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Seismic Isolation System (SEI) In-Vacuum Thermal Analysis

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Change Record:

Revision –01: initial release. Work done in March 2004 but unreleased till Jun 2005. The analysis and report are incomplete but may be of some value. The intent is to compare this analysis with pending thermal results from the SEI Technology Demonstrator at the Stanford ETF Facility and to complete the thermal analysis for the BSC and HAM designs.

1 Introduction

The purpose of this technical memo is to derive the thermal requirements for the in-vacuum, voice coil actuators for the advanced LIGO seismic isolation system. There are two advanced LIGO Seismic Isolation (SEI) systems employed; one for the HAM chamber and one for the BSC chamber. At the time of this memorandum, the designs for these SEI systems has not been completed. A rough design/configuration is shown for each chamber in Figures 1 and 2. Each system has two suspended in-vacuum stages (denoted stages 1 and 2) and an outer support structure (denoted stage 0). The voice coil actuators are between stages 0 and 1 and between stages 1 and 2. There are 3 vertical and 3 horizontal actuators between each stage (a total of 12). The stage 0-1 actuators are larger (higher force) that the stage 1-2 actuators.

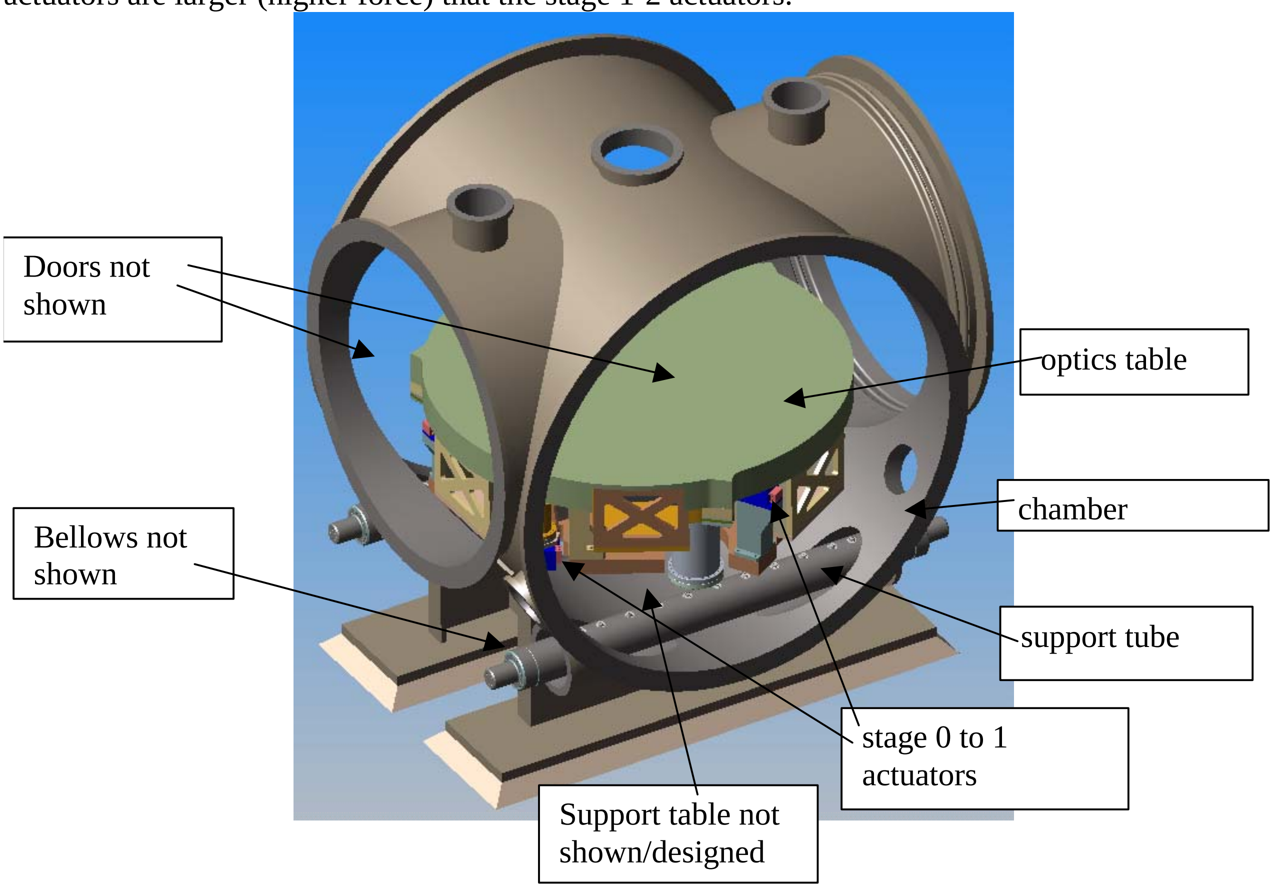

Figure 1: Overall HAM SEI system installation

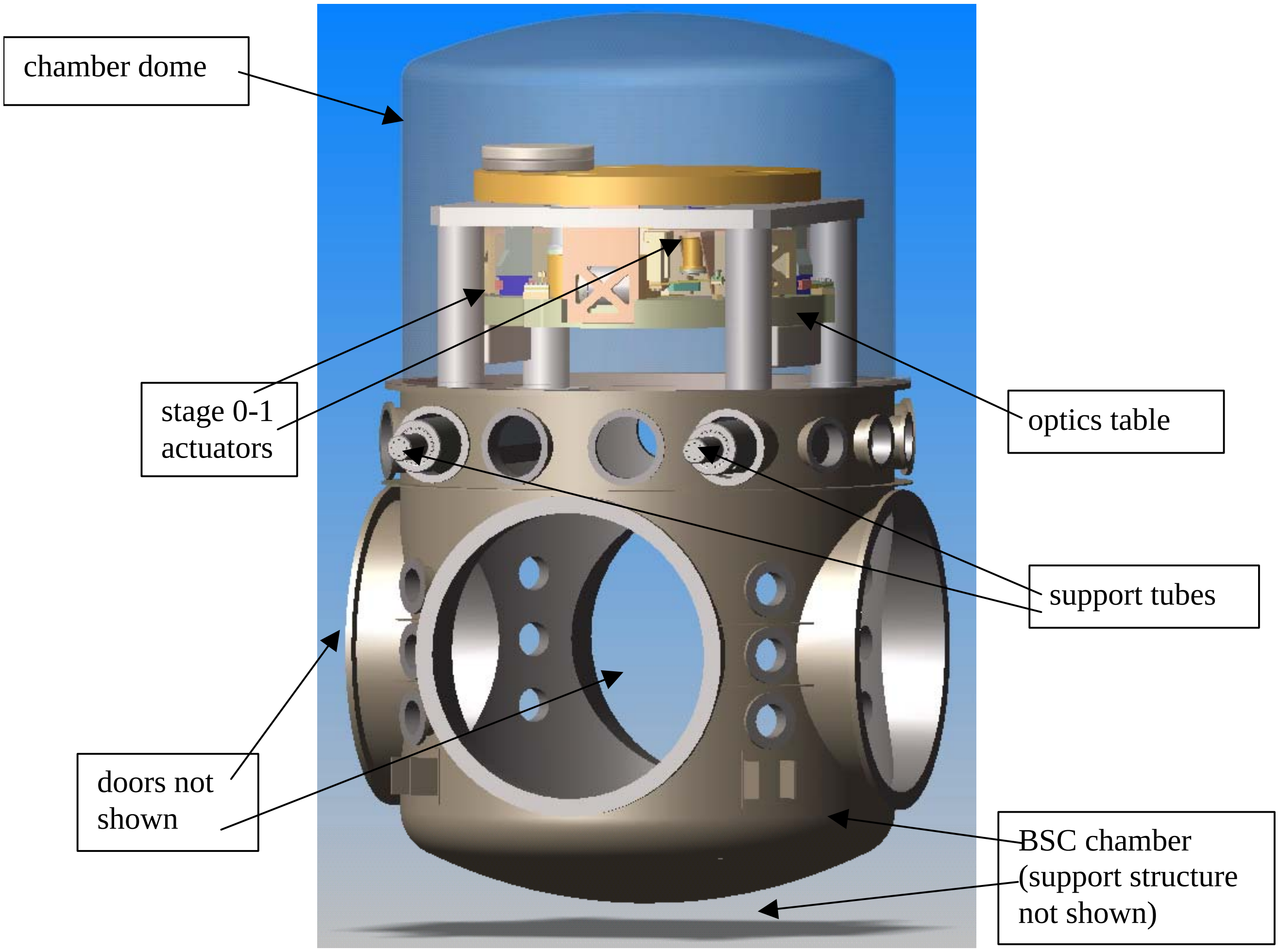

Figure 2: Overall BSC SEI system installation

A technology demonstrator system was built in the basic configuration of the HAM SEI system and deployed at Stanford University in the Engineering Test Facility (ETF). This ETF system is depicted in Figure 3. At the time of this writing the ETF unit is undergoing characterization and commissioning. Thermal performance results are not available as yet. However, since the ETF is a nearly full scale version of the HAM system, it's design details will be used in the analysis of thermal requirements.

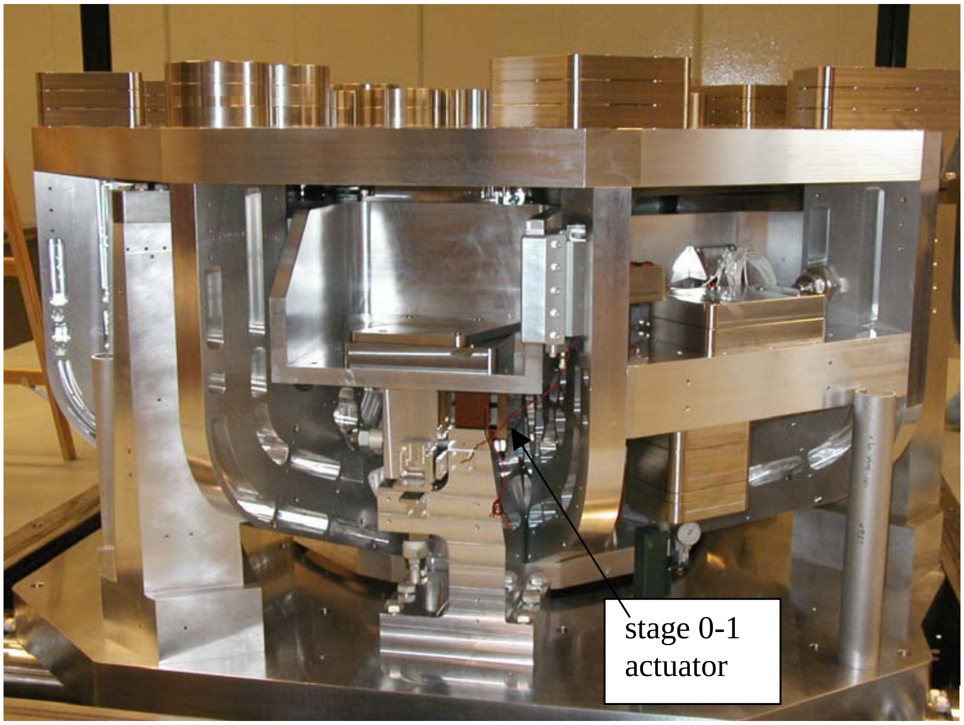

Figure 3: The ETF AdL SEI Technology Demonstrator (without the vacuum chamber shown)

2 HAM SEI System

A view of the current HAM SEI system design (sans a support table) is shown in Figure 4.

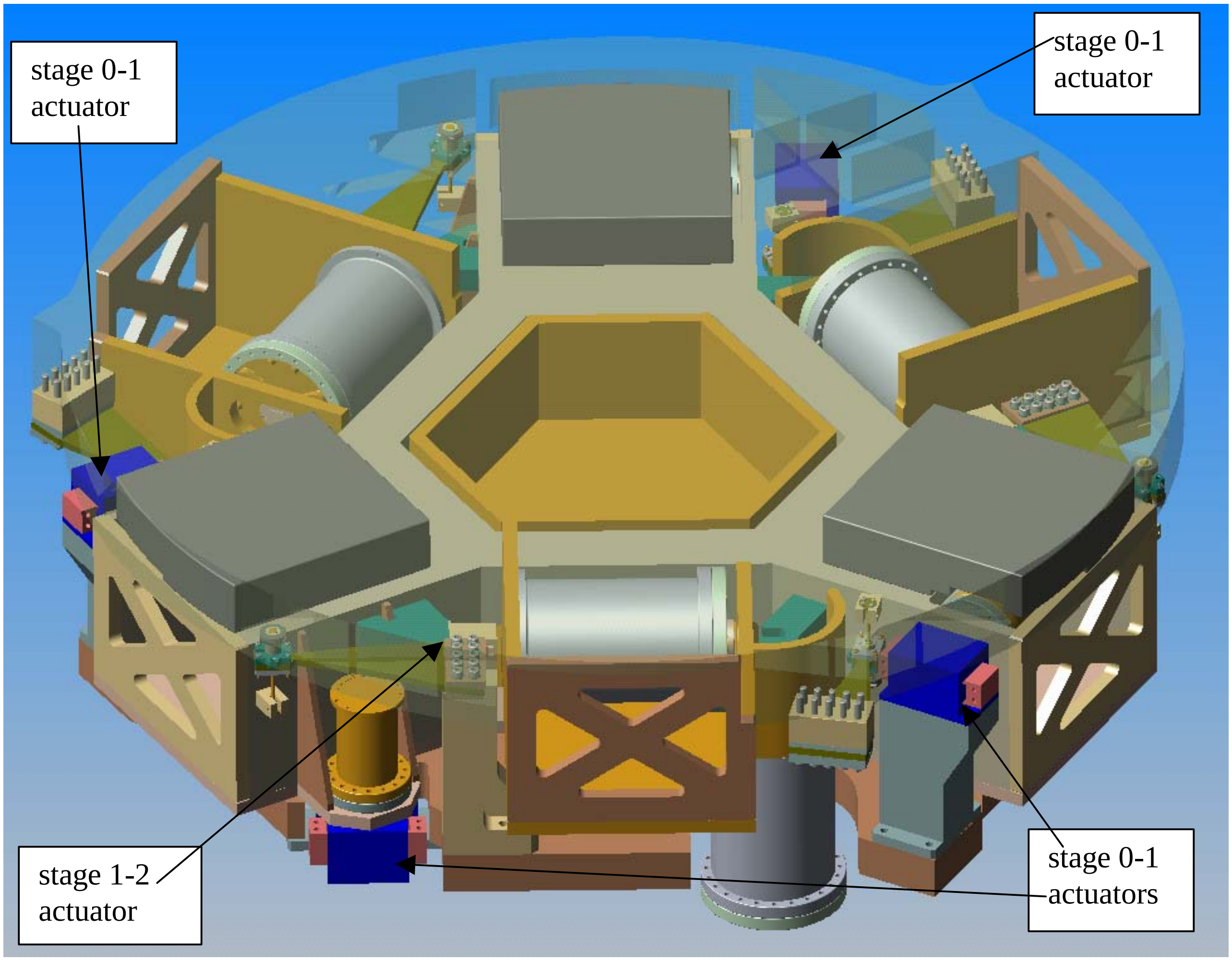

Figure 4: HAM SEI System (draft – in process)

[N.B.: The support table is missing, the actuators are mounted in reverse; The coil/bobbin should be mounted to stage 0 for the stage 0-1 actuator and to stage 1 for the stage 1-2 actuator.]

2.1 HAM Stage 0-1 Actuators

The base support structure for the AdL SEI system (denoted stage 0) is the structure between the Hydraulic External Pre-Isolator (HEPI) and the first isolated in-chamber platform (denoted stage 1). It includes the crossbeam, support tubes, support platform, the pillars used to mount the springs from which stage 1 is hung and the pillars used to support the vertical (3) and horizontal (3) voice coil actuators which provide control forces on the stage 1 structure. Since the stage 0 structure has yet to be designed for the HAM SEI system, the stage 0 structure for the ETF system was used as a representative example. A CAD depiction of the support structure is shown in Figure 5.

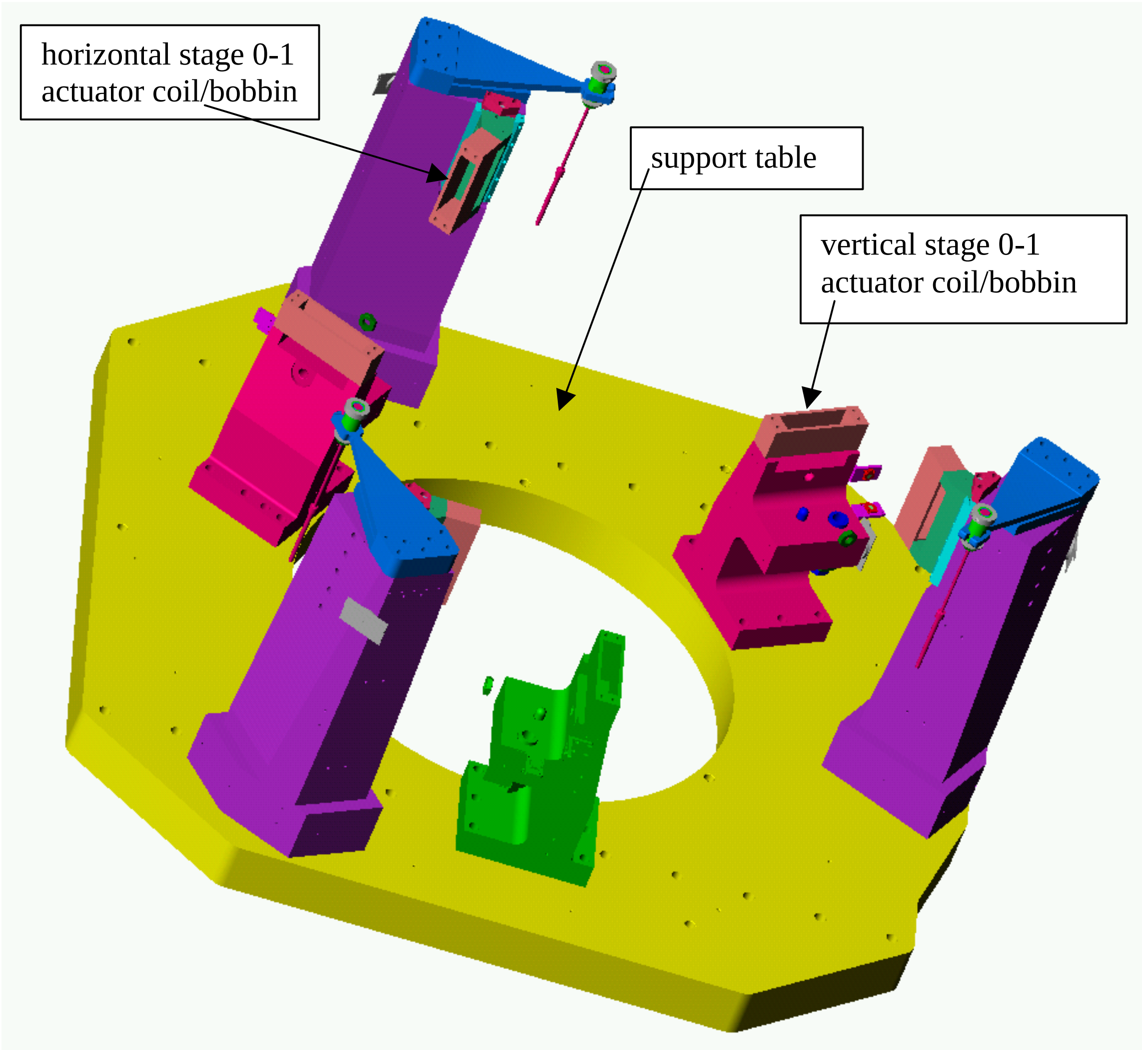

Figure 5: HAM Stage 0 Model

[N.B.: The support tubes are not shown.]

Photographs of the installation of the large actuator attaching structure and its placement within the ETF system are depicted in Figure 6 and 7.

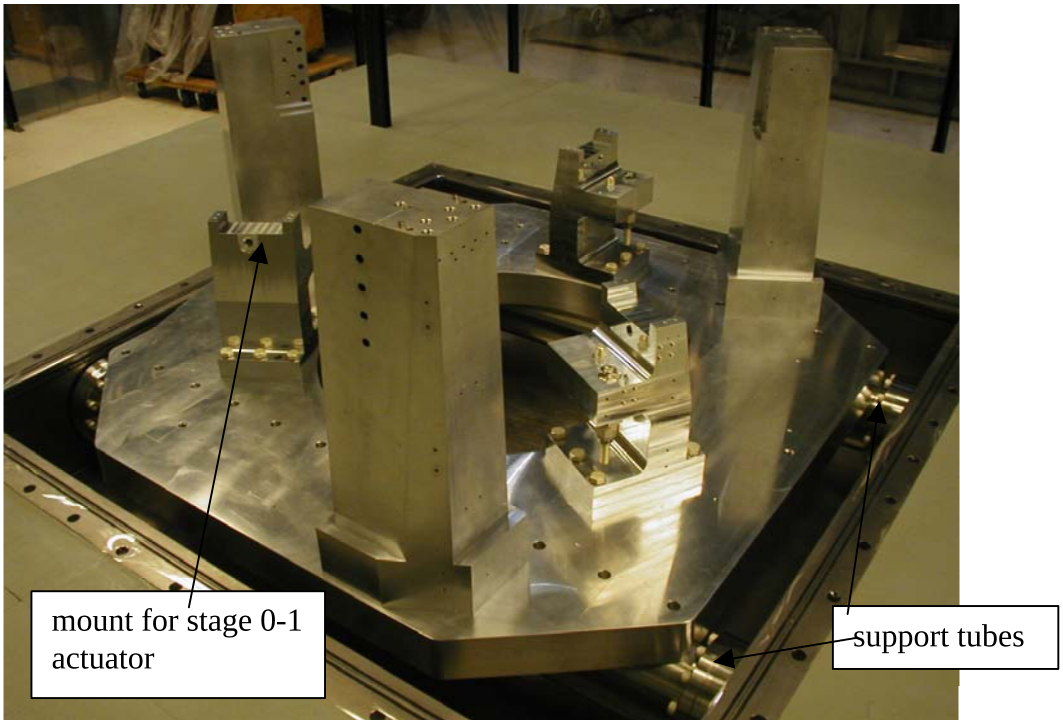

Figure 6: ETF Stage 0 partially assembled, showing the support pillars for the actuators.

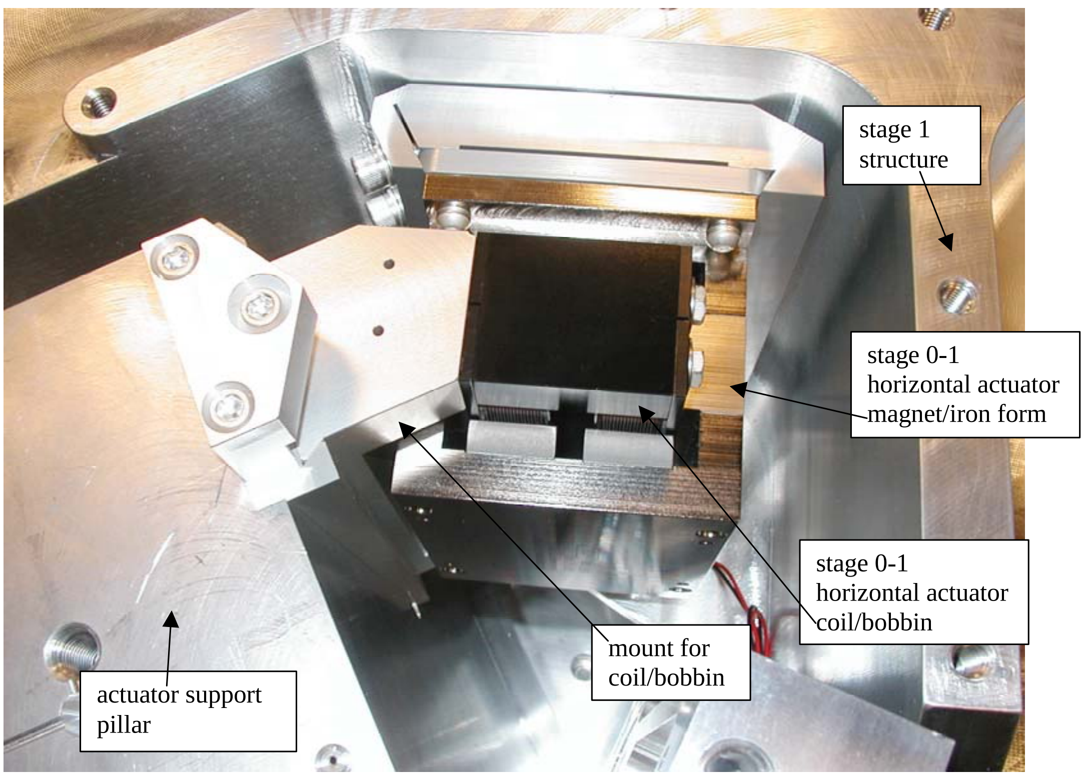

Figure 7: ETF Stage 0-1 horizontal actuator assembly.

[N.B.: In the HAM and BSC SEI prototype units now being designed, the dove-tail adjustment mechanisms, used on both sides of the ETF voice coil actuator, have been eliminated.]

2.1.1 Single Stage 0-1 Actuator, Steady-State

A simplified thermal model for the stage 0-1 actuators was developed to gain confidence in the finite element model (by comparison to more approximate analysis) and to better understand the dominant effects (Figure 8). A realistic simulation would require solution of the thermal transport (conductive and radiation) for all stages simultaneously with view factors accounting for the complex interchange between the inter-nested stages. Instead it is assumed that all of the radiation occurs from only the lower surface of the support table; The stage 1 and 2 structures are assumed to block view of the chamber walls from stage 0. The ends of the support tube are external to the vacuum system and assumed to be at room temperature (20 C). The support tubes are stainless steel (304L). All other structure is made of 6061-T6 aluminum alloy. The coil/bobbin was also assumed to be 6061-T6. The bobbin of the BEI/Kemco voice coil actuator is aluminum. No attempt was made to model the copper coil wire or the kapton/polyimide insulation and potting/adhesive. As a consequence the maximum temperatures cited for the coil are essentially the temperature at the interface of the coil/bobbin and it's mounting structure; If there is significant thermal resistance in the coil assembly then there will be significant gradients and a higher peak coil temperature.

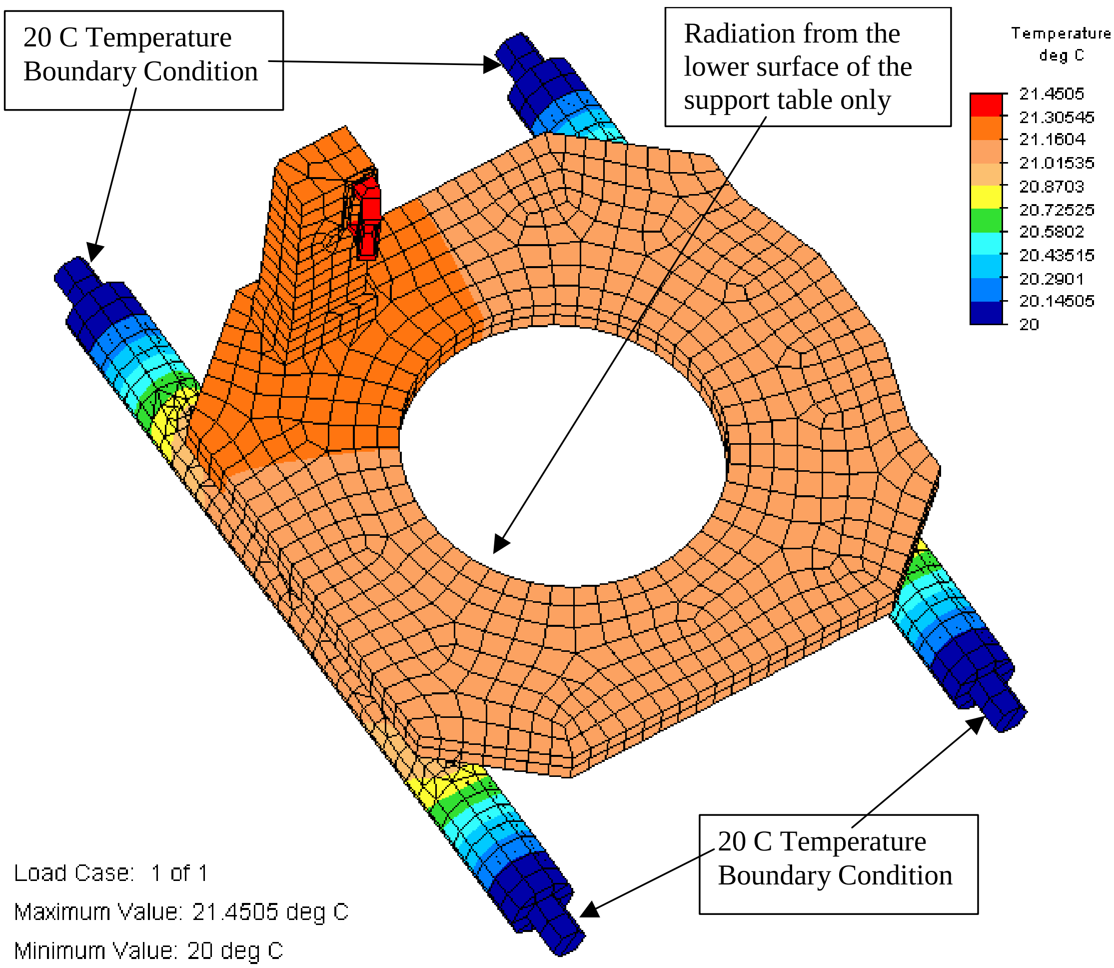

Figure 8: Stage 0 Finite Element Thermal Model (Algor) with temperature field for 1 W dissipation for a single stage 0-1 horizontal actuator

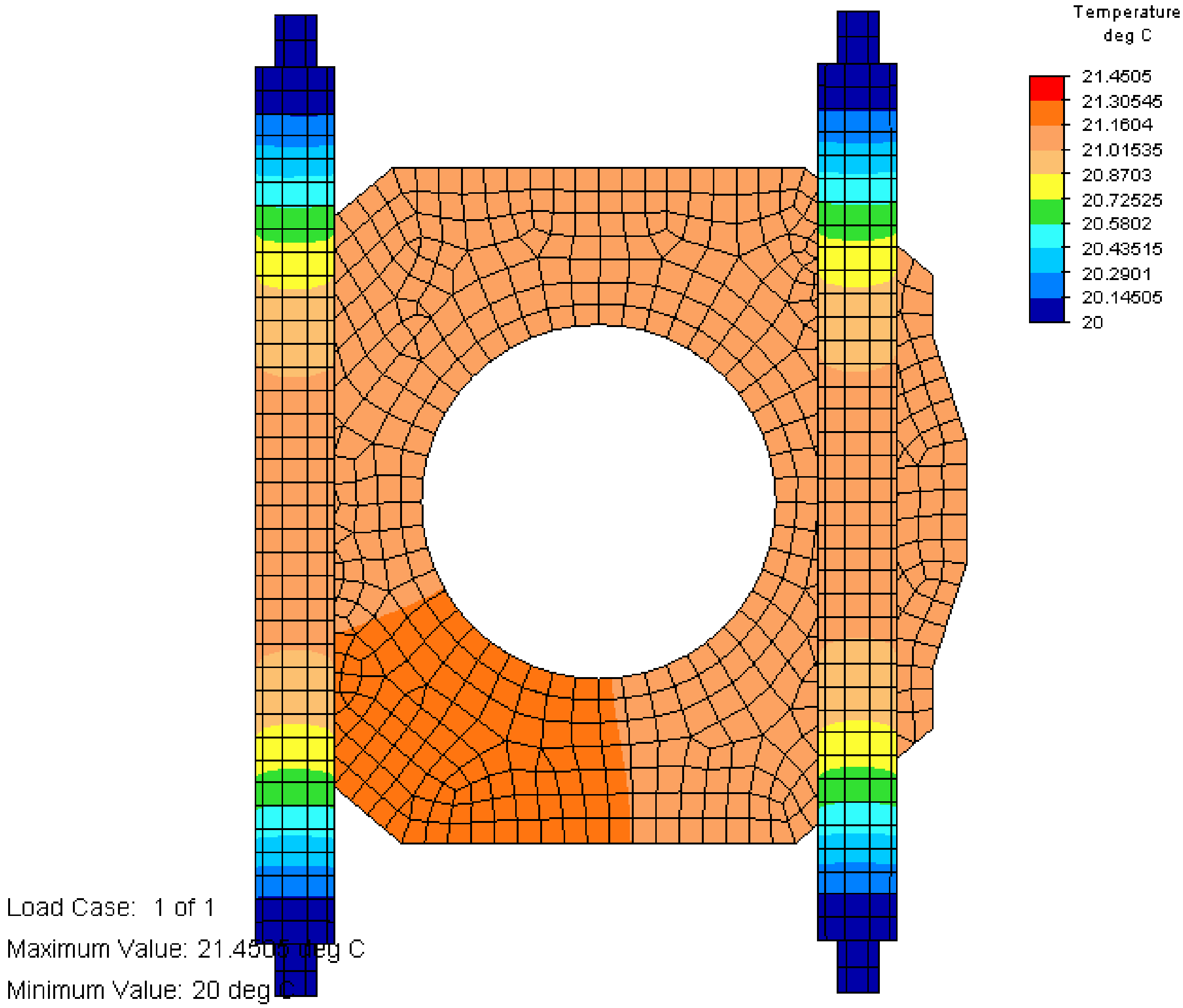

Figure 9: Stage 0 Finite Element Thermal Model (Algor) with temperature field for 1 W dissipation for a single stage 0-1 horizontal actuator

The surface total hemispherical emissivity of the aluminum structure is assumed to be 0.05, which is appropriate for 6061 Al alloy polished and degreased[1]. If the aluminum is 120 size, grit blasted then the emissivity is 0.40. However, this treatment may not be compatible with ultra-high vacuum (UHV) practice. It may be possible to increase the surface emissivity for temperature control in a UHV compatible manner, but this was not assumed in the analysis. Since the nominal operating conditions are for each actuator dissipating less than 25 mW, the temperatures will not be high enough to benefit significantly from radiation exchange. For the relatively short periods of time when the actuators are driven at maximum force and range, there is a large thermal mass to mitigate the temperatures.

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[1] SAE Aerospace Applied Thermodynamics Manual, Part 4C: "Spacecraft Thermal Balance", 1969, Table 4C-2 indicates that at 400 to 500 deg. R, 6061 Al alloy has a total hemispherical emissivity of 0.04 – 0.05 and 0.03 to 0.12 if chemically cleaned.

The coil/bobbin temperature as a function of dissipated power is shown in Figure 10 with both the finite element results and a simple lumped mass approximation. The simple thermal analysis for the single actuator assumes 5 serial resistances along the conductive path from the actuator to the end of the closest support tube (where the temperature is held fixed) as well as radiation from a patch of the underside of the table around the base of the pillar supporting the actuator:

- two mounting flanges: 1" by 1.936" by 1.125" long (Figure 11)
- mounting block base: 8" by 2.4" by ~1.36" long (Figure 11)
- pillar: 9" by 7.7" by ~23.25" (Figure 12)
- support plate from the pillar base to the nearest support tube
- support tube bosses:
- support tube:

The effective thermal resistance at the large (stage 0 to stage 1) actuator is ~1.5 C/W. Means to reduce this resistance were briefly explored through the use of oxygen free, high conductivity copper straps. However the massive aluminum pillars and support plate are already good conduction paths. In addition there are rather limited means for attachment to the inside of the vacuum shell. Nonetheless some modest reduction in the resistance could be achieved.

It should also be noted that the assumption of a constant 20C boundary condition at the ends of the support tubes is not conservative. Free convection was not modeled. It is unlikely that forced convection would be permitted due to concerns for acoustic noise sensitivity of nearby readout optics. There is of course considerably more structure tying the support tubes into the floor, but the conduction paths are long and resistive (steel).

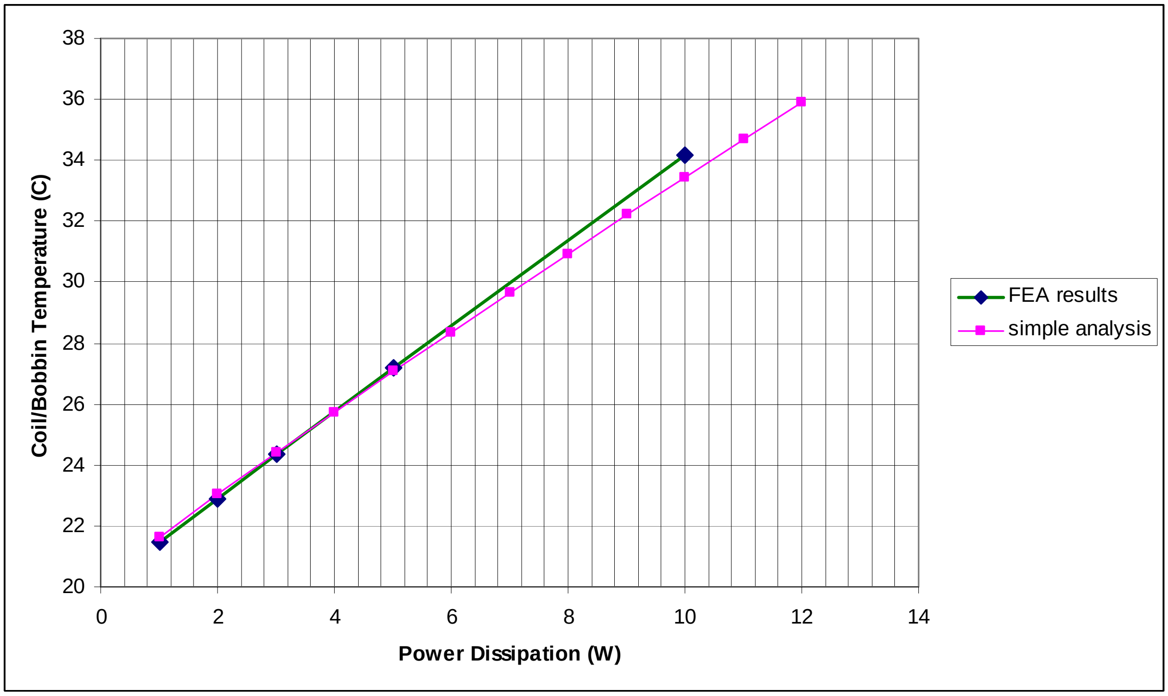

Figure 10: Coil/Bobbin temperature vs Actuator Power for a single actuator (with 20C ambient temperature, chamber absorptivity = 1, support table emissivity = 0.05)

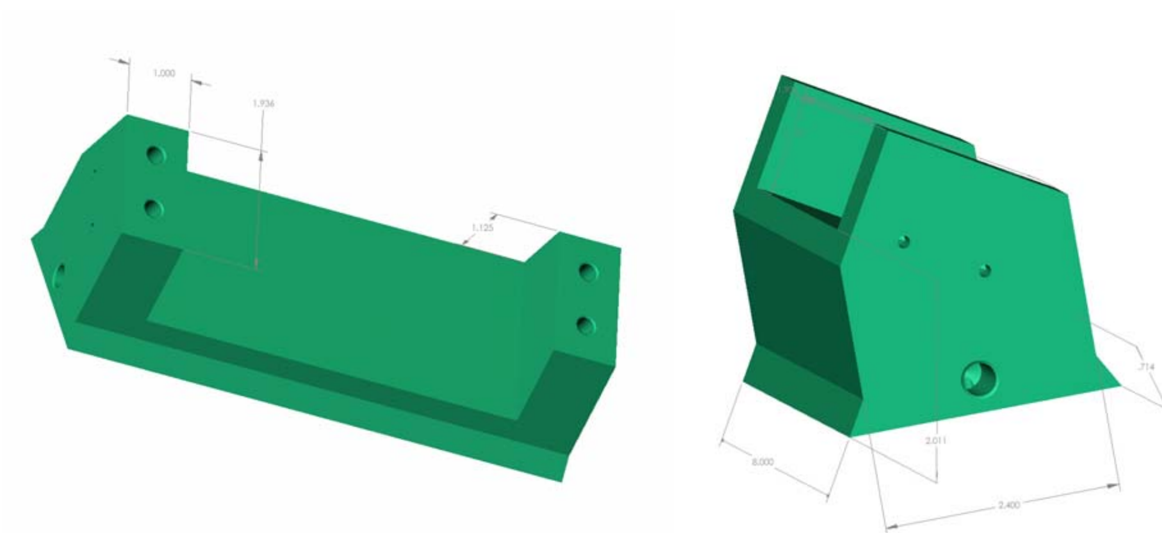

Figure 11: Dimensions of a representative coil/bobbin interface structure

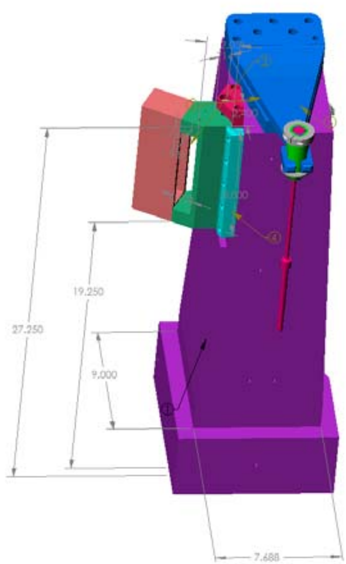

Figure 12: Dimensions of a representative voice coil support pillar

2.1.2 Six Stage 0-1 Actuators, Steady-State

The model described in the previous section was enhanced by (1) adding all 6 actuators on stage 0, (2) radiating heat from the pillar and support table edge surfaces which face outward toward the chamber walls (emissivity = 0.05) and (3) radiating heat from the support tube (stainless steel with a non-polished but machined surface[2], emissivity = 0.55). The model is depicted in Figure 13. The predicted temperature distribution for 10 W heating for each actuator are shown in Figure 14. The coil/bobbin temperature vs power dissipation in shown in Figure 15 and listed in Table x.

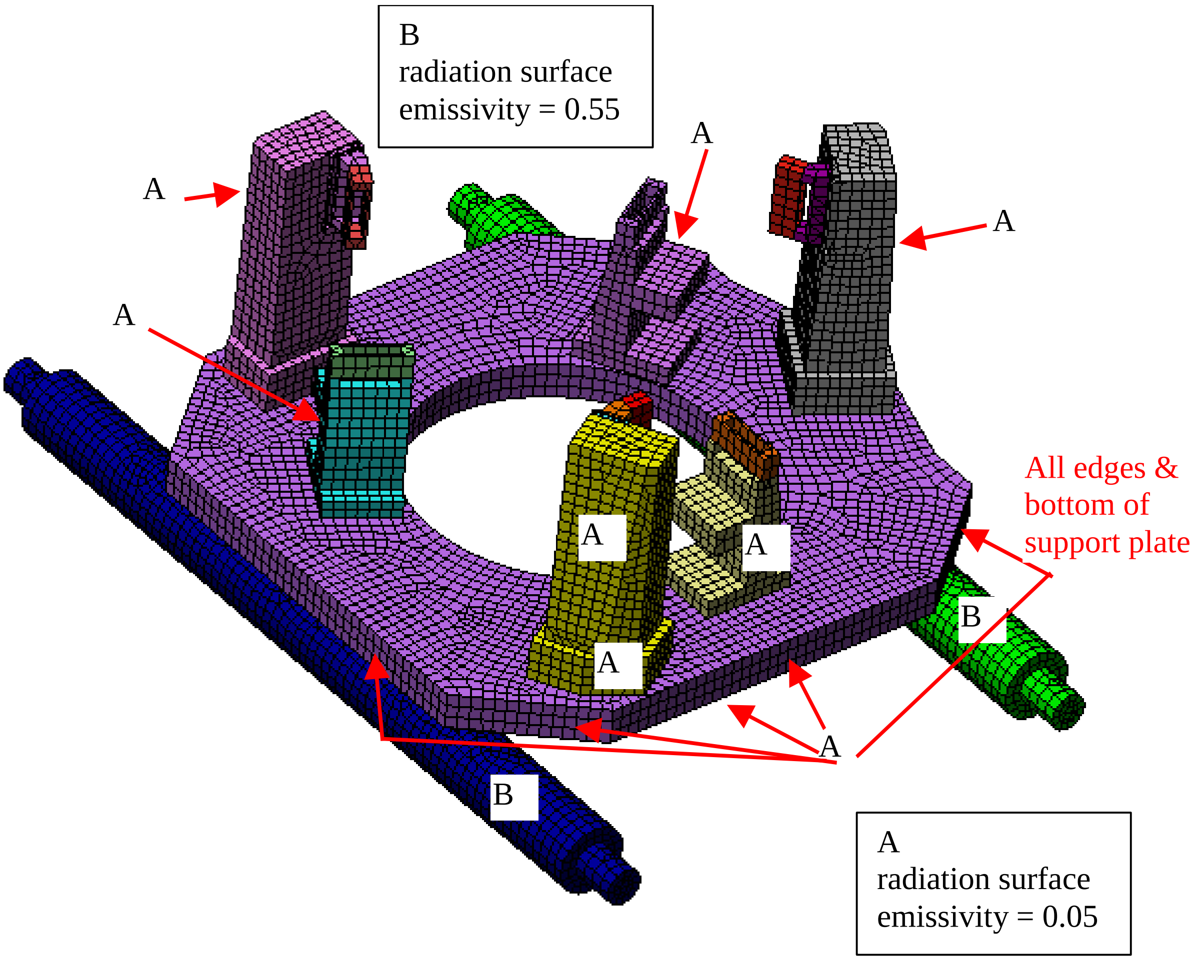

Figure 13: Stage 0 Model

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[2] SAE Aerospace Applied Thermodynamics Manual, Part 4C: "Spacecraft Thermal Balance", 1969, Table 4C-2, Table 4C-9 and Figure 4C-30 indicates that at 400 to 500 deg. R, 301 stainless steel has a total normal emissivity of 0.15 – 0.25 if polished and 0.5 – 0.6 as received. The chamber walls are discolored from vacuum baking and are an as-rolled condition. The emissivity and absortance are probably high, say ~0.55.

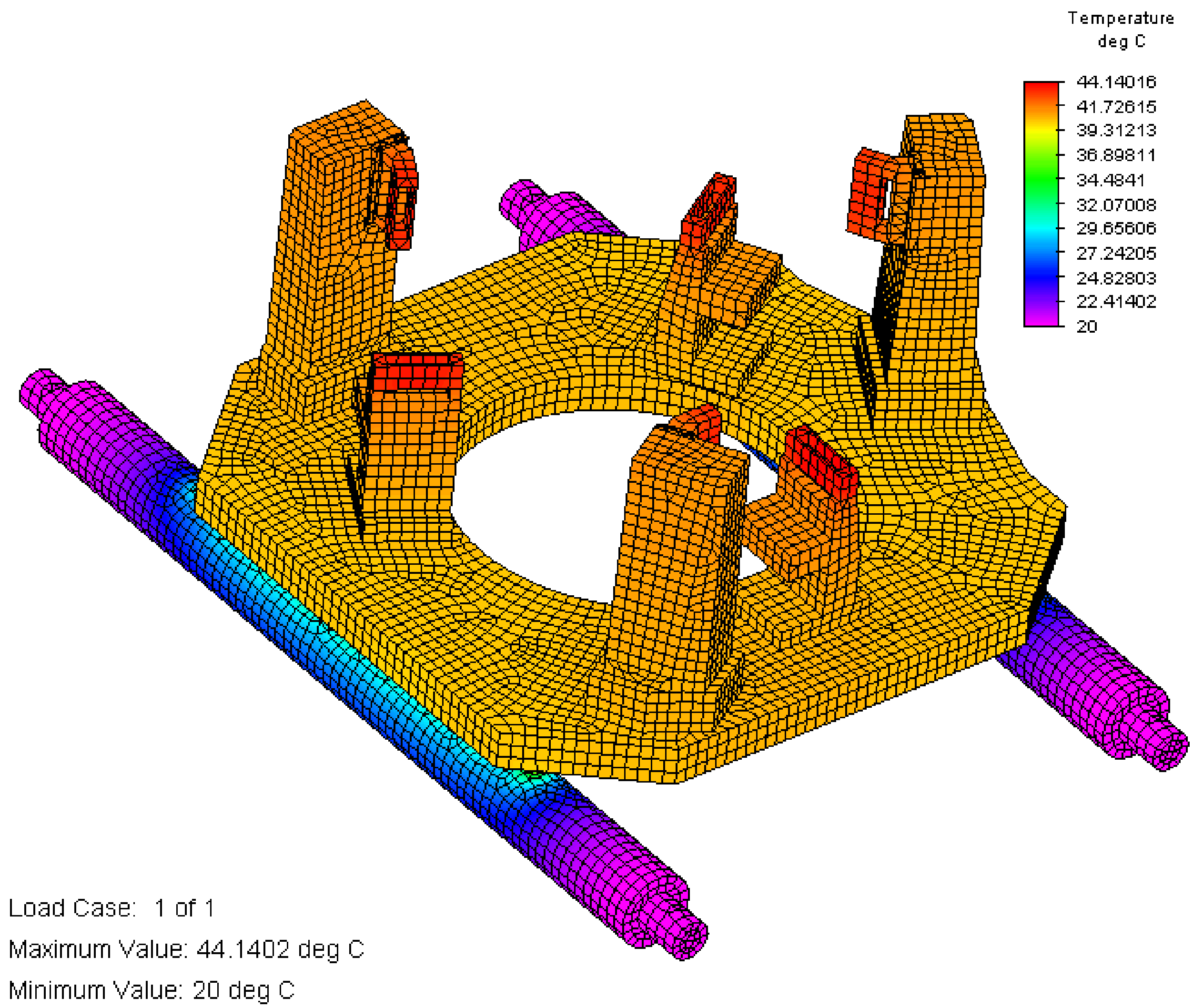

Figure 14: Stage 0 Temperatures for 60W of Stage 0-1 Actuation (10 W per voice coil)

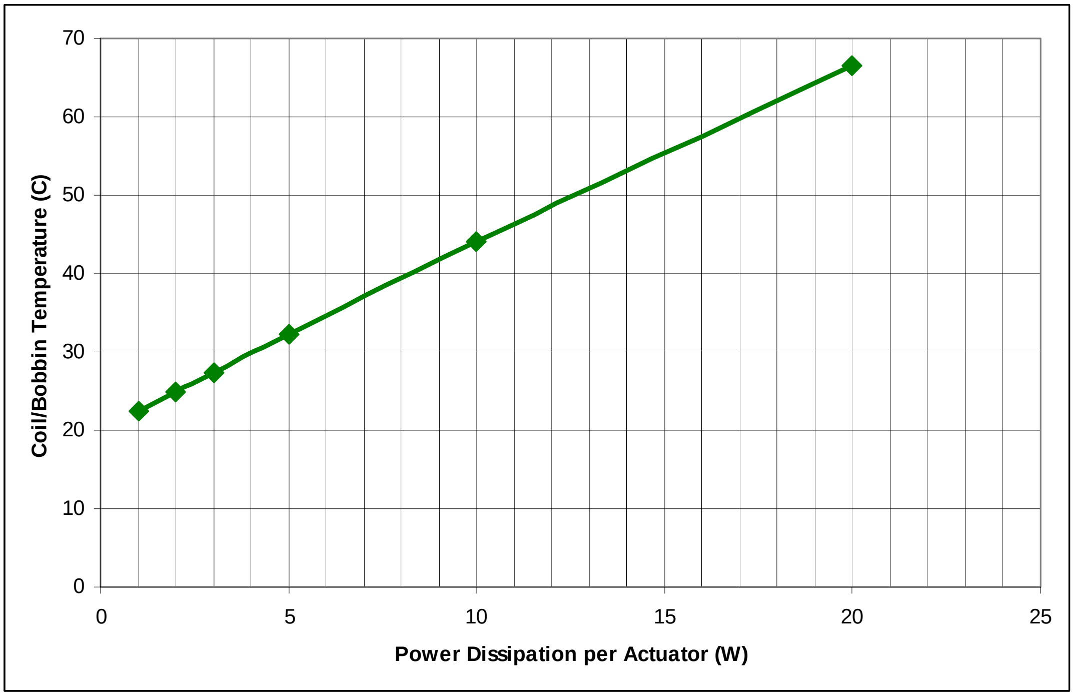

Figure 15: Stage 0-1 Coil/Bobbin Temperature vs Power Dissipation (per actuator)

Table 1: Coil/Bobbin Interface Temperature vs Dissipated Power (assuming all 6 actuators)

- radiation from edges and lower surface of support table (emiss=0.05)
- radiation from outer surfaces of pillars (emiss=0.05)
- radiation from support tube surfaces (emiss=0.55)
- ends of the support tubes are set to 20 C
- ambient = 20 C

Actuator Power Dissipation (W)	Coil/Bobbin Temp (C)
1	22.5
2	24.97
3	27.43
5	32.29
10	44.14
20	66.63

2.1.3 Stage 0-1 Actuator, Transient Analysis

The single actuator, steady state analysis (Figure 8) indicates that there is a negligible gradient in the actuator support pillar. As a lower bound approximation to get the thermal time constant associated with the stage 0-1 actuator, we can assume that all of the thermal capacitance is contained within the pillar and that the interfacing/mounting structure provides resistance but little thermal mass, as depicted in Figure 16.

FIGURE TBD

Figure 16: Simple Lumped Mass approximation for determining the thermal time constant

The dimensionless ratio of internal resistance (of the pillar) to external resistance (for the path from the pillar to the boundary condition at the ends of the piers), the Biot number is:

$$B_i = \frac{\bar{h}L}{k} = 0.06$$

where $\bar{h} = \frac{1}{R_p A}$ is the average unit surface conductance, R_p is the external resistance of the heat sink path from the pillar, A is the area associated with the surface conductance (0.045 m^2), L is the characteristic conduction length (the pillar length, 0.59 m,or its volume divided by the area, A) and k is the conductivity of the pillar material (aluminum, 6061-T6, or 171 W/m/K). When the Bi number is < 0.1, the error in the assumption that the temperature at any instant is uniform will be less than ~5%. Equating the change in internal energy of the pillar to the net heat transfer to the pillar from the coil and out of the pillar to the support tube:

$$C\rho V dT = \left[Q - \bar{h}A(T - T_a)\right]dt$$

where C is the specific heat (for 6061-T6, C = 896 J/kg/C), ρ is the density (2700 kg/m^3), V is the volume (0.027 m^3), Q is the voice coil heat dissipation (W), T is the temperature of the pillar and T_a is the ambient (boundary condition) temperature (20 C). The solution for the pillar temperature is then:

EQN TBD

The predicted transient thermal response of a stage 0-1 (large) actuator with 20 W of dissipation is shown in Figure 17 for the lumped mass model and in Figure 18 for the finite element analysis (FEA). The asymptotic (steady-state) temperatures for the lumped mass model, 50 C, compares to TBD C with the FEA. The time constant for the FEA results is significantly longer than the simple lumped mass model above, due to the inclusion on a significant amount of the support plate thermal capacity.

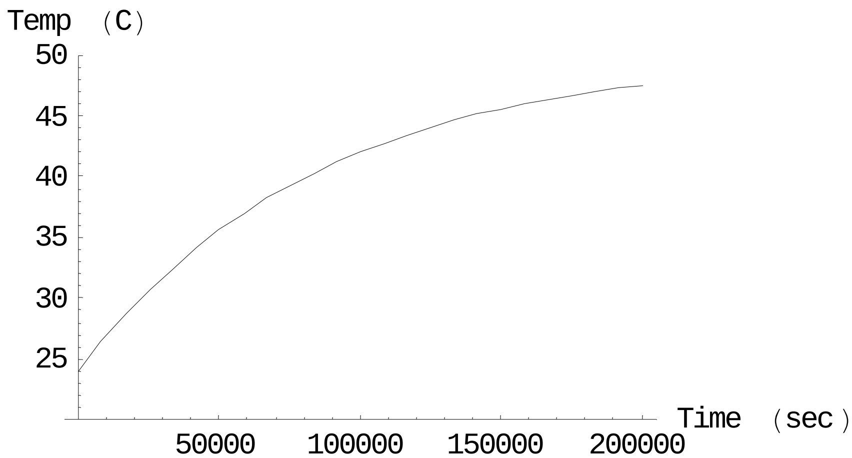

Figure 17: Lumped Mass Model Transient Response for 20W dissipation in a Stage 0-1 (large) actuator

FIGURE TBD

Figure 18: Finite Element Model Transient Response for 20W dissipation in a Stage 0-1 (large) actuator

2.2 HAM Stage 1-2 Actuators

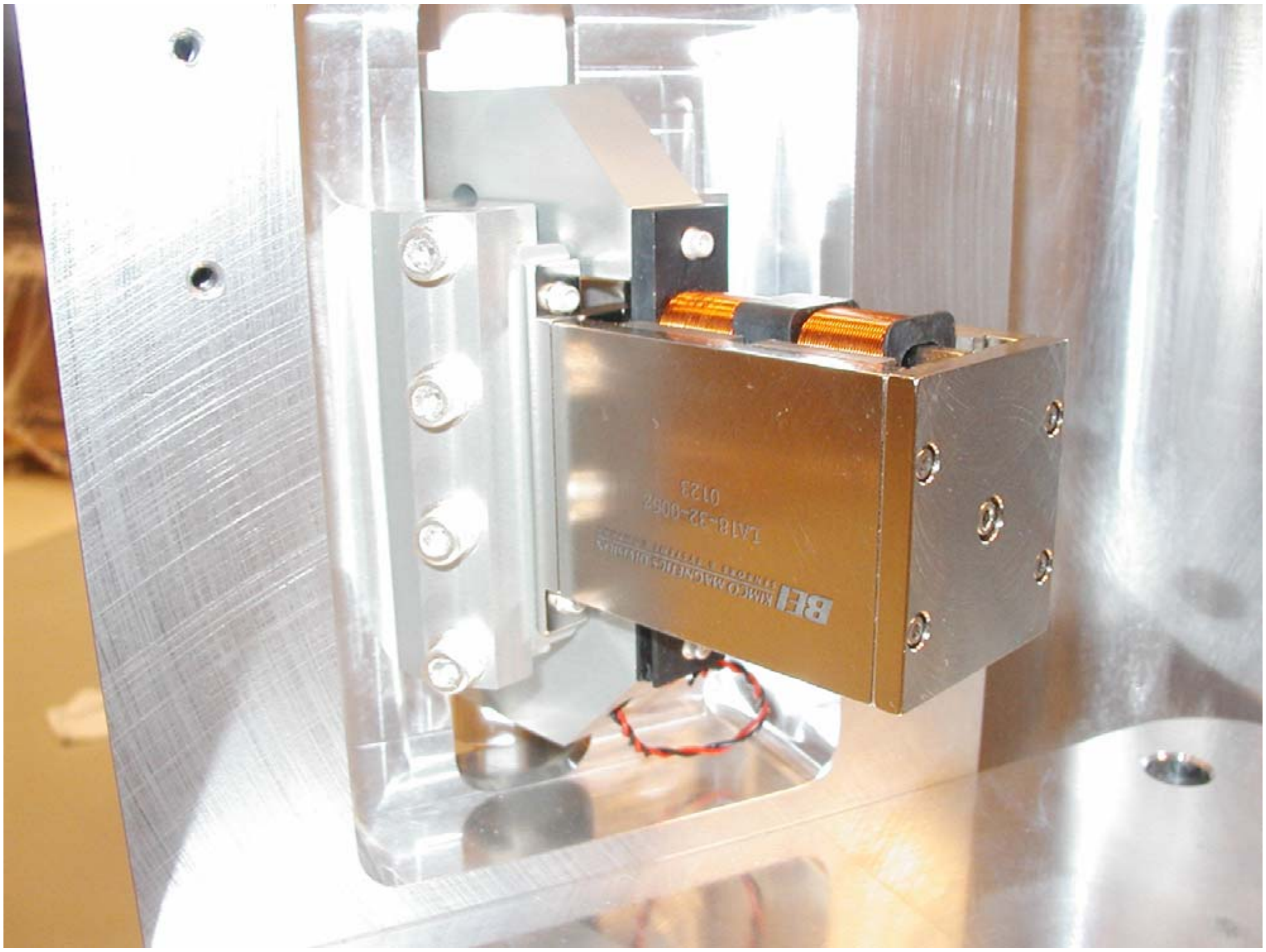

Figure 19: Stage 1-2 Actuator Assembly on the ETF SEI Technology Demonstrator

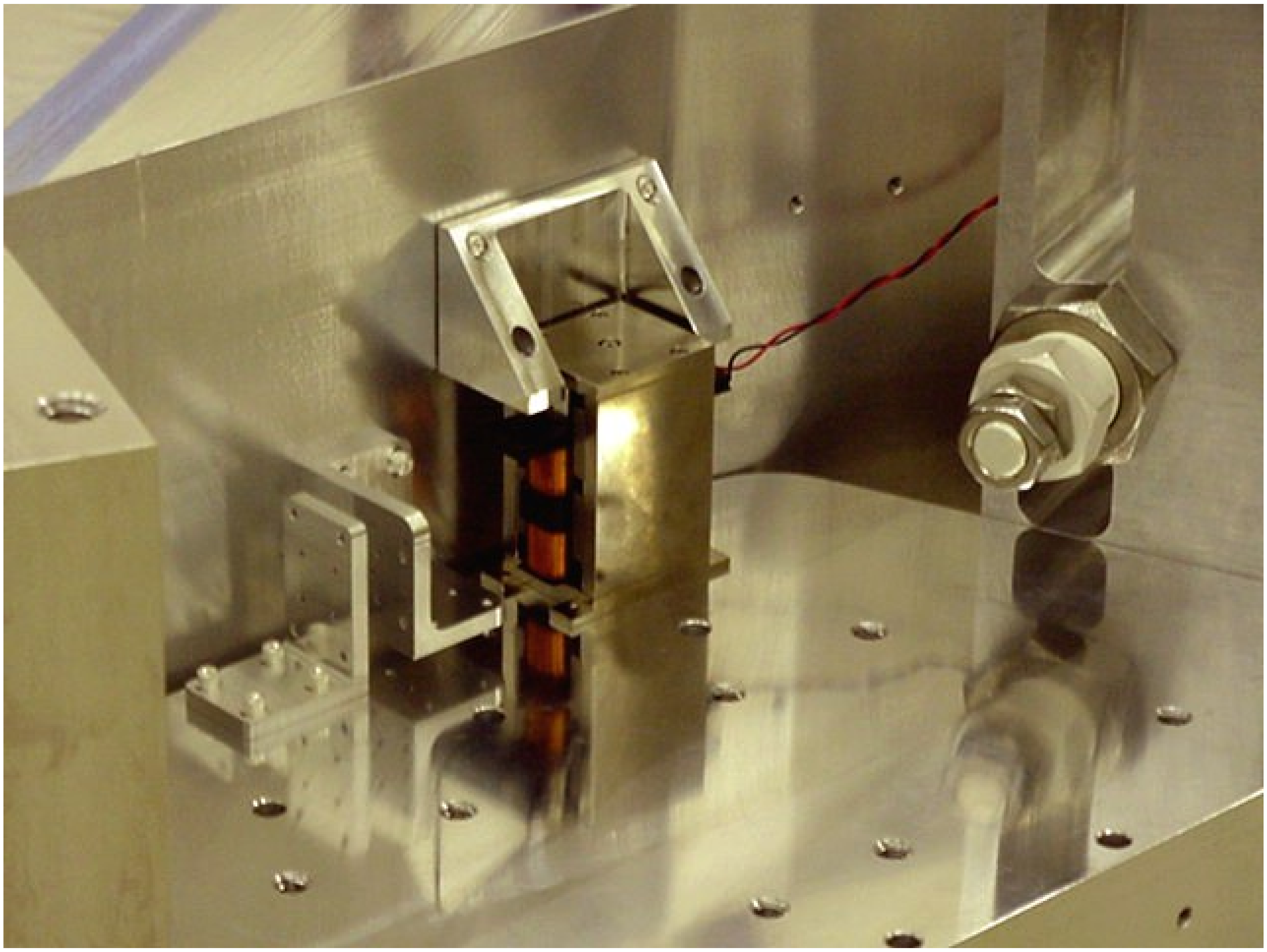

Figure 20: Vertical Stage 1-2 Actuator Assembly in the ETF SEI Technology Demonstrator

3 BSC

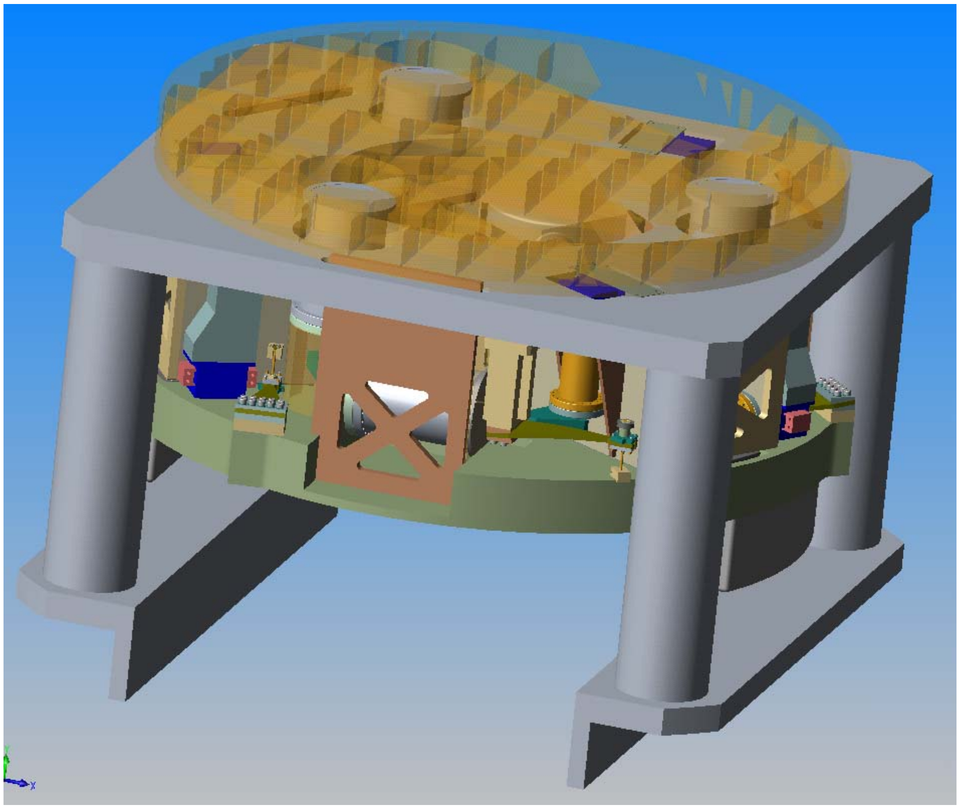

Figure 21: BSC SEI System (support tubes not shown)

The conduction heat path out to the support tube ends is much longer (more resistive) than in the case of the HAM.