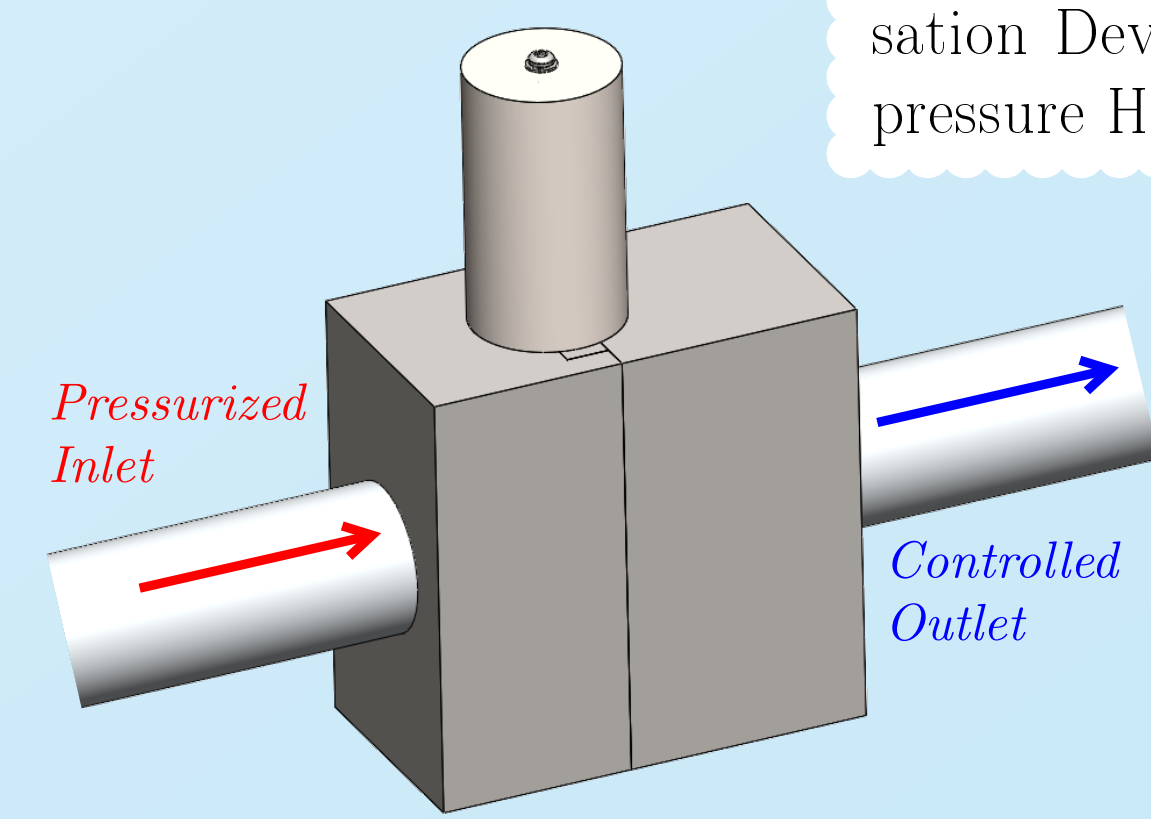


Mission:

Thermomechanical Flow Control

Modern defense technology research requires ever-increasing precision control of experimental conditions. Many experiments conducted by Sandia National Laboratories depend on sub-millimeter precision Hydrogen flow control without the luxury of an electronic feedback loop. Passive flow control has been used in consumer-grade thermostat regulators and in binary-state satellite spacecraft thermal switches[1]; but continuous, high-precision flow control would require a novel design never before produced.

Sandia commissioned the Noble Aggie Labs (the authors) to design and prototype a proof-of-concept Passive Temperature Compensation Device (PTCD) that thermomechanically restricts a high-pressure Hydrogen gas supply with medical precision.



Mission: Passively control a pin-size orifice with hair's-breadth precision under extreme pressures and temperatures.

Solution: Combine an aerospace-grade thermomechanical actuator with a novel diamond-orifice valve.

System Specification

Provided by Sandia

The device shall thermomechanically maintain a variable orifice such that

$$D_{effective} = A_1(T_{ambient} - 25^{\circ}\text{C}) + A_0$$

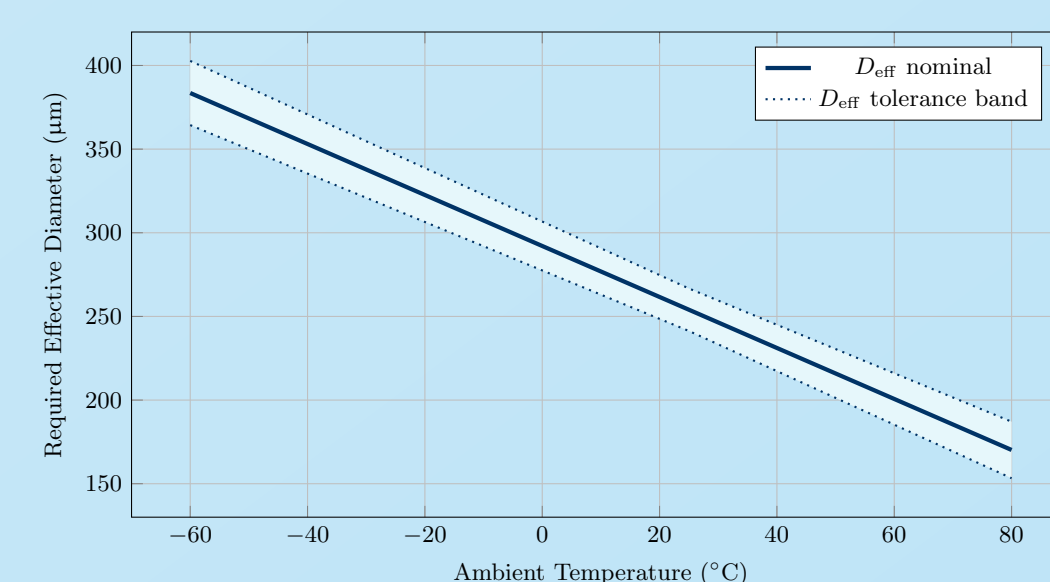
$$A_1 = 1.524 \frac{\mu\text{m}}{^{\circ}\text{C}} \pm 5\%$$

$$A_0 = 254 \mu\text{m} \pm 5\%$$

$$-60^{\circ}\text{C} \leq T_{amb} \leq 80^{\circ}\text{C}$$

$$689.5 \text{ kPa} \leq \Delta P \leq 68.95 \text{ MPa}$$

Hydrogen or any Noble gas



$$\begin{aligned} (D_{eff}(-60^{\circ}\text{C}) &= 383.5 \pm 19.2 \mu\text{m}) \\ (D_{eff}(80^{\circ}\text{C}) &= 170.2 \pm 16.9 \mu\text{m}) \end{aligned}$$

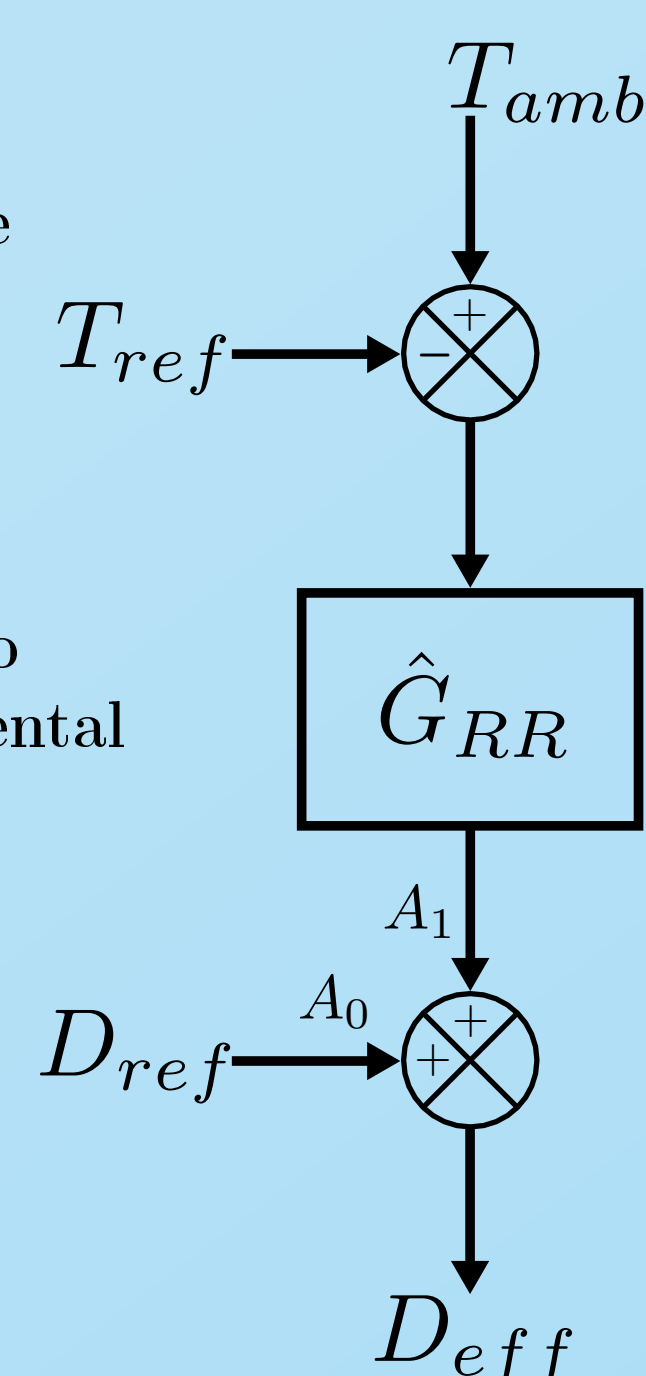
Design Approach

Thermomechanical flow control requires two subsystems:

- ◊ The *Actuator* takes advantage of the property of material thermal expansion[2] to translate temperature fluctuations into mechanical displacement.
- ◊ The *Valve* contains, seals, and controls the gas flow, driven by the actuator.

The PTCD architecture must meet strict specifications to achieve submillimeter precision under extreme environmental conditions:

- ◊ Linear output
- ◊ Simple, precise
- ◊ Compact
- ◊ High-strength
- ◊ Hermetically sealed
- ◊ Calibrateable
- ◊ Immune to Hydrogen embrittlement

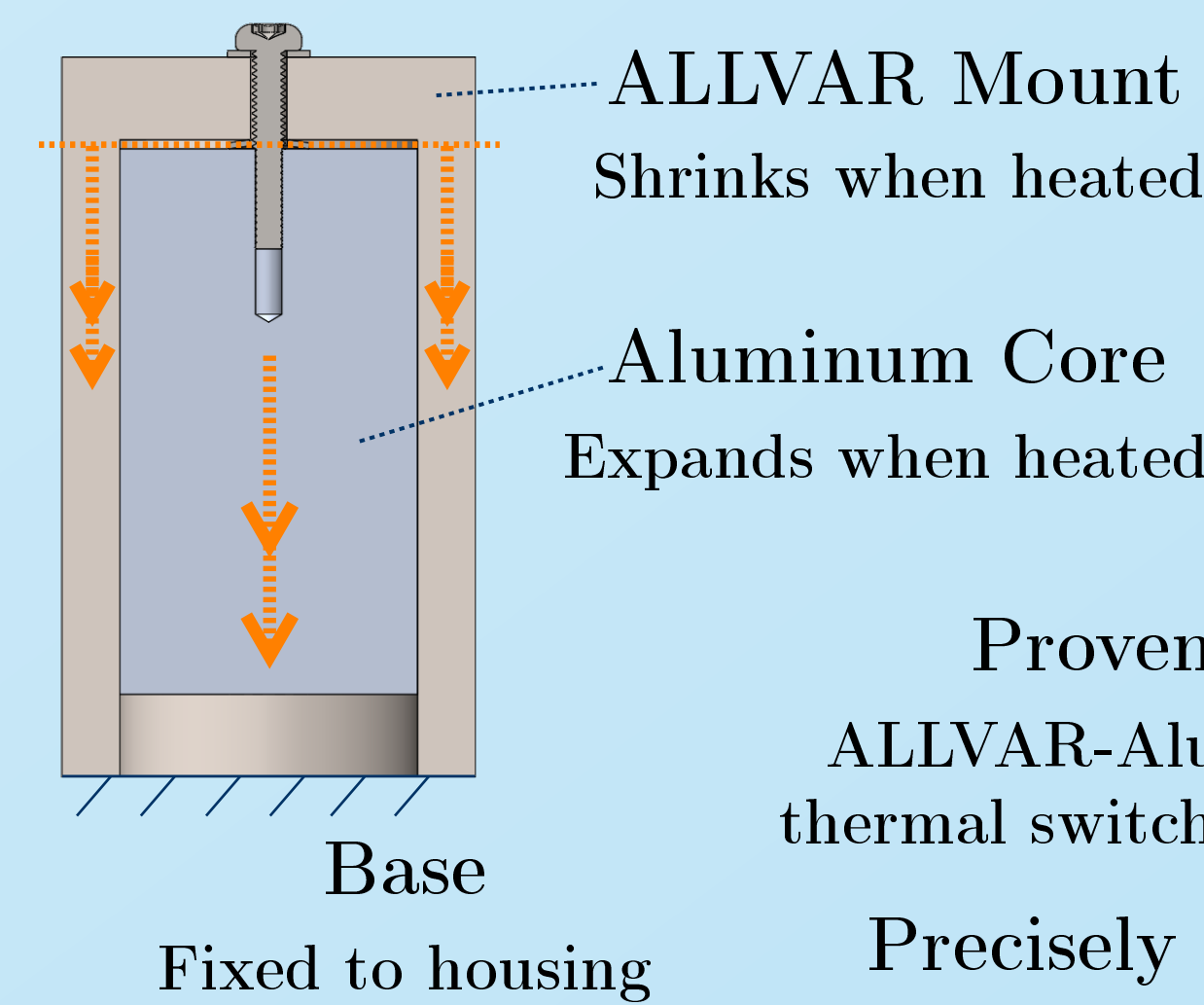


Block diagram representing the required passive system control Transfer Function

Design Innovations

The PTCD utilizes a combination of proven, aerospace-grade technology and novel innovations to accomplish its mission.

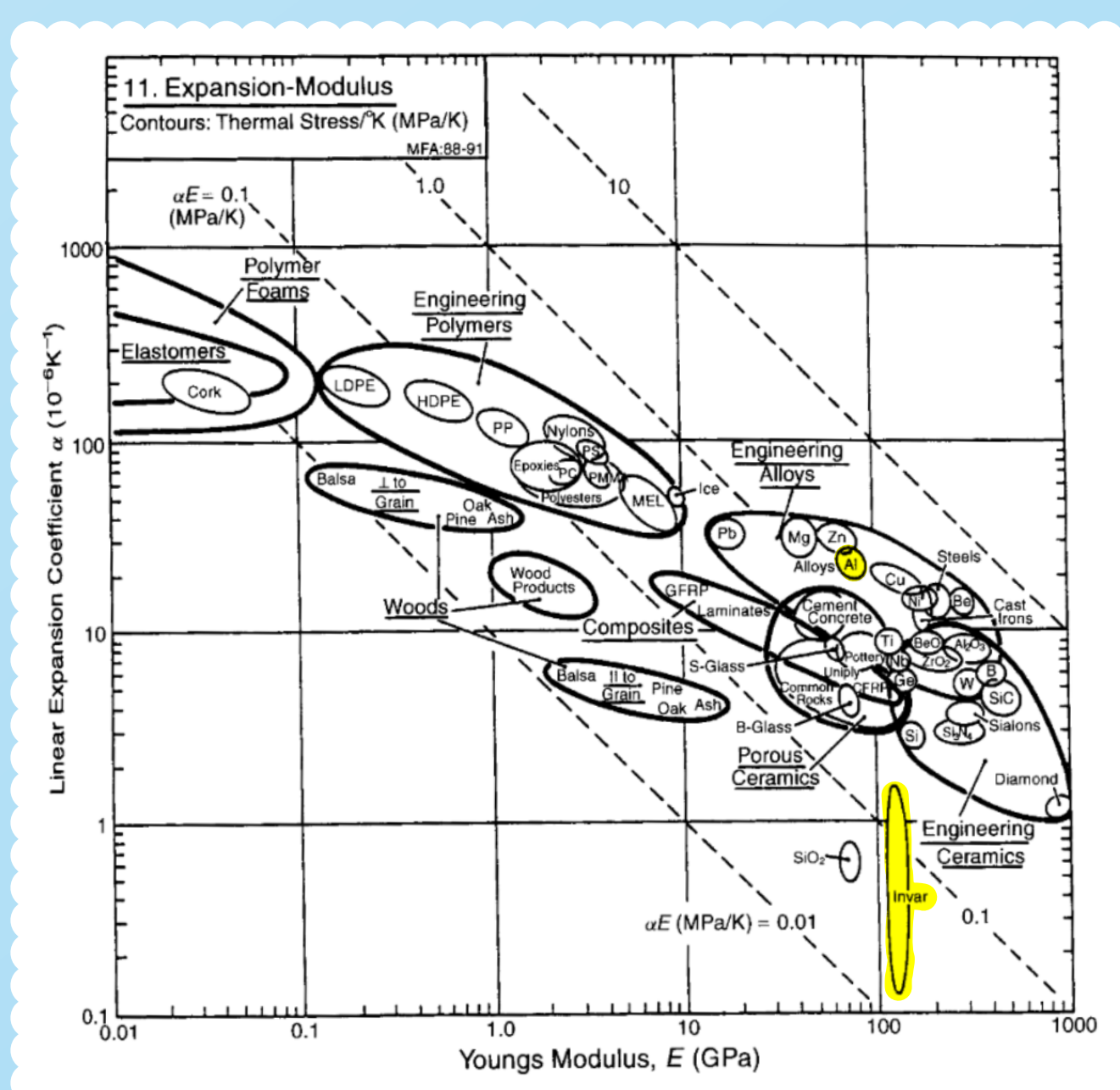
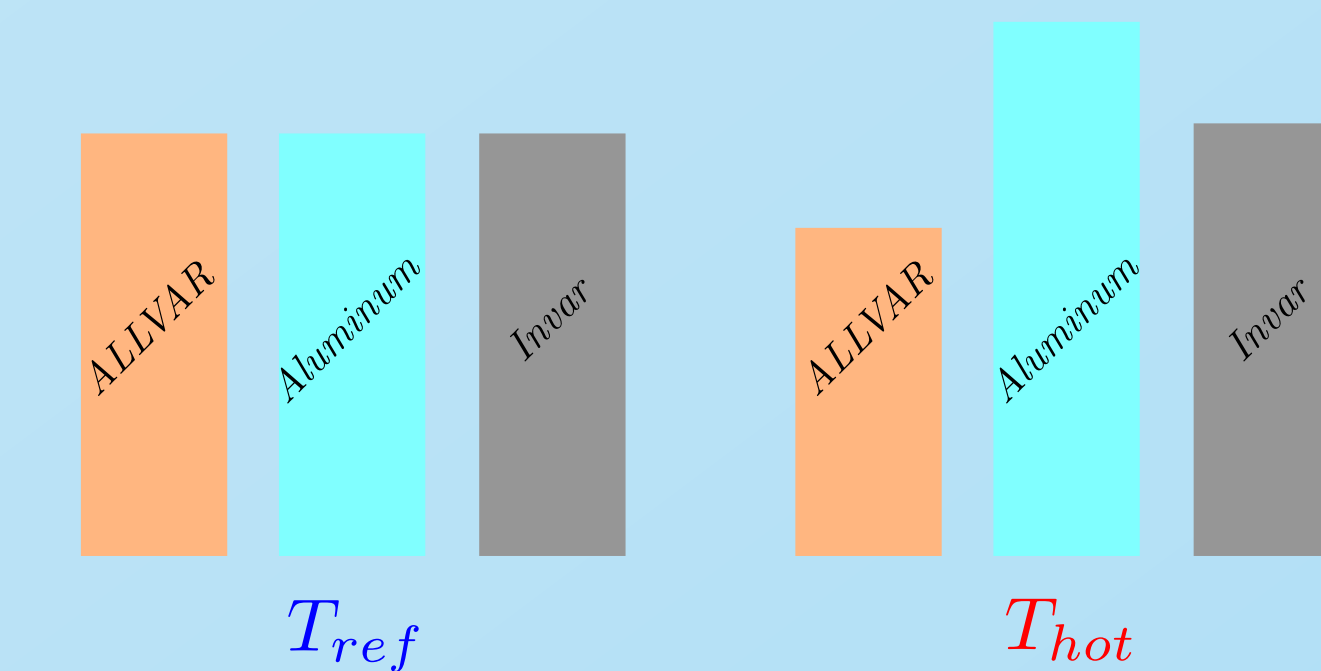
Bimetallic Actuator



Proven Strategy
ALLVAR-Aluminum used for thermal switches in spacecraft[1]
Precisely dimensioned to achieve exact displacement

Material Matters

- ◊ Aluminum Core
High, stable coefficient of thermal expansion (CTE) — rare among metals
- ◊ ALLVAR Mount
Unique proprietary alloy made by ALLVAR Alloys
Stable, negative CTE
Enables compound bimetallic actuation
- ◊ Invar housing
Unique Ni-Fe alloy¹ — imperceptible expansion rate prevents unwanted thermal distortion



The Ashby Plot[3] demonstrates that Invar is truly unique as a machinable, thermally neutral alloy. Its variants expand anywhere from 20 to 150 times less than Aluminum.

¹Fun Fact! Swiss physicist and metrologist Charles Édouard Guillaume won a Nobel Prize for the discovery of Invar 36 in 1920.

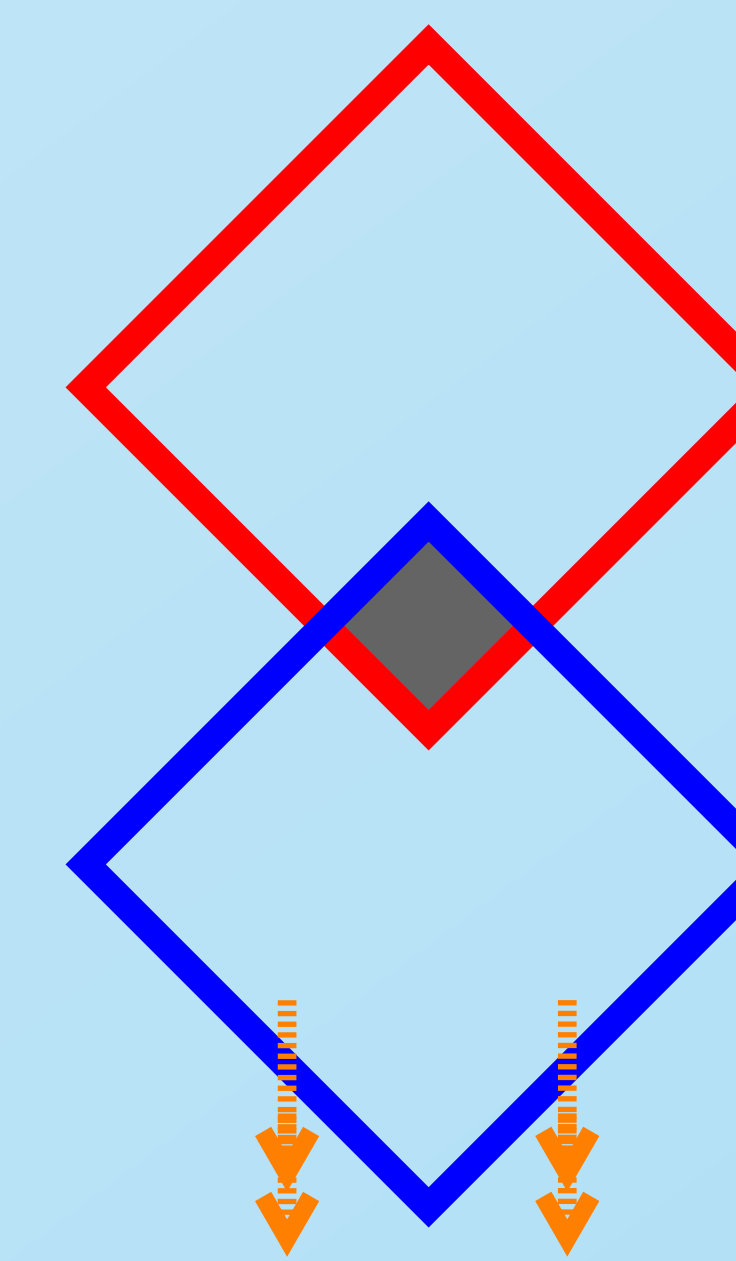
Variable-Diamond Orifice

The PTCD's novel architecture overcomes many shortcomings of its competitors.

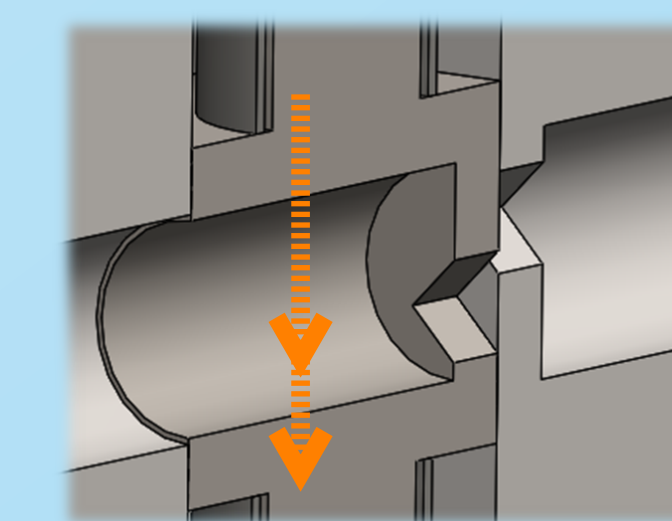
- ◊ Linear output
- ◊ Simple → precise

Why a square?

The specified Temperature-Diameter relationship is strictly linear. This requires an orifice that remains a regular polygon. The 45° tilt ensures that the side lengths shrink simultaneously.



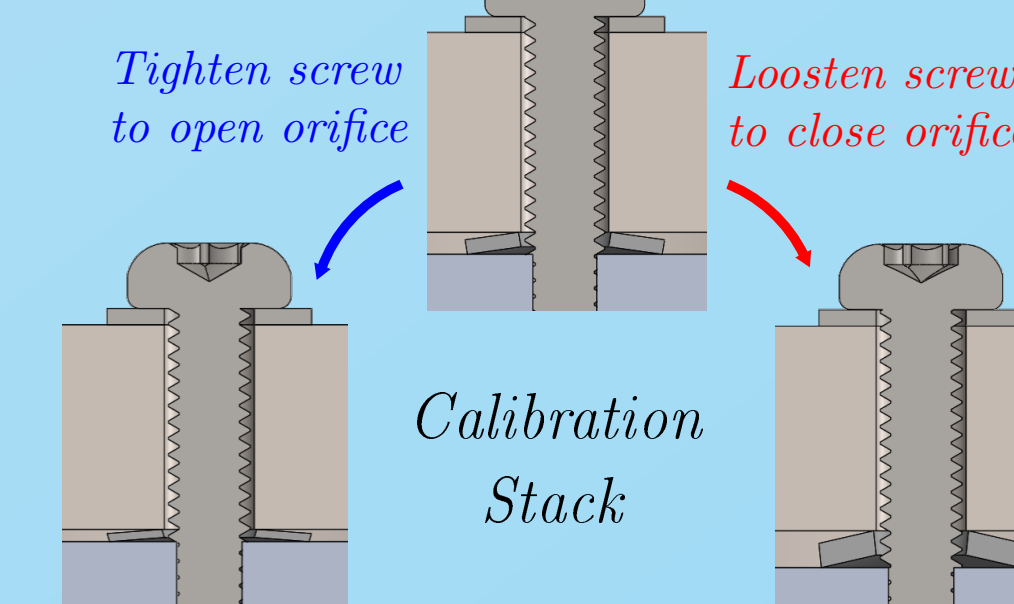
Two square holes are pressed against one another. Gas can only pass through the overlap between them, like the center of a Venn diagram.



Square holes are notoriously difficult to machine. These will be cut using Sinkers Electric Discharge Machining, which can cut a 76 μm fillet radius — a sharp, linear orifice.

Precision Machining

- ◊ Shaft fits
Finely-tuned sliding-contact fits for precise, frictionless action
- ◊ User calibration
Belleville washer in actuator maintains tension for tuneable setpoint
- ◊ High-fidelity welding
All parts are electron-beam welded for exact positioning and maximum strength



High-Pressure Hermetic Seal

Aerospace-grade flexible metal bellows seal the actuator-valve interface.

The secret sauce: Inconel 718, Nickel superalloy

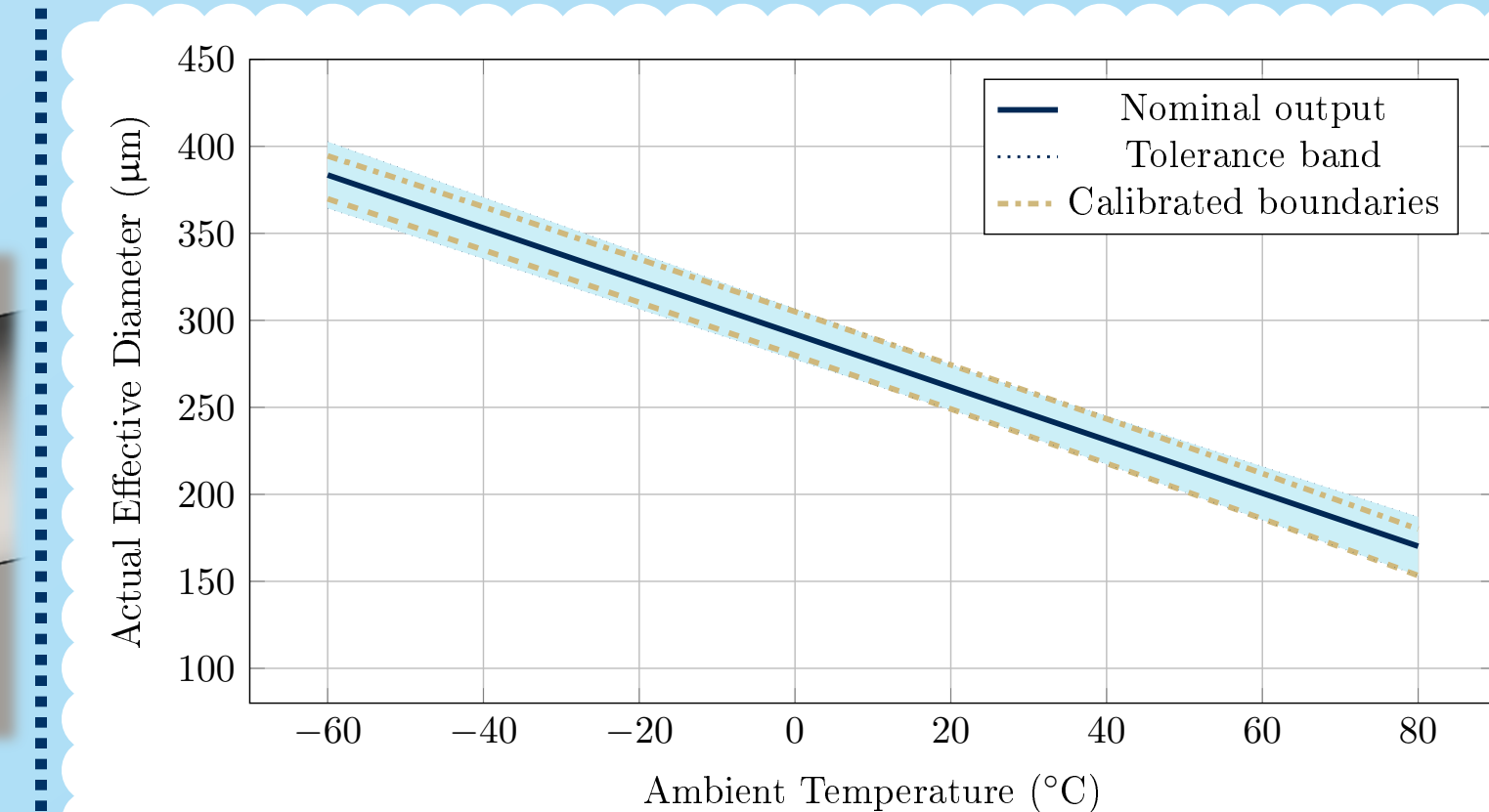
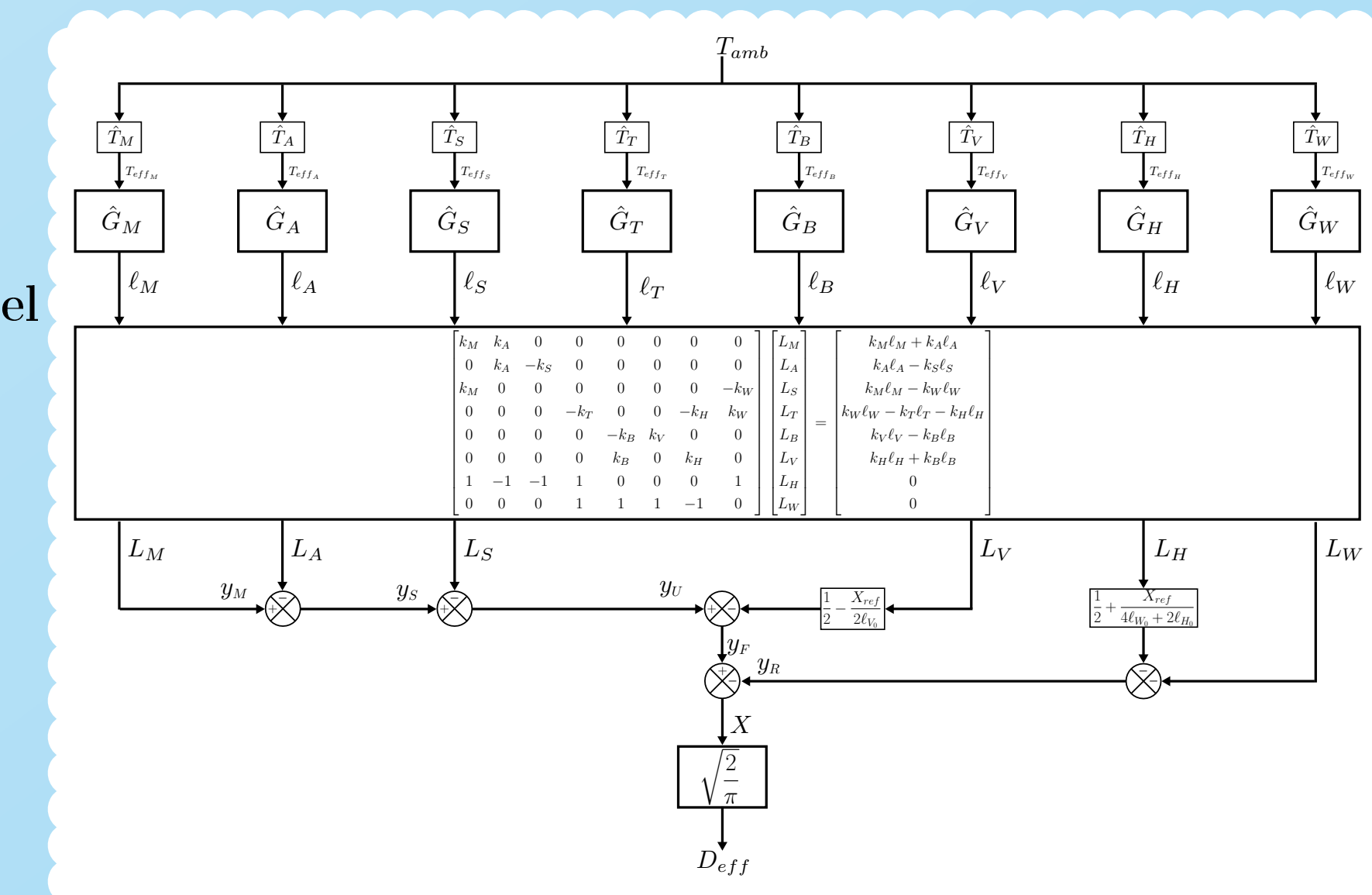
- ◊ Stronger than steel at high temperatures, cyclic loads
- ◊ Resists Hydrogen embrittlement and weld cracking
- ◊ Can withstand 74.12 MPa external pressure

System Performance Verification

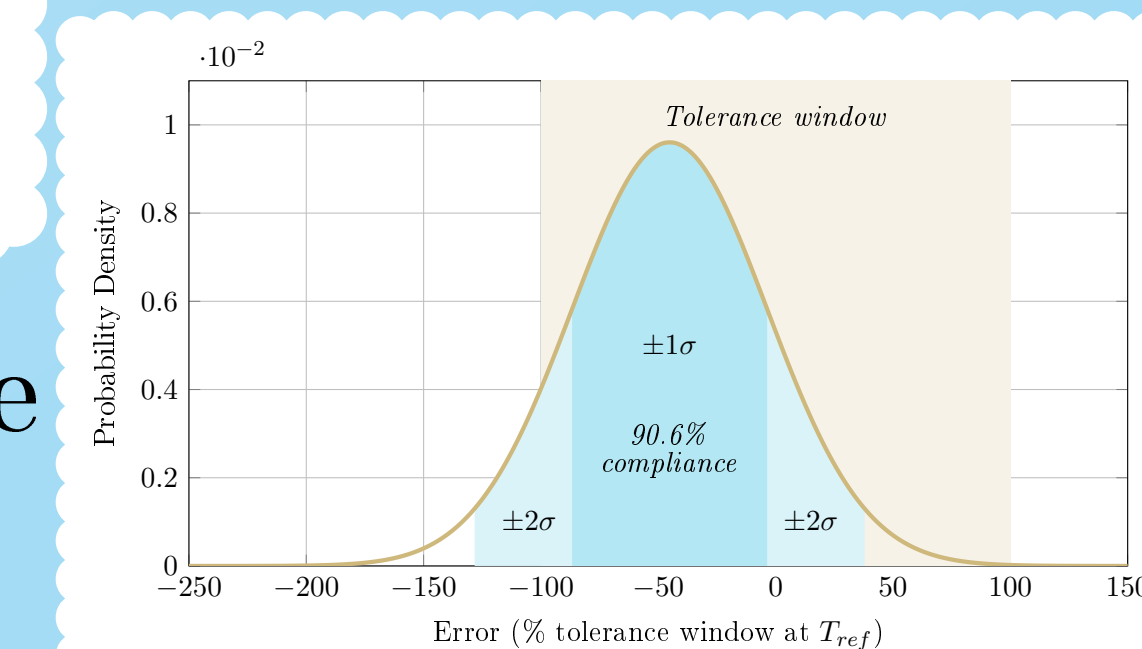
Two independent methods verified that the PTCD satisfies the Required Relationship: $D_{eff} = A_1(T_{amb} - 25^{\circ}\text{C}) + A_0$

1. Passive System Control Transfer Function

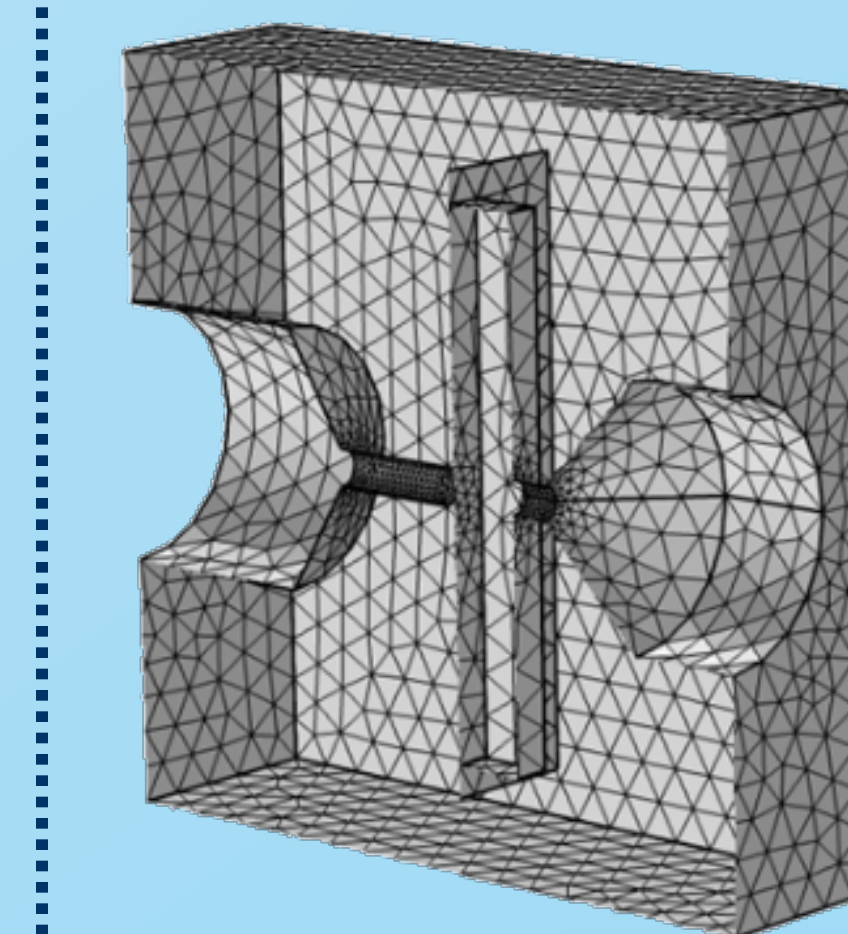
The analytically-derived static-response output model captures the coupled performance of every part and every anticipated source of error.



The above transfer function forecasts that 90.6% of devices will meet system specifications. Calibration corrects any stochastic error, yielding the expectation boundaries on the left.

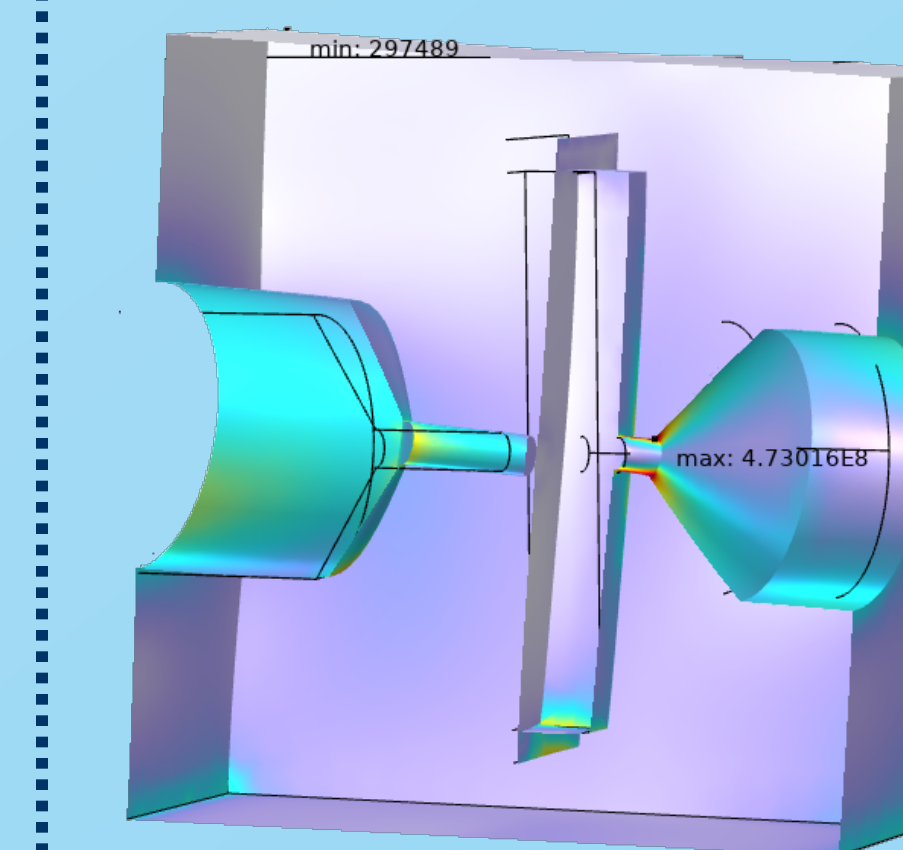
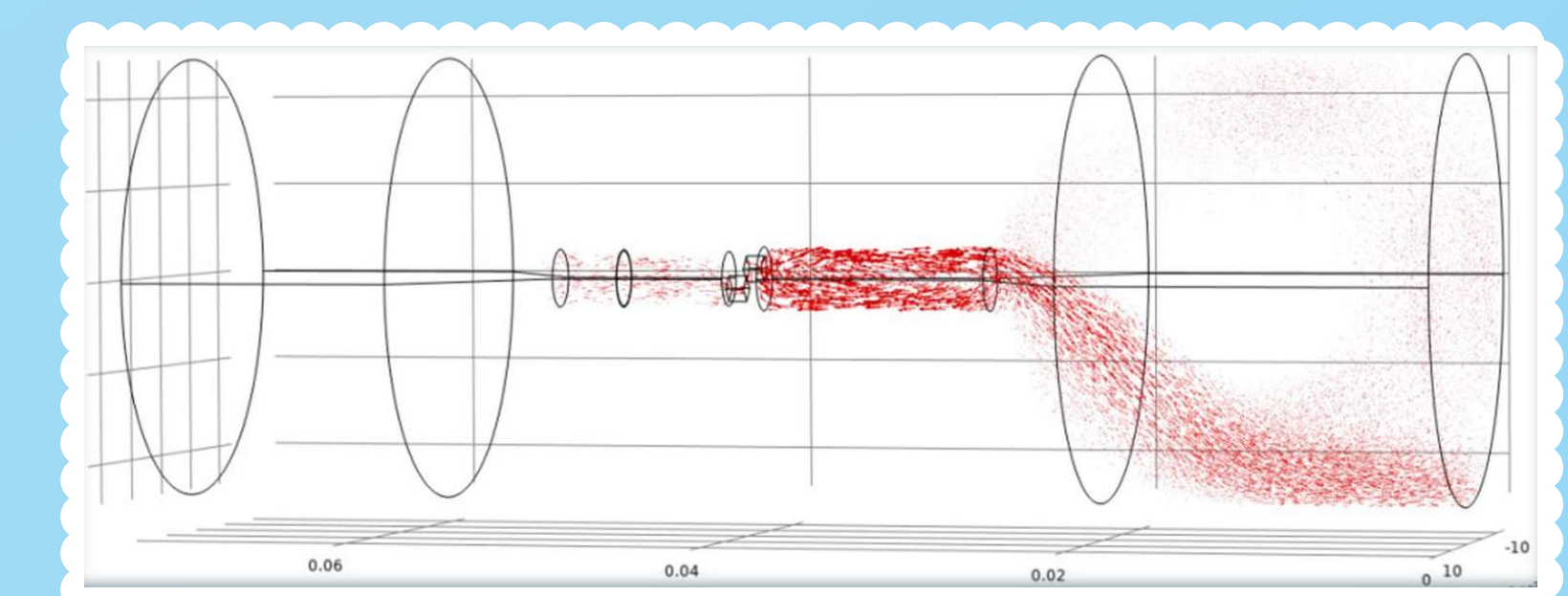


2. Computational Prototype

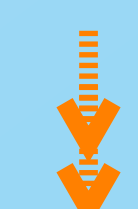


The PTCD was modeled in COMSOL and meshed into finite elements.

Fluid flow simulations produced position-specific pressure data.



Using these results, stress analysis tested against pressure-driven failure and identified key weaknesses. The design was revised to remedy pressure-driven failure. These were verified using hand calculations.

Legend		Bibliography	
PTCD	Passive Temperature Compensation Device	[1]	M. I. Ralphs, M. Jensen, A. Eames, and M. Sinfield, "A Suite of Thermal Switches for Surviving Extreme Thermal Environments in Space," <i>AIAA SciTech 2026 Forum</i> , Orlando, FL, Jan. 2026, doi: 10.2514/6.2026-1086.
CTE (α)	Coefficient of Thermal Expansion	[2]	R. C. Hibbeler, <i>Mechanics of Materials</i> , 9th ed., Pearson, Saddle River, NJ, 2014.
	Indicates action of the PTCD when heated	[3]	M. F. Ashby, <i>Materials Selection in Mechanical Design</i> , 5th ed., Pergamon Press, Oxford, UK, 1992.
The authors would like to extend their sincere gratitude to Dr. Bradley Bon, distinguished member of Sandia National Laboratories in Livermore, CA for his invaluable assistance in the development of this design.		© 2026 by the Noble Aggie Labs <i>Miguel Cuaycong, Jon Pizarro, Nicholas Metta, Isaiah Mathew, John Bodine, Sam van der Veen</i>	