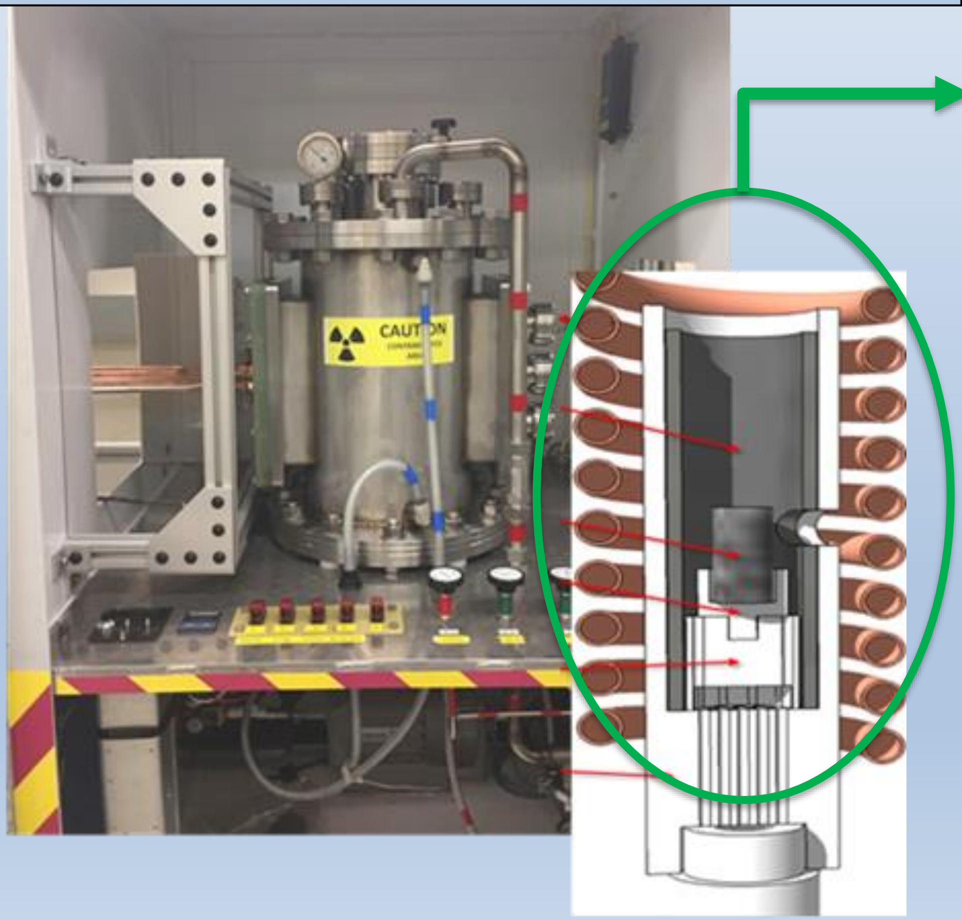

| | $H_2 + C = C_xH_y$ | Hydrogen | Neutron | CTE | Stable interface | Porosity | Cracks | Composition |
|---|---|---|---|---|---|---|---|---|
| **Experimental** | **Y** | **Y** | | **Future** | **Future** | **Y** | **Y** | **Y** |
| **Modeling** | **Y** | | **Y** | | **Future** | **Y** | **Y** | **Y** |

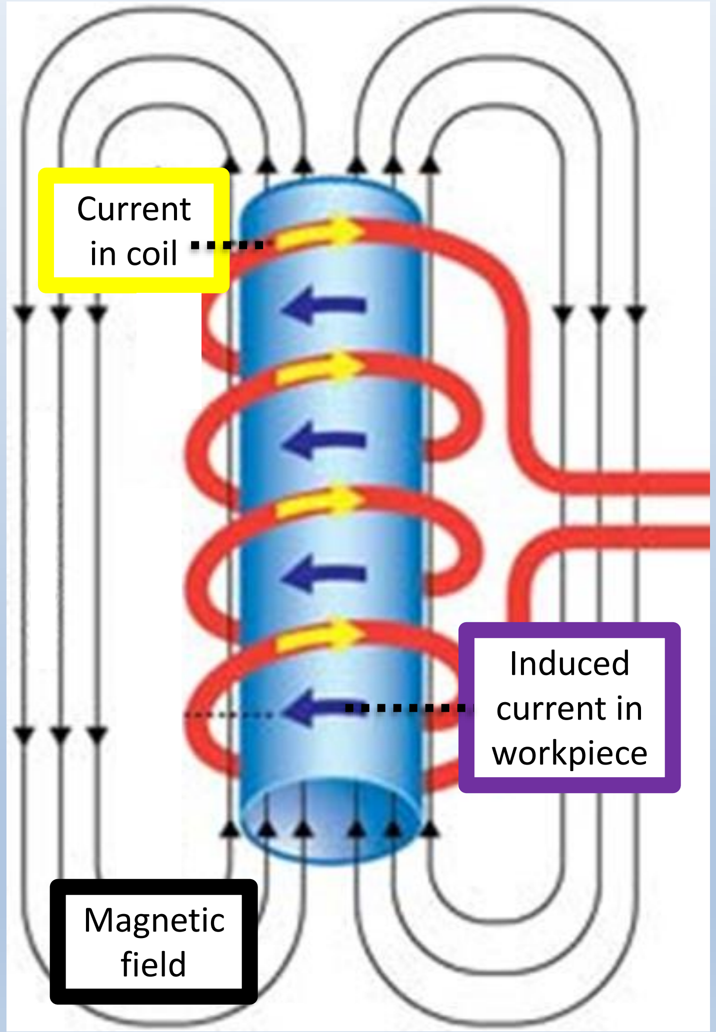
Metal-rich (M-rich); Carbon-rich (C-rich)

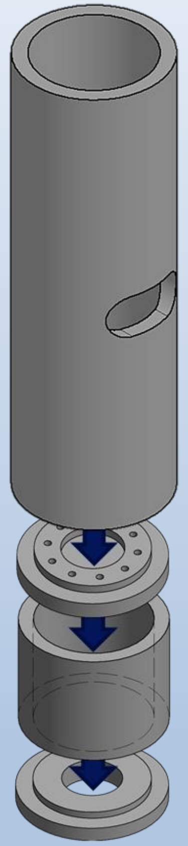
For more information, attend the lightning talk by William "BJ" Tucker on "Refractory Carbides for Hydrogen Erosion Resistance in Carbon Tubes for Nuclear Thermal Propulsion" on Tuesday May 9, 2023 @ 4:05 pm MDT

# Using hot hydrogen testing to understand carbide behavior in relevant environment

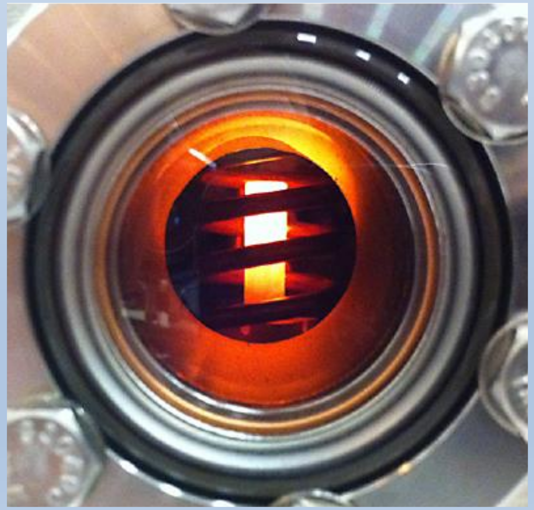
## Compact Fuel Environment Element Test (CFEET)





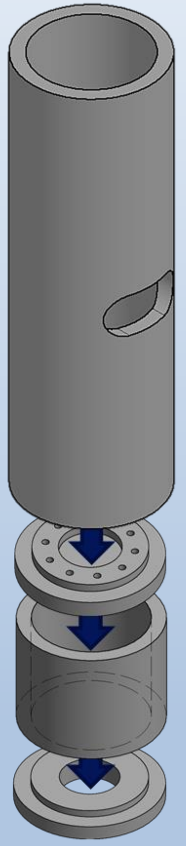



Tungsten susceptor

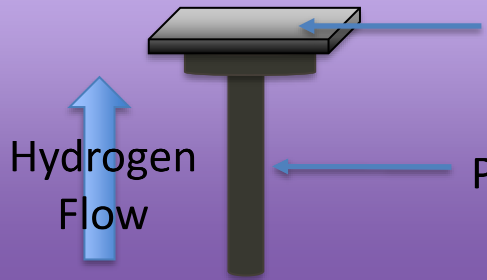
Side view

# Designed an improved sample holder for CFEET tests to achieve boundary layer on sample



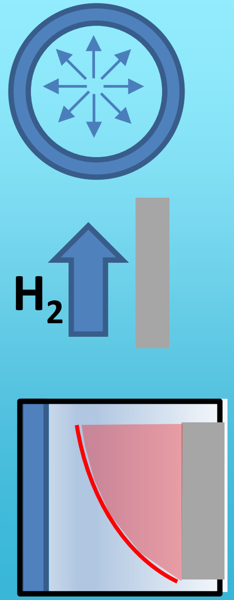
Tungsten susceptor

## Previous CFEET test setup

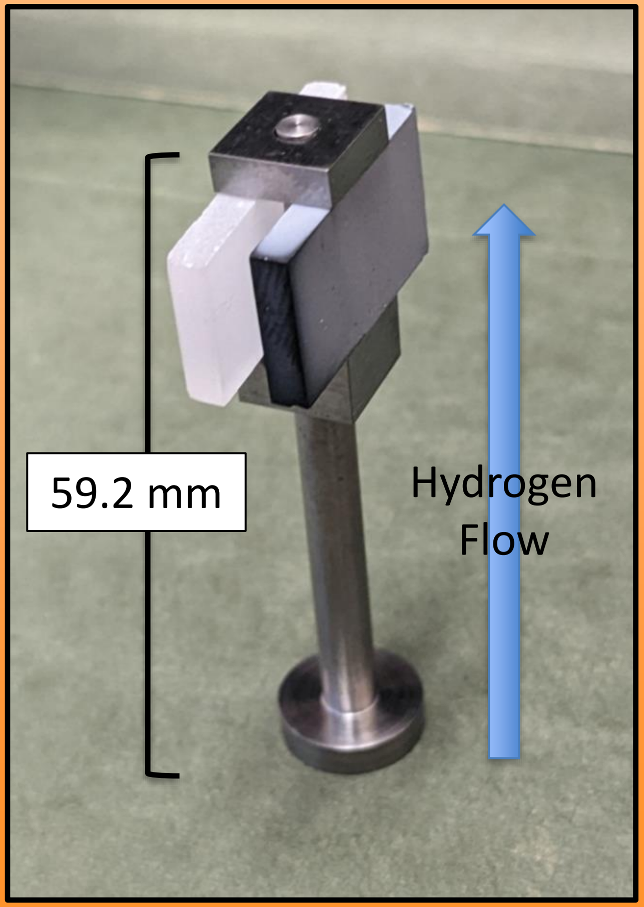


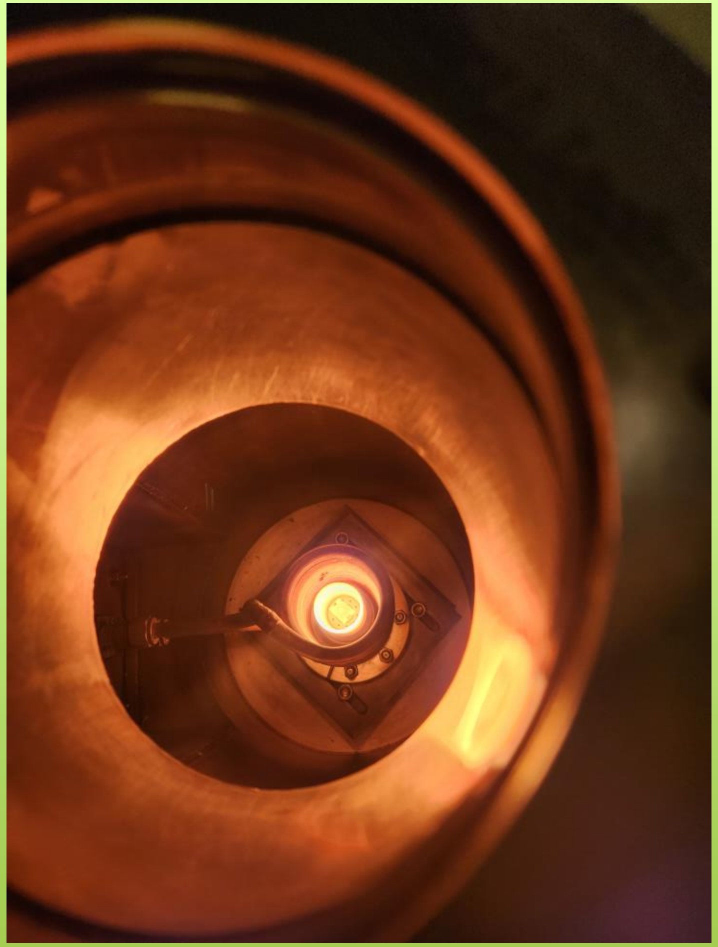

## Issues with previous setup

- Symmetry for heating
- Parallel to flow
- Well developed boundary layer on sample




## New setup

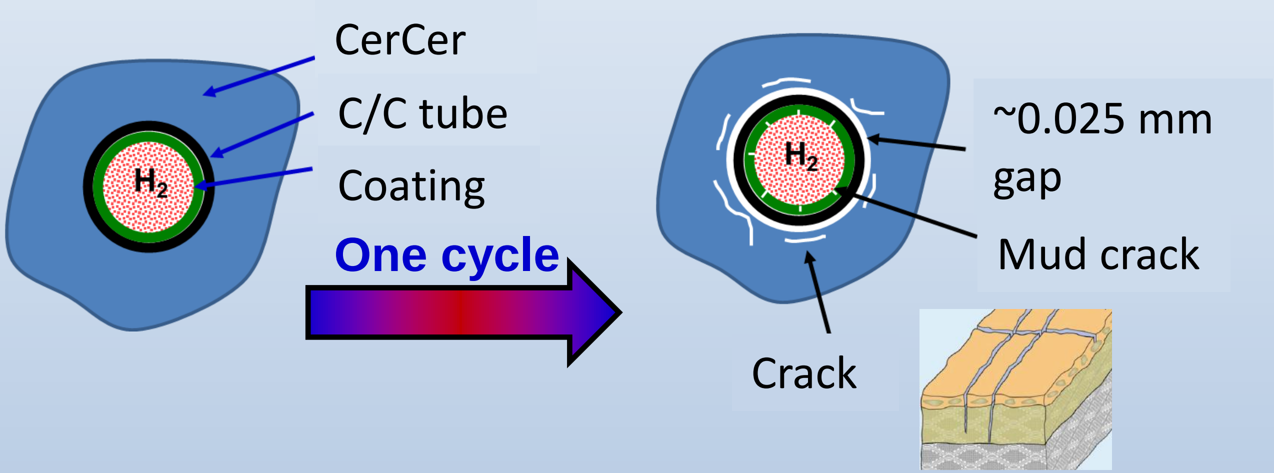


April 2023 CFEET test of TaC using new fixture

# Using thermomechanical modeling of tube to elucidate challenges with tube-fuel integration

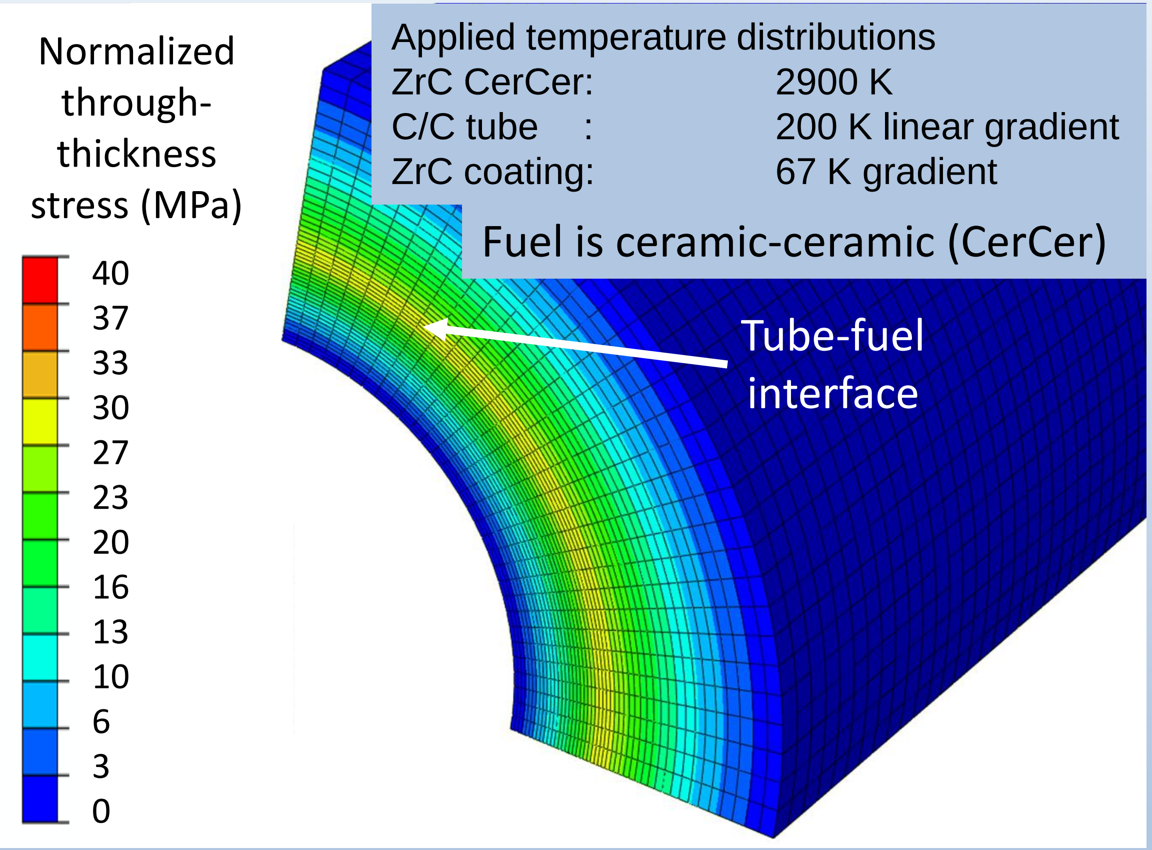
- Finite element modeling (FEM) used for preliminary understanding of stress states




- Stresses due to coefficient of thermal expansion (CTE) mismatch are very large

**Challenge: Can we overcome CTE mismatch with a different design configuration?**

**Problem greatly reduced if CerCer and coating are pseudo-ductile**




For more information, please attend "*The Challenges with Material Interfaces in a Nuclear Thermal Propulsion Engine Heat Exchanger*" by Sarah Langston at 10:30 am MDT on May 8, 2023

# In the next year, coated C/C tubes will be manufactured and tested in relevant conditions

**Concluding remarks**

- Desired geometry is achievable using C/C
- Coating C/C remains a tall pole
- Developed an experimental assessment method for C/C tubes
- FEM used to investigate tube integration with CerCer to form fuel assembly

**Future work**

- Chemical vapor deposition to coat inner diameter of C/C
- Coated C/C samples for CFEET testing to characterize behavior
- Manufacture mixed carbide samples for CFEET testing
- Continued experimental characterization of the coated C/C tubes at Kratos SRE

# Questions?

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*This work is supported by the NASA Space Technology Mission Directorate through the Space Nuclear Propulsion project*