Passive Temperature Compensation Device

SANDIA DESIGN AWARD REPORT

Prepared by the

Noble Aggie Labs

Team 019

Miguel Cuaycong, Jon Pizarro, Nicholas Metta,
Isaiah Mathew, John Bodine, and Sam van der Veen

EME 185: Mechanical Systems Design Project
University of California, Davis

Advised by Professor Jonathan Schofield and Teaching Assistant Xiangpu Wang
Sponsored by Dr. Bradley Bon, Sandia National Laboratories

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Problem Statement

Sandia National Laboratories conducts numerous experiments requiring the flow of precisely controlled Hydrogen gas. These experiments are sensitive to fluctuations in temperature; the flow must be adjusted to compensate for these changes. However, power and space constraints prohibit the use of embedded control systems. Sandia commissioned the Noble Aggie Labs from UC Davis to design and prototype a Passive Temperature Compensation Device (PTCD) that controls high-pressure Hydrogen gas flow and thermomechanically adjusts its effective orifice diameter according to the relationship $D_{\text{eff}} = A_1(T_{\text{amb}} - 25\,°\text{C}) + A_0$, where $A_1 = -1.524 \cdot 10^{-3}\,\frac{\text{mm}}{°\text{C}} \pm 5\%$, $A_0 = 0.254\,\text{mm} \pm 5\%$, and $(-60\,°\text{C} \leq T_{amb} \leq 80\,°\text{C})$[1]. The PTCD must contain, seal, and restrict the gas at a maximum pressure of 68.95 MPa, resist Hydrogen diffusion and embrittlement, and fit within a $(10\,\text{cm})^3$ mechanical envelope.

Sandia Impact

Sandia National Laboratories develops technologies that support national security and advance scientific discovery, often under extreme environmental constraints where active control systems are impractical. The PTCD directly addresses this problem: precision flow control of high-pressure hydrogen gas achieved entirely through geometry and material selection, with no power source or control logic required. This approach aligns with the National Academy of Engineering Grand Challenge of engineering the tools of scientific discovery, as the device enables experiments requiring precisely controlled gas flow under conditions where embedded electronics are prohibited. Beyond Sandia's laboratories, passive temperature-compensating devices have broad applicability in aerospace, precision research, and high-pressure industrial systems, demonstrating that sub-millimeter precision flow control is achievable through purely mechanical means.

Design Approach

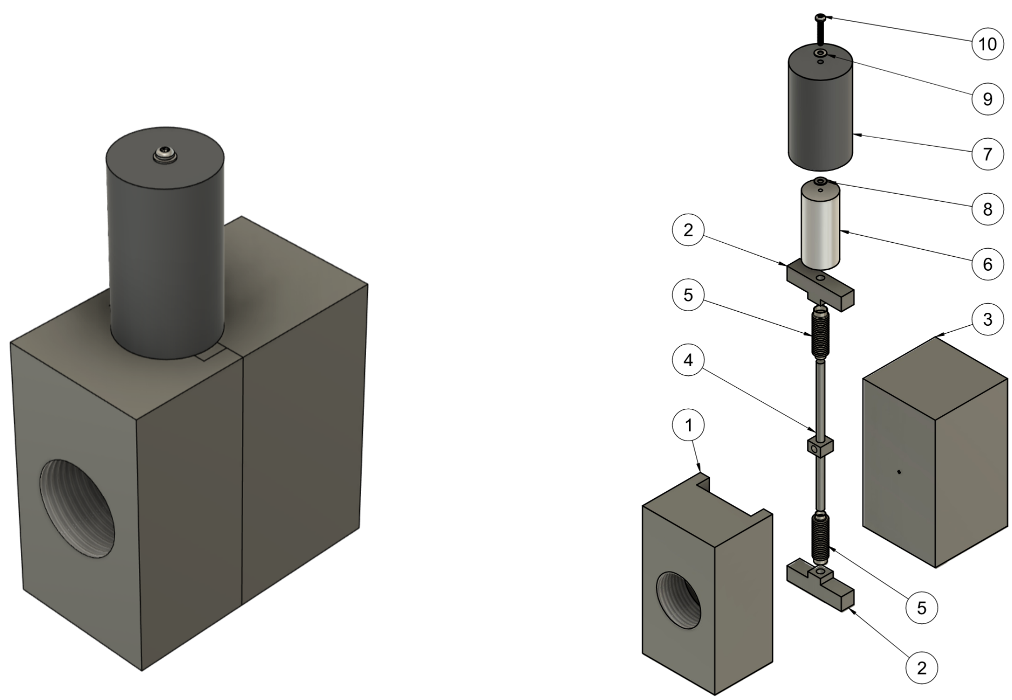
The primary design requirement is that orifice flow area vary linearly with ambient temperature over the specified temperature range. The system was divided into two subsystems: the actuator, which thermomechanically responds to ambient temperature, and the valve, which restricts gas flow as driven by the actuator. For the combined system to produce a first-order linear output, each subsystem must independently exhibit a single degree of freedom and a linear response. Candidate designs for each subsystem were evaluated against defined criteria using a scoring matrix, which prioritizes linearity and simplicity.

For the actuator, candidates included a bimetallic coil, wax bladder, and piston-cylinder assembly and were evaluated against a thermal expansion rod. All the other candidates were rejected on the basis of nonlinearity or mechanical complexity. Aluminum was selected for the rod material due to its high, consistent coefficient of thermal expansion (CTE) and machinability. Allvar 30 was selected for the mount instead of steel because its negative CTE increases rather than reduces actuator displacement.

For the valve, all conventional valve types were evaluated, including stopper, panel, rotary, and pinch valve configurations, and were rejected for their inability to produce a linear flow area response. A novel geometry was developed in which two plates with square orifices are rotationally offset by 45 degrees. The overlapping area between the orifices varies linearly with relative plate displacement, satisfying the linearity requirement through geometry alone, with a single moving component.

Final Solution

The final design of the Passive Temperature Compensation Device, pictured in Figure 1, successfully meets the above specifications, thermomechanically controlling Hydrogen gas flow with extreme precision using a simple, compact architecture.



(a) *Complete assembly* **(b)** *Complete assembly exploded view*

Figure 1: *Overall PTCD assembly and exploded view highlighting internal components.*

The bimetallic actuator, the functional core of the PTCD, leverages the difference in Coefficients of Thermal Expansion between two metals. An Aluminum 6061 expansion rod (6) nests inside a hollow, cylindrical ALLVAR mount (7). Aluminum's expansion rate $\alpha_{\mathrm{Al}} \approx 22.85 \, \frac{\mu\mathrm{m}}{\mathrm{m}\,^\circ\mathrm{C}}$[2]; it expands when heated. ALLVAR, a proprietary technology made by ALLVAR Alloys, shrinks when heated at a rate of $\alpha_{\text{ALLV}} \approx -30\,\frac{\mu\text{m}}{\text{m}\,^\circ\text{C}}$ [3]. The mount, secured at its base, lowers the assembly as it shrinks while the aluminum rod, fastened to the mount from above by the screw-washer assembly (8, 9, 10), simultaneously expands downwards. Temperature decrease produces the reverse effect. The assembly linearly translates the ambient temperature into compound relative displacement according to the governing equation $\Delta L = (L_{\text{actuator}}\alpha_{\text{Al}} - L_{\text{mount}}\alpha_{\text{ALLV}})\,\Delta T$. At full range, the actuator drives the valve 267 µm.

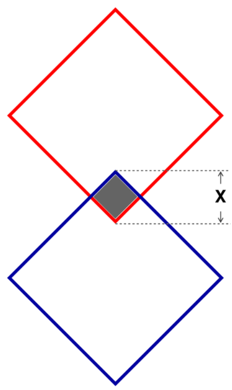


Figure 2: *Orifice geometry*

The valve subsystem comprises the central orifice, structural housing, and associated hermetic seals. A novel orifice architecture was required to achieve the linear relationship between displacement (provided by the actuator) and effective diameter. While most gas flow control valves exhibit a first-order change in orifice area, the specified temperature-diameter translation required that the orifice remain a regular polygon. The PTCD achieves this with a unique diamond-overlap approach, pictured in Figure 2. The valve stem (4) and housing outlet (3) each contain a small square hole rotated 45°. When assembled, these are pressed against one another and slightly offset such that gas may only flow through the overlap between them. As the actuator drives the valve stem downwards, its diamond (pictured as blue in Fig. 2) descends relative to the fixed diamond on the housing, shrinking the overlap and restricting the flow. Their 45° rotation allows the orifice to remain a square, resulting in a linear output. As calculated in Appendix A.1, the bimetallic actuator and diamond orifice combine to produce the exact linear relationship required by Sandia.

The orifice is cut using wire electrical-discharge machining, allowing for a very small minimum corner radius (0.076 mm), which is critical for achieving the required precision in flow control. All contact surfaces are coated with a physical vapor deposition (PVD) coating to prevent galling.

The valve housing components are responsible for maintaining the structural integrity of the device under the specified internal pressure of 68.95 MPa. Pressure-stress calculations in Appendix A.2 verify that the housing can withstand this internal pressure. The housing includes the valve inlet (1), which connects to the gas source, the housing center pieces (2), which contain the valve internal components, and the valve outlet (3), which directs the flow through the orifice. The housing is designed with a compact form factor to meet the specified mechanical envelope while providing sufficient material thickness and support to withstand the internal pressure without deformation that could affect the orifice geometry. The housing is fabricated from Invar 36, a one-of-a-kind alloy renowned in the aerospace industry for its low CTE ($\alpha \approx 1.3 \frac{\mu m}{m\,°C}$) [4–6], ensuring that unwanted thermal expansion is minimized.

Sealing of the valve is achieved through a combination of welded joints and two Inconel 718 bellows (5) [7]. The bellows provide a hermetic seal while allowing for the necessary axial motion of the valve stem, ensuring that the device can operate under the specified internal pressure without leakage. The use of two bellows (upper and lower) provides a balanced response to the internal pressure, minimizing the net force on the valve stem and thus reducing the load on the actuator. This design choice is critical for maintaining the precision of the device, as it prevents deformation of the valve components under pressure that could otherwise affect the orifice geometry.

Weld joints are used throughout the assembly to enable simple mates with minimal degrees of freedom, contributing to the overall robustness of the design [8]. Electron beam welding was selected for its ability to create strong, precise welds, all of which will be verified through full radiographic inspection.

Calibration of the device is performed during final assembly through the use of a manually torqued adjustment screw and a Belleville washer (8). By adjusting the preload on the Belleville washer via the adjustment screw and consequently the vertical position of the valve orifice, the user can ensure that the actuator's motion corresponds to the required orifice diameter at the reference temperature of 25 °C. This eliminates any constant-offset error introduced by stochastic machining and assembly errors.

Throughout the design, exact interface dimensions and tolerances were carefully calculated to ensure that components fit together with the necessary precision to meet the required specifications. The design also incorporates features to facilitate assembly and encourage access for welding. Compared to previous iterations, the final design achieves a more compact and robust configuration with fewer unique parts.

Evaluation and Verification

After completion of the final design iteration, verification of the PTCD control output was conducted both analytically and numerically. Analytical verification consisted of derivation and calculation of the passive system control transfer function, commonly used in the field of control systems [9]. The resulting computation, represented graphically in Appendix B, analytically estimated the effect of machining errors, thermal expansion of every part, and spring reactions from the bellows. The transfer function produced the system output results shown in Figure 3, verifying satisfaction of the required relationship despite these sources of error. The gold line, the function-estimated output, fits well within the tolerated error band, demonstrating a real prototype would likely produce similarly satisfactory results.

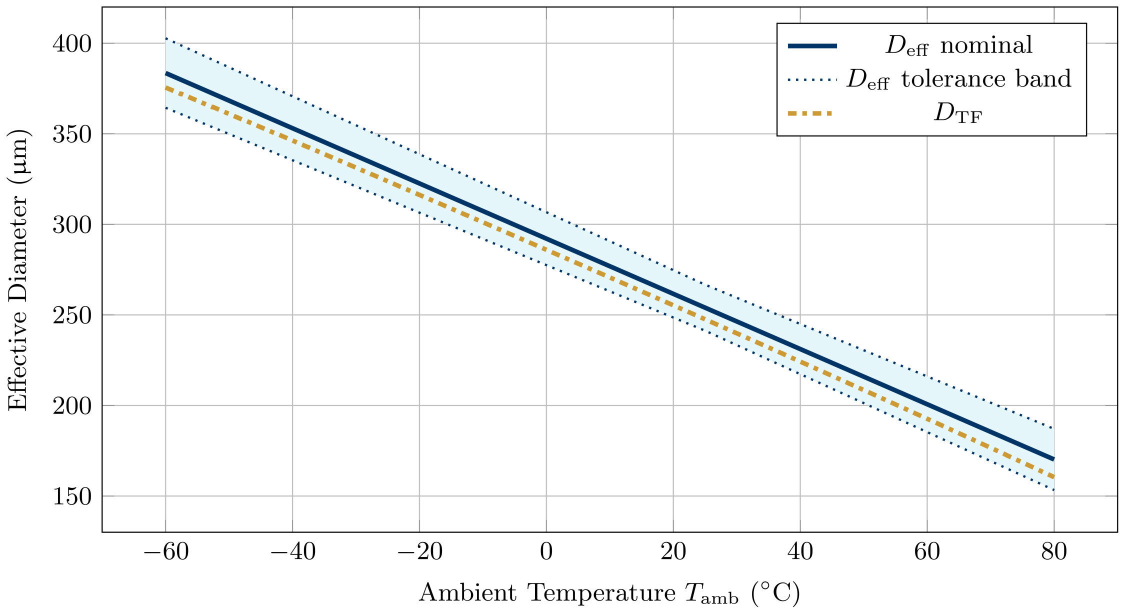


Figure 3: *System Verification*

Numerical verification of the PTCD will consist of a computational prototype to test against various failure modes. This is still in-progress and will be completed by the end of the academic quarter. The following section discusses this verification in more detail.

Improvements and Future Work

The current PTCD design reliably accomplishes the specified requirements under extreme temperature and pressure conditions. Further computational verification is currently in progress, including finite-element stress analysis, dynamic fluid pressure analysis, and thermal analysis to further validate the design prior to physical testing. The primary challenge anticipated in future development is manufacturing repeatability, which should be the focus of subsequent design iterations.

The client, after fabricating the first prototype, will physically validate the design with two tests: a dry test, in which the device is subjected to a controlled ambient temperature and the effective orifice diameter is optically measured; and a wet test, in which fluid flows at a specified inlet pressure and ambient temperature for 60 seconds while pressure drop is recorded.

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Appendix A - Derivations and Calculations

A.1 System Output of the PTCD

The Required Relationship given in the problem statement

$$D_{\text{eff}} = A_1(T_{\text{amb}} - T_{\text{ref}}) + A_0$$

where

$$A_1 = -1.524 \cdot 10^{-3}\,\frac{\text{mm}}{^\circ\text{C}} \pm 5\%$$
$$A_0 = 0.254\,\text{mm} \pm 5\%$$
$$T_{\text{ref}} = 25\,^\circ\text{C}$$
$$(-60\,^\circ\text{C} \leq T_{amb} \leq 80\,^\circ\text{C})$$

stipulates a linear temperature-diameter control output with the following endpoints:

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

The PTCD is tuned to produce exactly these results. Each subsystem contributes one control derivative to the system output relation

$$D_{PTCD} = \frac{dL}{dT}\frac{dX}{dL}\frac{dD}{dX}\Delta T + D(T_{\text{ref}}) \tag{A.1}$$

$\frac{dL}{dT}$ is driven by the actuator subsystem, which converts changes in temperature to length change according to the relation

$$\begin{aligned} \frac{dL}{dT} &= (L_{\text{core}}\alpha_{\text{Al}} - L_{\text{mount}}\alpha_{\text{ALLV}}) \\ &= \left[(32.991\,\text{mm})\left(22.85\,\frac{\mu\text{m}}{\text{m}\,^\circ\text{C}}\right) - (37.991\,\text{mm})\left(-30\,\frac{\mu\text{m}}{\text{m}\,^\circ\text{C}}\right)\right] \\ &= 1.91\,\frac{\mu\text{m}}{^\circ\text{C}} \end{aligned} \tag{A.2}$$

As the actuator expands and L increases, it directly drives the valve stem. The orifice height X, defined in Figure 2, decreases as much as L increases. Thus, $\frac{dX}{dL} = -1$.

$\frac{dD}{dX}$ is driven by the valve subsystem orifice geometry. The area of the orifice is defined by its side length

$$A = s^2$$

The effective diameter, D_{eff}, is the diameter of a circle of equal area, $A = \frac{\pi}{4}D_{\text{eff}}^2$. The PTCD orifice is the diamond-shaped overlap between two 45°-rotated squares with area $A = s^2$, where s is the side length of the overlap diamond. Since the actuator drives the orifice height X, the Pythagorean theorem gives $s = X/\sqrt{2}$, so:

$$\frac{\pi}{4}D_{\text{eff}}^2 = \frac{X^2}{2} \qquad \Longrightarrow \qquad D_{\text{eff}} = \sqrt{\frac{2}{\pi}}X \tag{A.3}$$

Thus,

$$\frac{dD}{dX} = \sqrt{\frac{2}{\pi}} = 0.798 \tag{A.4}$$

Finally, the reference orifice diameter is set by the position of the valve stem hole such that

$$D_{ref} = 0.254\,\text{mm} \tag{A.5}$$

therefore

$$D_{PTCD} = (1.91\,\frac{\mu\text{m}}{^\circ\text{C}})(-1)(0.798)\Delta T + 0.254\,\text{mm} \tag{A.6}$$

as prescribed.

A.2 Pressure Vessel Structural Verification

The valve housing is modelled as a thick-walled cylinder of Invar 36 under internal pressure $P = 68.95$ MPa. Principal stresses[10, Sec. 3-14] at the *inner wall* (worst case) are:

$$\sigma_\theta = P\left(\frac{r_o^2 + r_i^2}{r_o^2 - r_i^2}\right) = 68.95\left(\frac{19.53^2 + 9.53^2}{19.53^2 - 9.53^2}\right) \approx 112.1 \text{ MPa} \quad \text{(hoop)} \tag{A.7}$$

$$\sigma_r = -P \approx -68.95 \text{ MPa} \quad \text{(radial)} \tag{A.8}$$

$$\sigma_z = P\left(\frac{r_i^2}{r_o^2 - r_i^2}\right) \approx 21.6 \text{ MPa} \quad \text{(longitudinal)} \tag{A.9}$$

The von Mises equivalent stress is:

$$\sigma_{\text{vm}} = \sqrt{\frac{(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_\theta)^2}{2}} \approx 156.8 \text{ MPa} \tag{A.10}$$

With a material yield strength $S_y = 370$ MPa (Invar 36):

$$FS = \frac{S_y}{\sigma_{\text{vm}}} = \frac{370}{156.8} \approx 2.36 \tag{A.11}$$

For weldments, the ASME B31.3 minimum wall thickness (with $E = 1.0$ from 100% radiographic inspection) is:

$$t_{\min} = \frac{P\,D_o}{2(S\,E\,W + P\,Y)} = \frac{68.95 \times 39.06}{2(246.7 + 27.6)} \approx 5.17 \text{ mm} \;<\; t_{\text{actual}} \tag{A.12}$$

Both checks confirm structural viability with comfortable margins.

Appendix B - Computational Modeling: System Transfer Function

Figure B.1 represents the transfer function, derived and encoded into C++ to verify the expected results from the PTCD. The details of its derivation are too in-depth for presentation here, but the curious reader might find the following summary enlightening.

Each block represents a subpart of the system, which takes one value as its input and outputs a new value. The ambient temperature is input into each of eight independent parts. The first row of blocks represents temperature adjustment as each part equilibrates with the hotter internal gas. The second row represents the thermal expansion of every part, including those which are not supposed to expand. The resulting length values of these mechanically coupled parts are entered into a spring-force balance (a system of eight linearly independent equations), giving the final length of each part. These are properly summed to find the position of each orifice, whose difference comprises the height of the final overlap between them. This is then converted to the effective diameter.

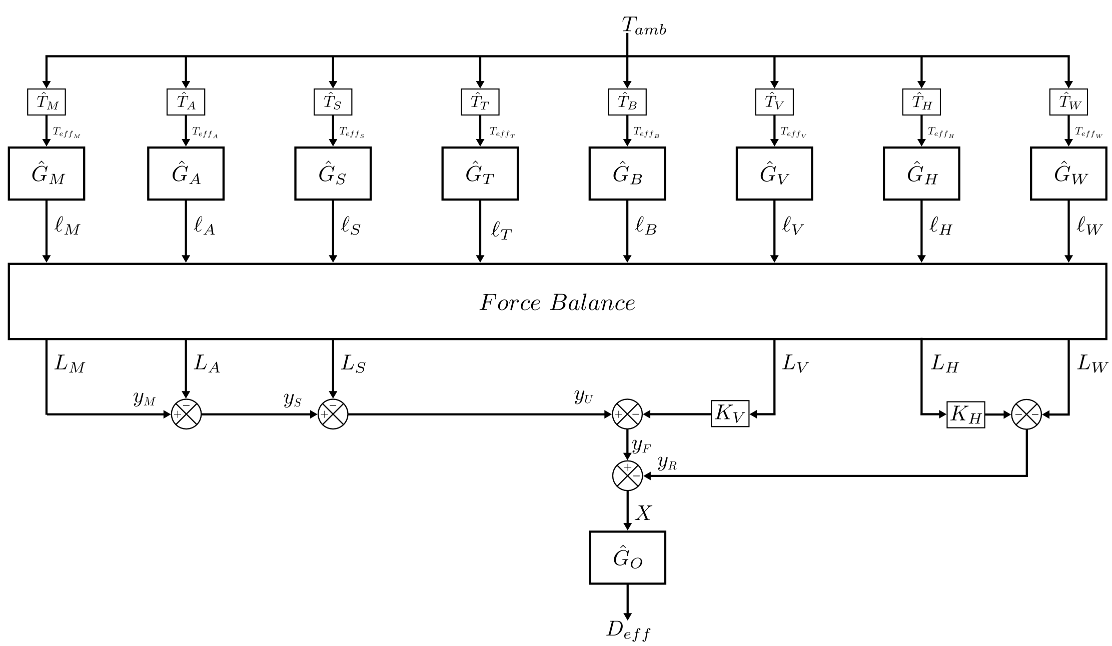
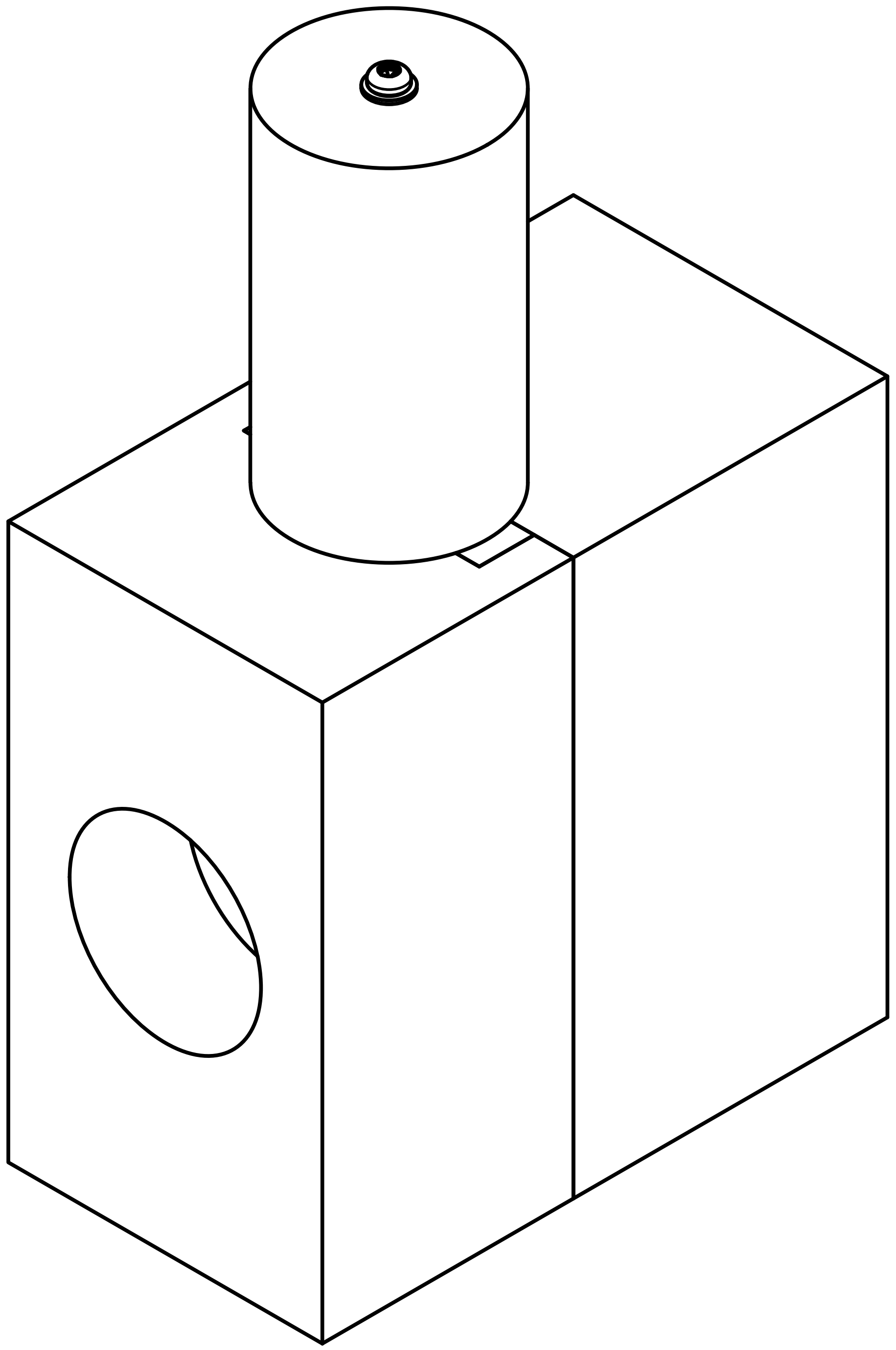
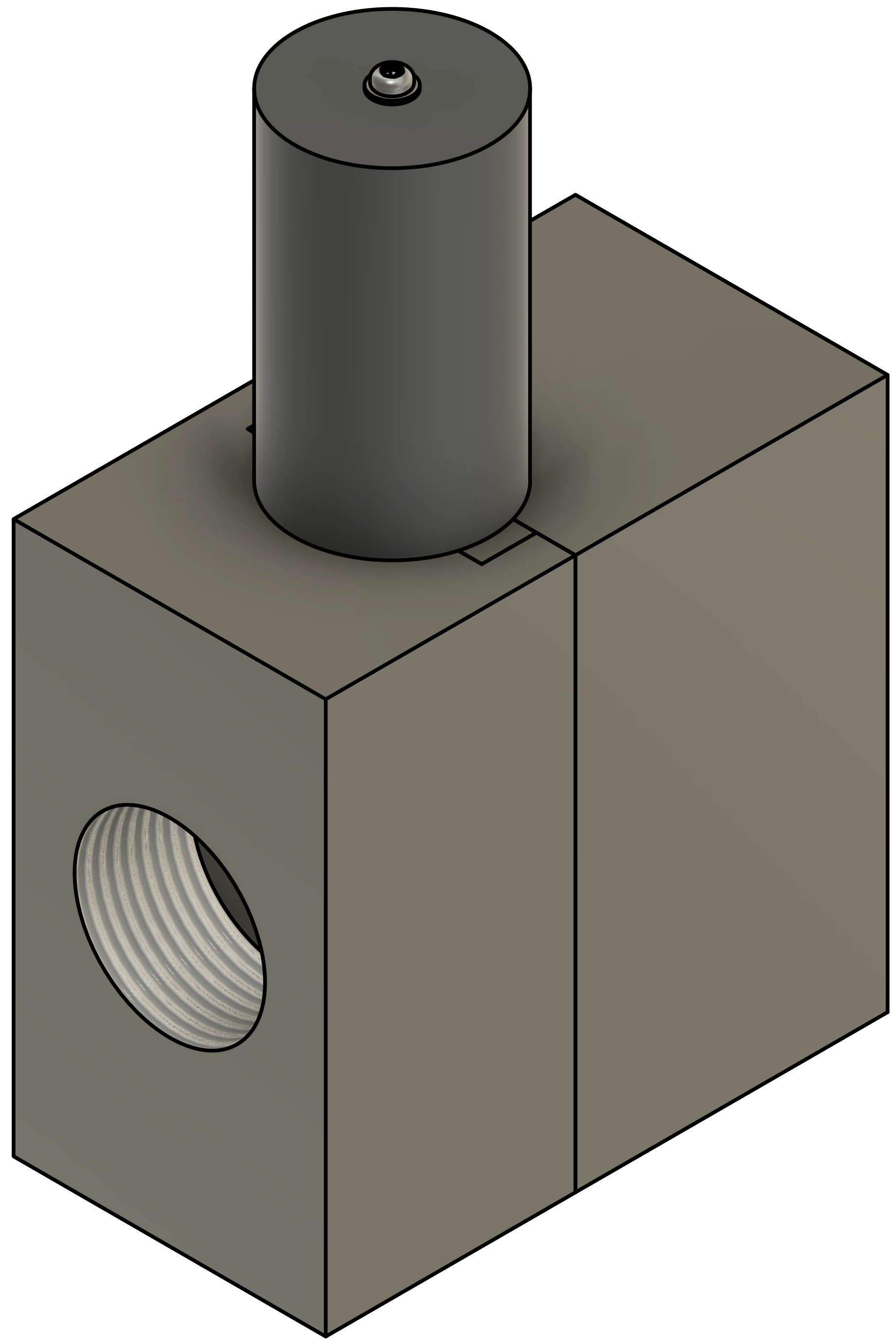


Figure B.1: *Transfer Function Block Diagram.*

Appendix C - Bill of Materials and Assembly Drawings

Part ID	Part Name	Purchased stock or part	Stock or part number	Supplier	Purchased units	Cost	Cost/part
V1, V2, V3, V4	Housing center, inlet, outlet; Valve orifice	82.55 mm x 76.2 mm x 44.45 mm billet Invar 36	CUSTOM ITEM	McMaster-Carr	SAE	$401.17	$401.17
I718-159-27-430	Bellows	Metal Bellows, Inconel 718	I718-159-72-430	Mini-Flex	SAE	$727.48	$727.48
A1	Actuator	⌀15.875 mm x 152.4 mm 6061 Aluminum rod	8974K289	McMaster-Carr	SAE	$2.85	$0.71
A2	Mount	⌀19 mm x 45 mm ALLVAR Alloy 30 rod	CUSTOM ITEM	ALLVAR	SI	$841.53	$841.53
90362A141	Screw	Screw, Pan Head Torx, 18-8 SS, M2 x 0.4mm x 12mm, T6 Drive	90362A141	McMaster-Carr	SI	$13.79	$0.14
93475A195	Standard washer	Washer, Flat, 18-8 SS, M2, 2.2mm ID x 5mm OD x 0.2-0.4mm THK	93475A195	McMaster-Carr	SI	$1.78	$0.02
93237A101	Belleville washer	Washer, Spring Lock, 316 SS, M2, 2.2mm ID x 5mm OD x 0.6mm THK, Heavy	93237A101	McMaster-Carr	SI	$12.36	$0.49
						$2,000.96	$1,971.54





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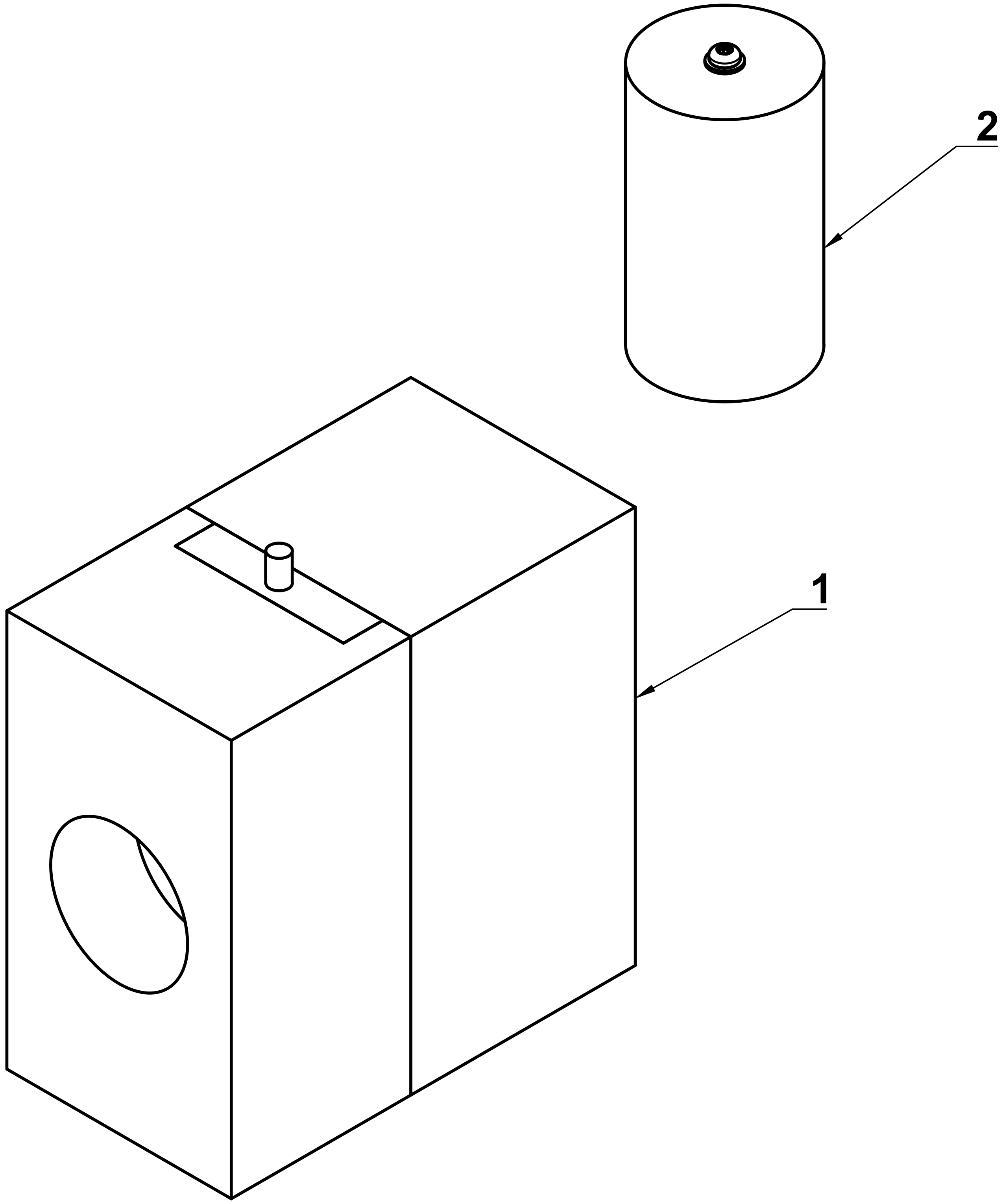
Sub-Assembly Identification		
Item	Name	Number
1	Valve Sub-Assembly	V0
2	Actuator Sub-Assembly	A0



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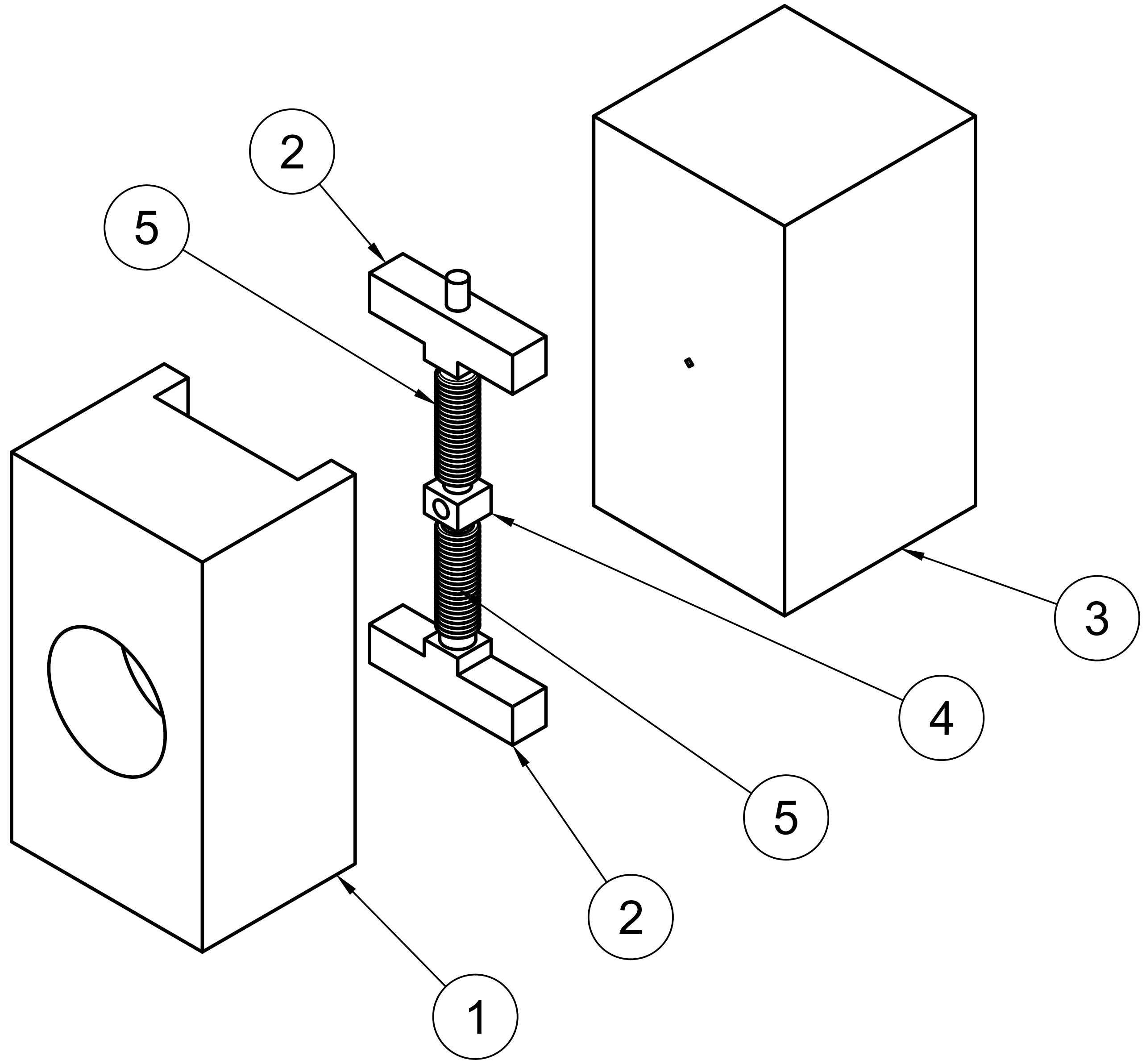
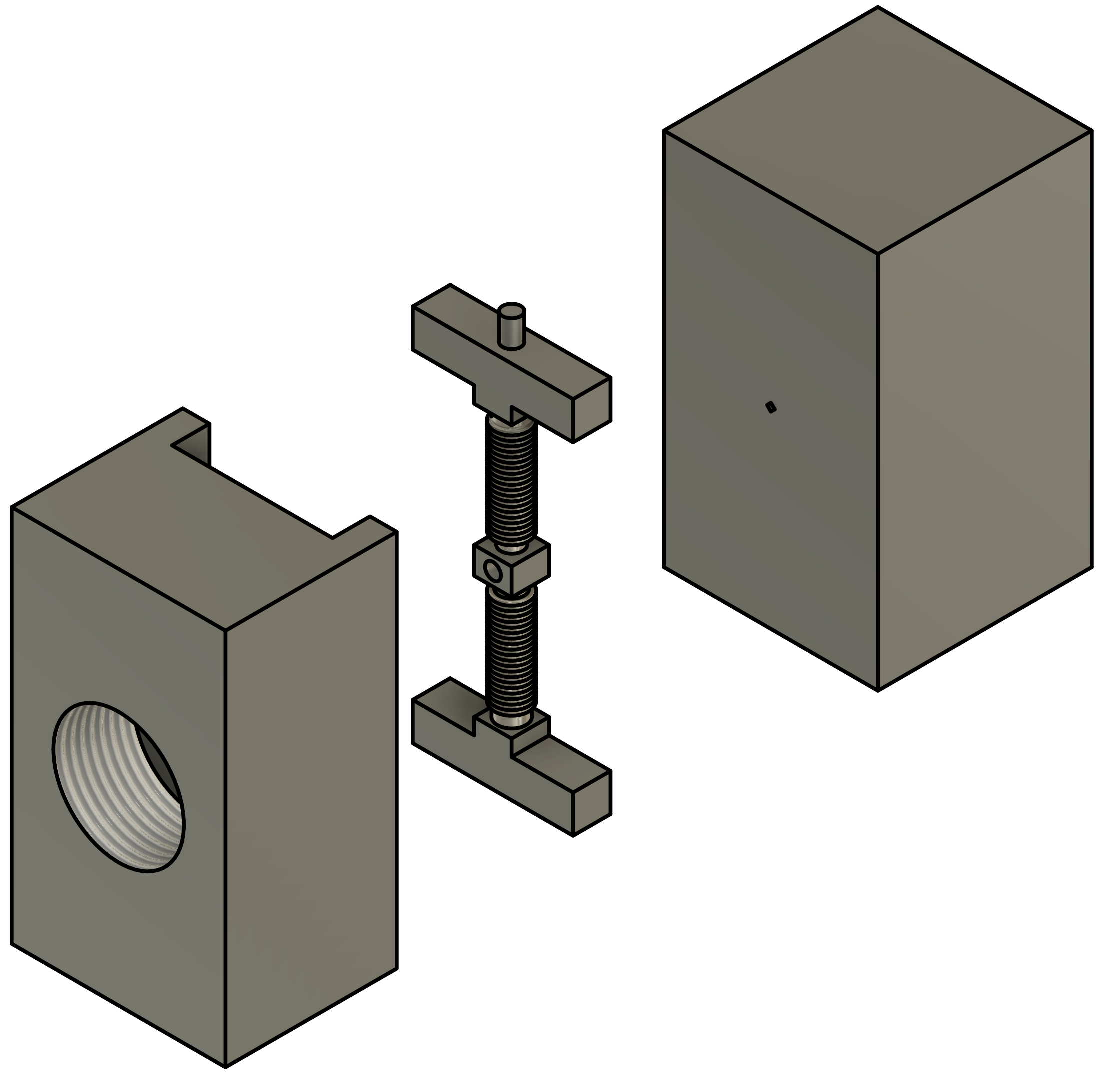
Parts List				
Item	Qty	Part Name	Part Number	Material
1	1	Housing Inlet v6	V2	Invar 36
2	2	Housing Center v3	V1	Invar 36
3	1	Housing Outlet v4	V3	Invar 36
4	1	Valve Orifice v3	V4	Invar 36
5	2	Bellows v2	I718-159-72-430	Inconel 718





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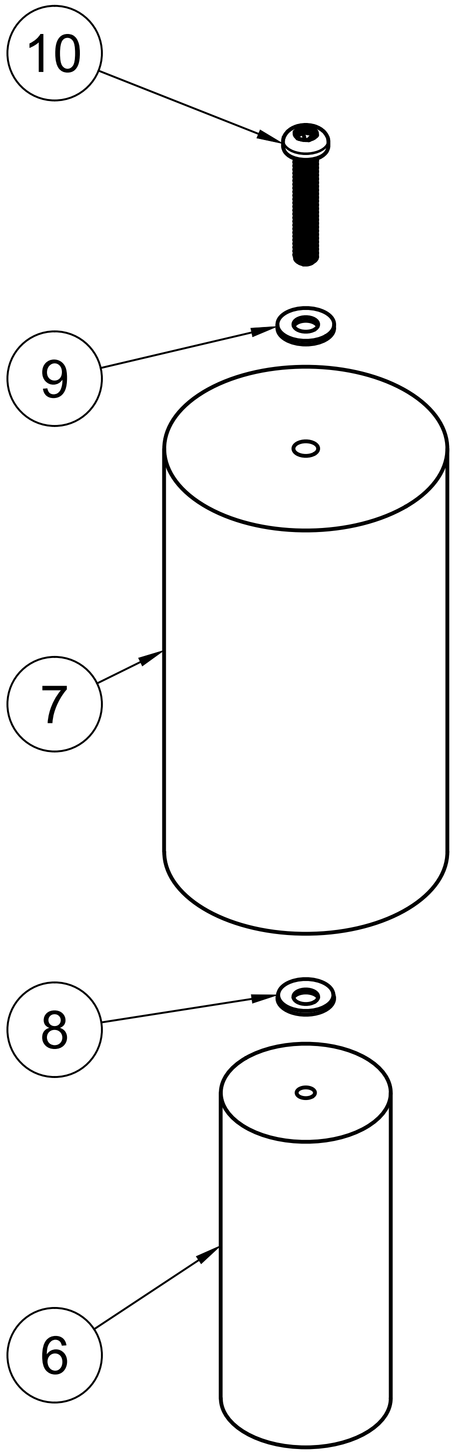

Parts List				
Item	Qty	Part Name	Part Number	Material
6	1	Actuator v5	A1	Aluminum 6061
7	1	Mount v4	A2	Allvar
8	1	Belleville Washer v2	93237A101	Stainless Steel 316L
9	1	Standard Washer v3	93475A195	18-8 Stainless Steel
10	1	Screw v2	90362A141	18-8 Stainless Steel

Department: UC DAVIS COLLEGE OF ENGINEERING

Part: ACTUATOR SUB-ASSEMBLY

Team: NOBLE AGGIE LABS

Rev.: 2

Sponsor: Sandia National Laboratories

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MM

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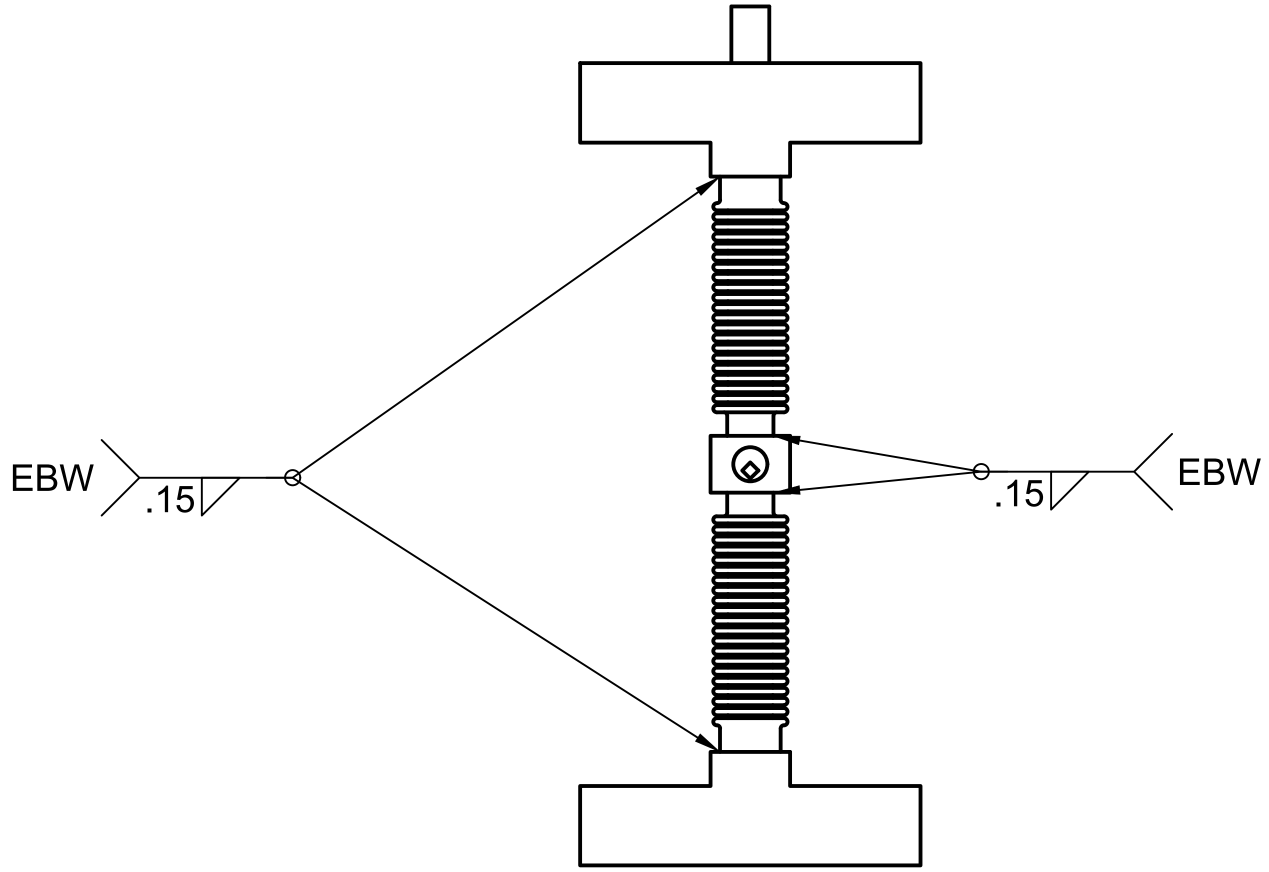

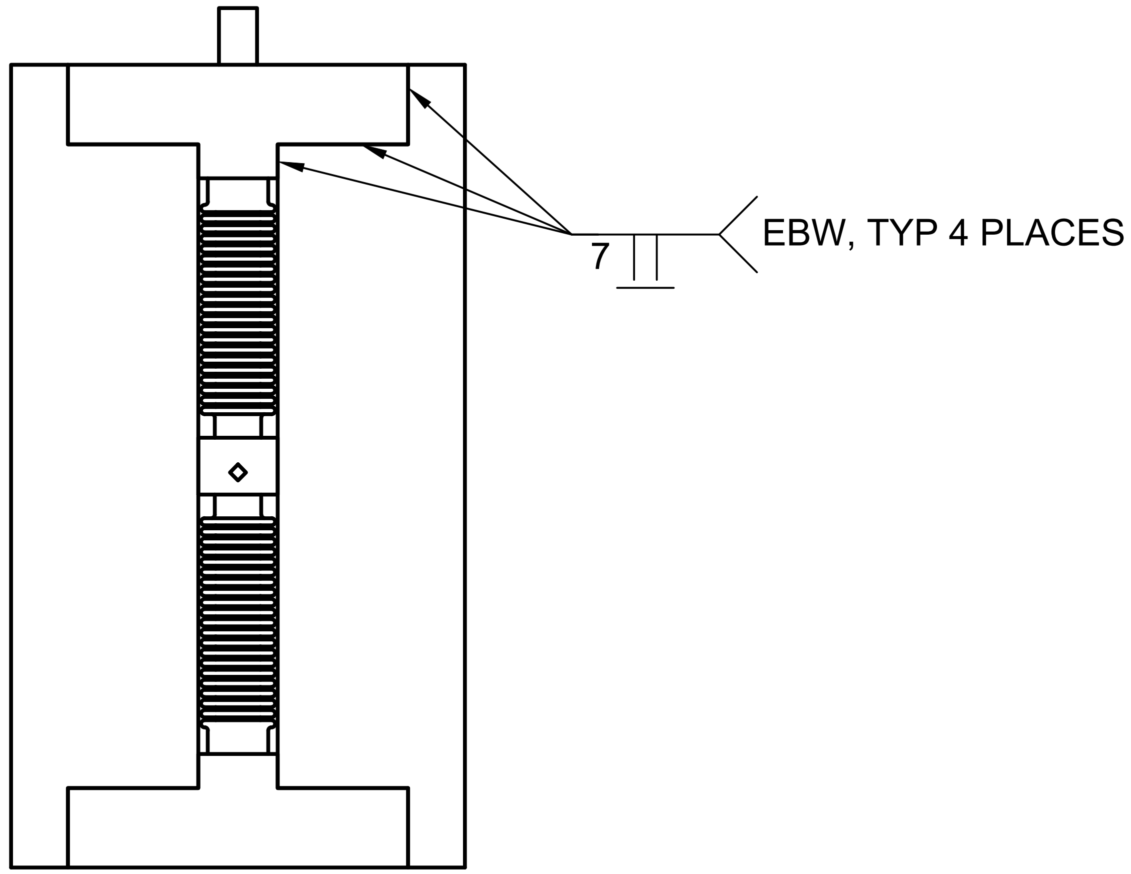

GENERAL NOTES:

1. WELDING PROCESS: ELECTRON BEAM WELDING (EBW).
2. NO FILLER METAL TO BE USED (AUTOGENOUS WELDING).
3. MATING SURFACES MUST BE INTIMATE. MAXIMUM GAP NOT TO EXCEED 0.01 MM.
4. SURFACES TO BE WELDED MUST BE CLEAN AND STRICTLY FREE OF OIL, GREASE, AND OXIDATION PRIOR TO WELDING.
5. PURGE INTERNAL CAVITIES WITH INERT GAS DURING WELDING TO PREVENT OXIDATION AND SPATTER.
6. ALL WETTED LBW JOINTS SHALL BE SUBJECT TO 100% RADIOGRAPHIC EXAMINATION (RT) TO ENSURE A WELD JOINT EFFICIENCY (E) OF 1.0.

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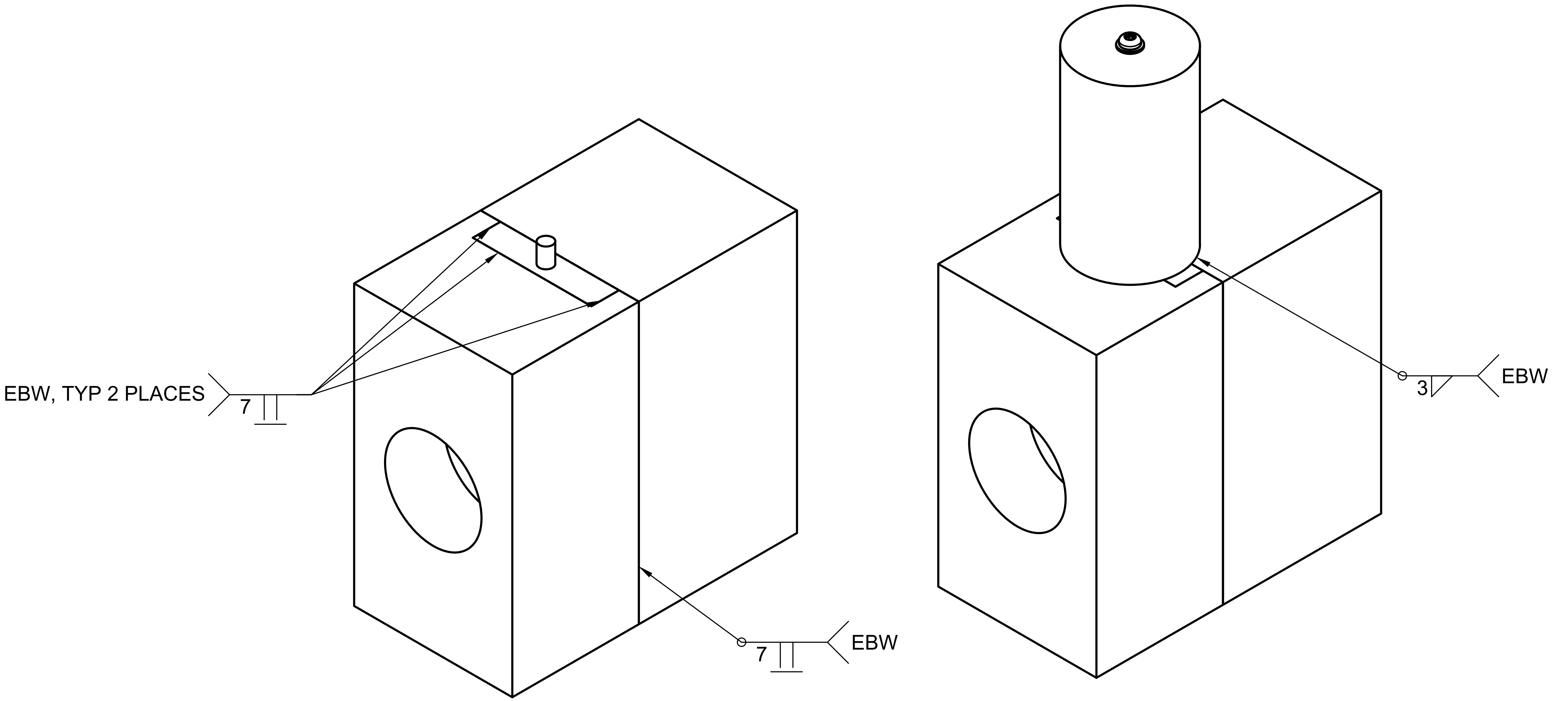

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		Team: NOBLE AGGIE LABS — Rev.: 2
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