

Gripper Test Assembly Status of Fabrication and Assembly Report – FY2023

Nuclear Science & Engineering

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Executive Summary

The Gripper Test Assembly (GrTA) is an experimental test article designed for use at the Mechanisms Engineering Test Loop (METL) at Argonne National Laboratory (ANL). The GrTA will test mechanical components intended for use in compact in-vessel fuel handling machines (FHM) for sodium cooled fast reactors (SFR). The GrTA will test radial and thrust ball bearings, radial and thrust roller bearings, ball screws and nuts, spline shafts and ball nuts, radial spur gears, and universal joints submerged in liquid sodium at high temperatures (250°C-650°C). These components will be tested in a prototypic, full-scale gripper head and under prototypic SFR fuel handling loads. The design of the GrTA was completed in FY2022 and has progressed into fabrication and initial assembly.

All custom manufactured components have been fabricated and delivered to ANL following inspection. All custom gears have been fabricated and delivered to ANL. Bearings, ball screws, and spline shafts have been purchased to allow for initial assembly in air, and sodium compatible versions have either been purchased or are in design at appropriate manufacturers. The drive motor systems that operate the various functions of the GrTA have been purchased and delivered to ANL. Instrumentation and control hardware has been purchased and delivered to ANL as well.

All sodium facing components of the GrTA have been assembled and show proper fit. The three main functions of the GrTA are to raise or lower a gripper head under prototypic fuel handling loads, rotate the gripper head while carrying a fuel handling load, and extend or retract gripper jaws that lock a fuel assembly to the gripper head. All three functions have been demonstrated in air, while under no load. The GrTA project will move forward next fiscal year by completing the initial assembly, incorporating the drive system and I&C, and preparing the assembly for introduction to sodium.

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1. Background

Refueling systems for liquid metal cooled fast reactors are designed to handle fresh and used core assemblies (fuel, reflector, and shield core assemblies) within the reactor vessel in an opaque coolant environment without visual reference. These refueling machines are designed to work in a sodium (or other fast reactor coolants) and argon vapor space environment and are engineered with a rotatable plug system to allow for the movement of fresh and spent fuel into and out of the reactor core. The refueling machines are a critical component in any reactor and thus need to undergo extensive testing in a prototypic environment to ensure that they will meet all of the system functions and requirements.

Argonne National Laboratory (ANL) has developed an innovative compact fuel handling machine (FHM) design for the Advanced Fast Reactor-100 (AFR-100) that is based upon some mechanisms used in previous reactor designs, such as the U.K.'s Prototype Fast Reactor (PFR) and some mechanisms that have not been used in sodium. This compact refueling machine supports the reduction in size of the AFR-100's reactor vessel, and if fully developed, would support and inform the development of the in-vessel refueling machines for such commercial reactors as the GEH PRISM reactor plant, the ARC Clean Energy's ARC-100 reactor, and the Natrium reactor in development by Terrapower, among others. This refueling system is a vital component of a fast reactor that supports reducing the cost of the reactor and increasing its reliability. The compact fuel handling machine is designed to extend into a narrow slot in the upper internal structure (for example in the PRISM reactor concepts) during reactor refueling and retract into a structural support tube mounted to a single rotating plug in the reactor head.

The compact fuel handling machine (Figure 1) performs the following functions during operation:

1. Rotate the fuel handling machine with respect to the rotatable plug.
2. Extend or retract the fuel handling arm which radially positions the gripper over the core while holding or not holding a core assembly.
3. Raise or lower a structural component that is used to hold down the surrounding core assemblies during a core assembly removal.
4. Extend or retract the gripper jaws to engage or disengage a core assembly.
5. Raise or lower the gripper head to insert or remove a core assembly into the core and grid plate structure or remove a core assembly from the core and break it free of the grid plate structure.

6. Rotate the gripper to correctly orient the core assembly with the reactor core before insertion of the core assembly.

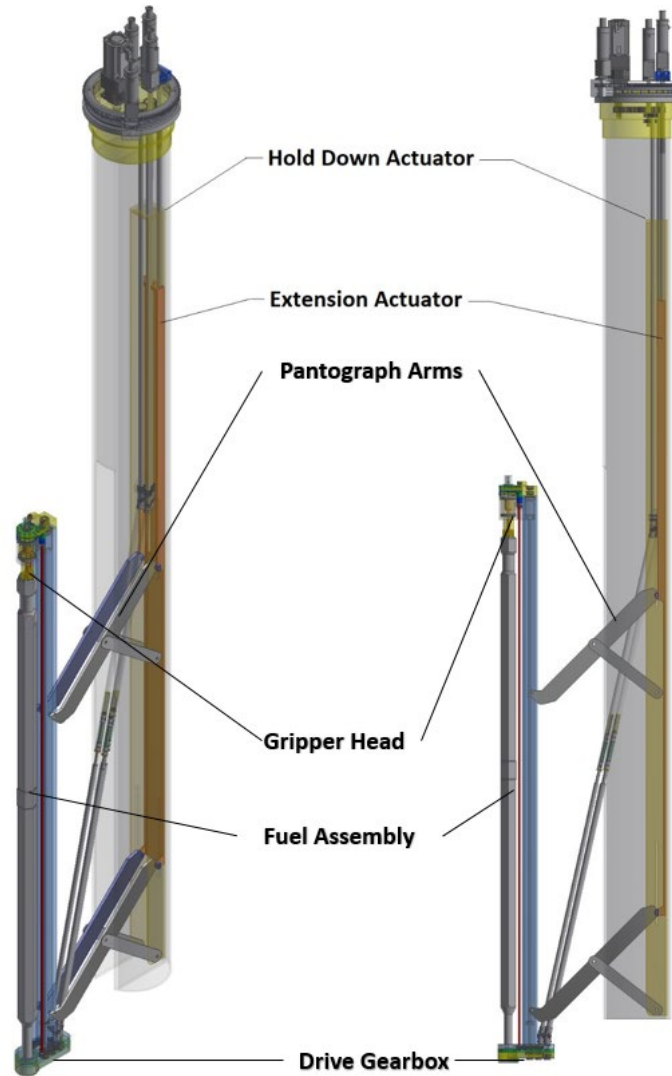


Figure 1: Overview of the ANL Compact Fuel Handling Machine.

Due to a lack of current operational experience and literature regarding the use of the various mechanisms that must function while submerged in the liquid sodium, preliminary test articles have been developed to bridge this gap. The Gear Test Assembly (GTA) was the first test article developed in this process and examined the use of gears and bearings in high temperature liquid sodium [1]. Testing in the GTA successfully demonstrated the use of gears and bearings in sodium, albeit with reduced lifetimes. The lessons learned in the GTA testing informed the design of the next test article in the FHM development process, the Gripper Test Assembly (GrTA). The Gripper Test Assembly will test several more mechanisms submerged in liquid sodium at the Mechanisms Engineering Test Loop (METL) at ANL.

2. Gripper Test Assembly Overview

The Gripper Test Assembly (GrTA) is designed to simulate the gripper operation of the ANL compact fuel handling machine under expected mechanical and thermal loading prototypic to sodium fast reactor refueling operations. The mechanical components used in the design of this compact fuel handling machine include radial and thrust ball bearings, radial spur gears, ball screws, recirculating ball nuts, ball spline shafts, recirculating ball splines, universal joints, radial and thrust cylindrical roller bearings, fasteners, welds, various connection pin designs, and rolling contact joints. These components will be submerged in reactor-grade liquid sodium and operated under load at temperatures between 200°C-350°C, and may be exposed to temperatures up to 650°C while under no load. All mechanical components will be fully submerged in the sodium coolant to prevent buildup of sodium frost or oxide that could otherwise impede mechanical function. The GrTA is designed to operate in the 28-inch test vessels available at the METL facility, with a cross-section of the assembly shown in Figure 2

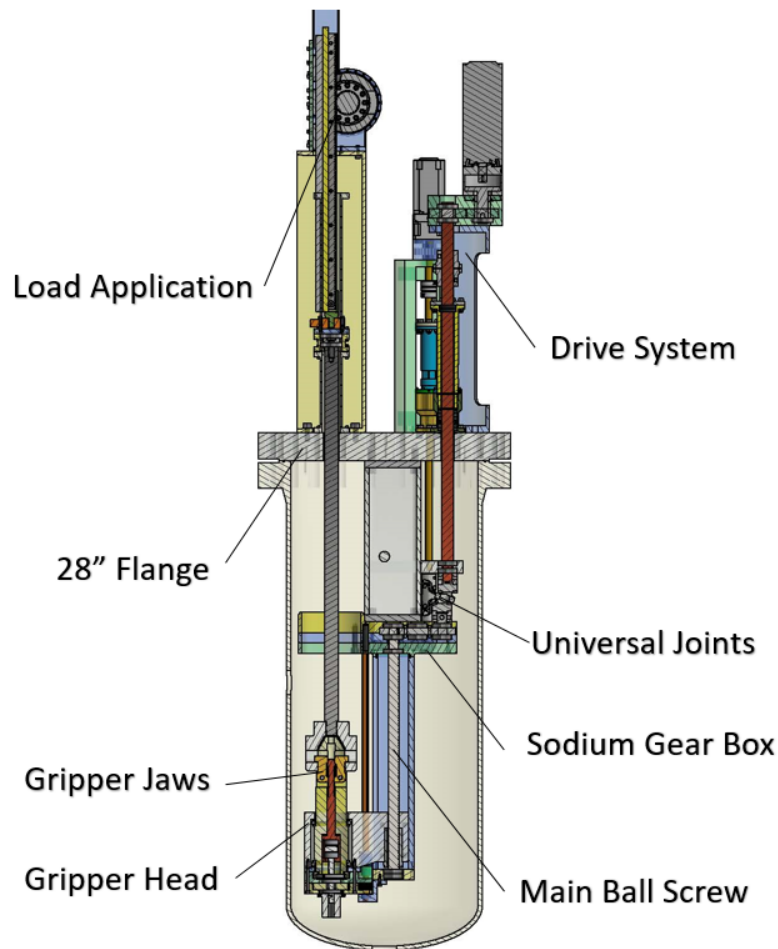


Figure 2: Cross section of GrTA showing installation in 28" METL Test Vessel.

2.1. Design Requirements

The design requirements of the GrTA have been developed as follows:

1. Simulate operation of a fuel handling machine gripper assembly in a simulated sodium fast reactor environment by testing all prototypic types of mechanical components used in the FHM design.
2. Reduce the width of the gripper assembly to fit a 10-inch wide slot in an upper internal structure of an SFR. This particular requirement is only for certain vendor reactors and not all vendor reactors.
3. Operate components under load in liquid sodium at elevated temperatures (350°C). May include exposure to higher temperatures (550°C) under no load.
4. Select material combinations to prevent galling (self-welding), galvanic corrosion, and minimize impact of surface alloying element reduction through diffusion processes.
5. Raise and lower simulated core assembly with a maximum load of 6,000 lbs. (~27kN).
6. Rotate core assembly while fully raised and supporting the weight of the core assembly, 1,000lbs. (~5kN).
7. Open and close gripper jaws while lowered to engage/disengage the core assembly.
8. Isolate individual gripper actuation motions so operation of one does not affect the others.
9. Use simple mechanisms to reduce the number of components.
10. Minimize the number and types of seals required for operation.

The GrTA is designed to operate by isolating the various control motions. Extension or retraction of the gripper jaws, rotation of the gripper post, and raising or lowering the gripper head are isolated to ensure that the operation of one does not affect the others. For example, the rotation of the gripper post does not cause the jaws to extend or retract.

The system is fully monitored during operation using various sensors located throughout the system. Several computers collect monitoring data and process the data in real time to adjust control parameters, notify operators of off normal conditions or stop the loading should an overload or failure be detected.

Drive shafts penetrate through the top of the test vessel flange and transfer the required torque to operate the mechanisms from DC servo motors located outside the test vessel. The shafts use various sealing systems to prevent leakage of the argon cover gas into the experimental hall.

The GrTA is computer controlled with automatic operation and data acquisition. Automatic fault identification and system shutdown will be programmed into the operating system and with remote notification of the operator.

2.2. Testing Criteria and Operation Parameters

The Gripper Test Assembly is designed to operate in a high temperature liquid sodium environment. The assembly is mounted on the top flange (vessel cover) of a 28-inch diameter stainless steel test vessel. The test vessel is part of the Mechanisms Engineering Test Loop (METL) located in building 308 at Argonne National Laboratory. The design sodium test temperature is in the range of 200 to 550°C, but most fast reactor refueling operations are around 350°C in temperature or less.

The unit is designed with a programmable resisting force from 0 to 27,000 Newtons to simulate the transient loading cycle representing fuel handling loads for installation or removal of a stuck core assembly inside a liquid sodium cooled reactor. The data for handling loads was obtained from the Fast Flux Test Facility (FFTF) reactor where the maximum load measured was (5,000 lbf) 22,241 Newtons, but 20% was added for unknown factors for a maximum load of (6,000 lbf) 26,690 Newtons.

The high temperature liquid sodium environment prohibits the use of normal lubricants inside the vessel. Therefore, the choice of material combinations for rolling or sliding mechanical components is critical.

Material combinations must be chosen with a minimal galling potential as well as minimizing the galvanic corrosion potential and reactions of alloy constituents with the sodium in the high temperature liquid environment. The mechanical components will utilize liquid sodium as the primary “lubricant”.

All mechanical components have been designed and analyzed in accordance with the appropriate commercial or nuclear specifications and include lifetime modification factors in accordance with those standards. Lifetime reduction factors for operation in a high temperature liquid sodium environment will be determined through the experimental results with respect to operation in a normally lubricated environment.

The full-size fuel handling machine was designed to raise fully a core assembly in approximately 60 seconds with the ball screw turning at 350 rpm having a lead of 12 millimeters. This was to accommodate the full 4.2-meter length of the core assembly under consideration. The load cycle for the design of the fuel

handling machine was 10% at maximum load and 90% at normal load and all component lifetimes were calculated to accommodate the expected lifetime of the reactor (although all mechanical components may be replaced at normal maintenance intervals). Options to remove the fuel handling machine during reactor normal operation or leave it in were considered.

The maximum vertical length of travel for the gripper test assembly allowed by the METL 28-inch diameter test vessel is 0.575 meters. Therefore, at 350 rpm, the travel time is reduced to approximately eight seconds. The loading cycle times will also be modified for 25% at maximum load and 75% at normal load.

The loading profile for the GrTA will initially consist of a high load - 27,000 N (simulating a stuck core assembly at 6,069 pounds-force) resisting load for a period of two seconds (followed by a reduction to 4,500 N (simulating the weight of the heaviest core assembly at 1000 pounds) for the remaining six seconds. As the loading profile is programmable, any transient loading scheme may be used (for instance, an intermediate initial load followed by a simulated “sticking” peak load and then reduction to normal core assembly load). Table 1 outlines the operation sequence with loads and times for a full scale FHM and the GrTA.

A report covering the design and analysis of many of the GrTA components has been released and is available on OSTI [2].

Table 1: Operation sequence for full scale FHM and GrTA.

MOVEMENT	FULL SCALE		GRTA	
	Load [kN]	Time [s]	Load [kN]	Time [s]
LOWER HEAD	0	60	0	8
EXTEND JAWS	0	10	0	10
RAISE ASSEMBLY	27	6	27	2
RAISE ASSEMBLY	4.5	54	4.5	6
ROTATE ASSEMBLY	4.5	variable	4.5	variable
LOWER ASSEMBLY	4.5	54	4.5	6
LOWER ASSEMBLY	27	6	27	2
RETRACT JAWS	0	10	0	10
RAISE HEAD	0	60	0	8

3. Component Procurement

3.1. Custom Fabricated Components

The design of the GrTA was completed in FY2022 and the project was sent out for fabrication in the same year. The fabrication of all custom structural and mechanical components used in the GrTA were contracted to a local machine shop that has completed similar projects for the group in the past. The contract was awarded in March 2022 and progress was periodically inspected by ANL engineers during fabrication. Fabrication was completed following inspection in December 2022, and delivery was made to ANL in January 2023. The following images were taken during final inspection at the manufacturer.



Figure 3: Assortment of stainless steel components following inspection at the manufacturer.



Figure 4: Assortment of custom fabricated components following inspection at the manufacturer.

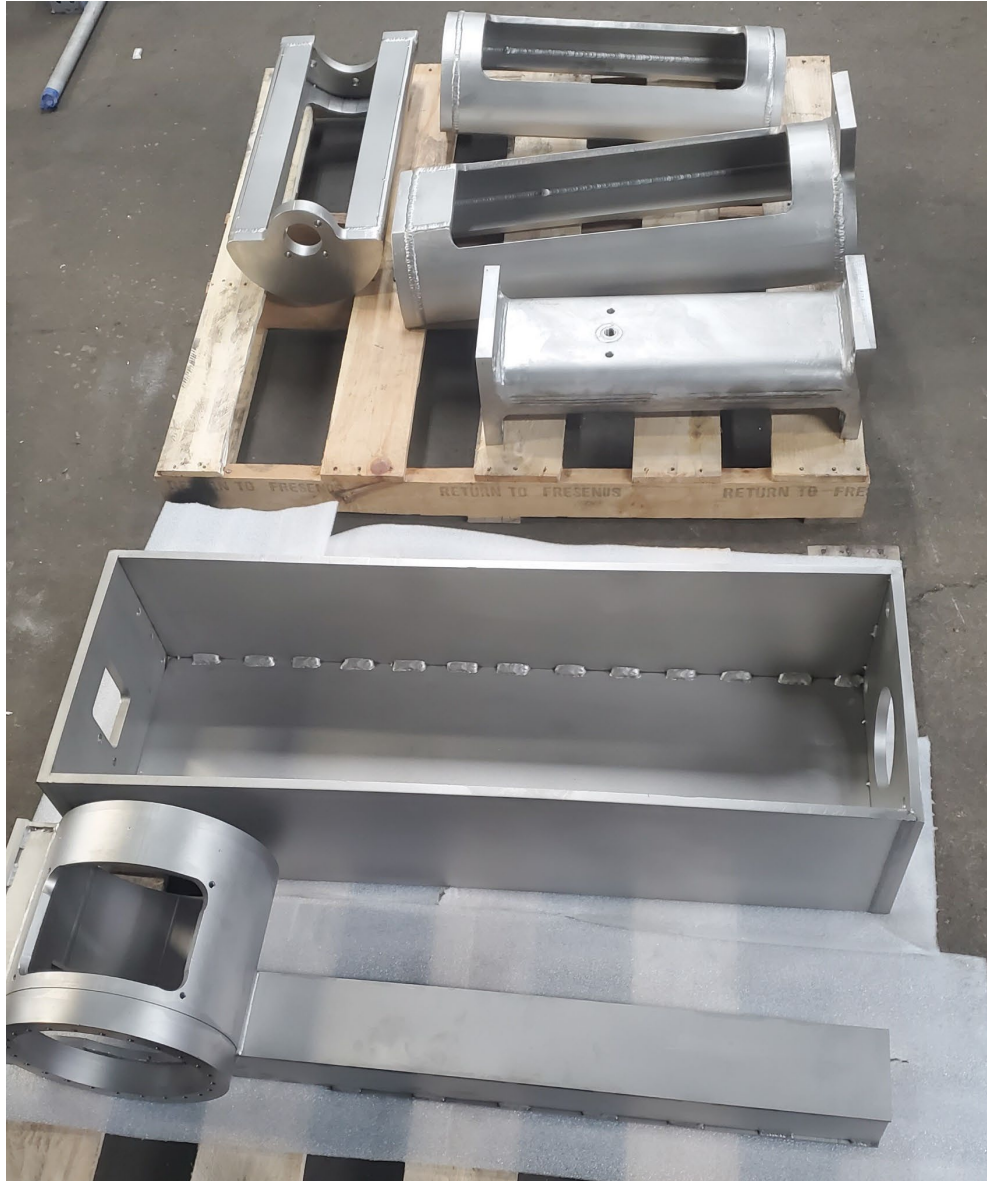


Figure 5: External support structures following inspection at the manufacturer.

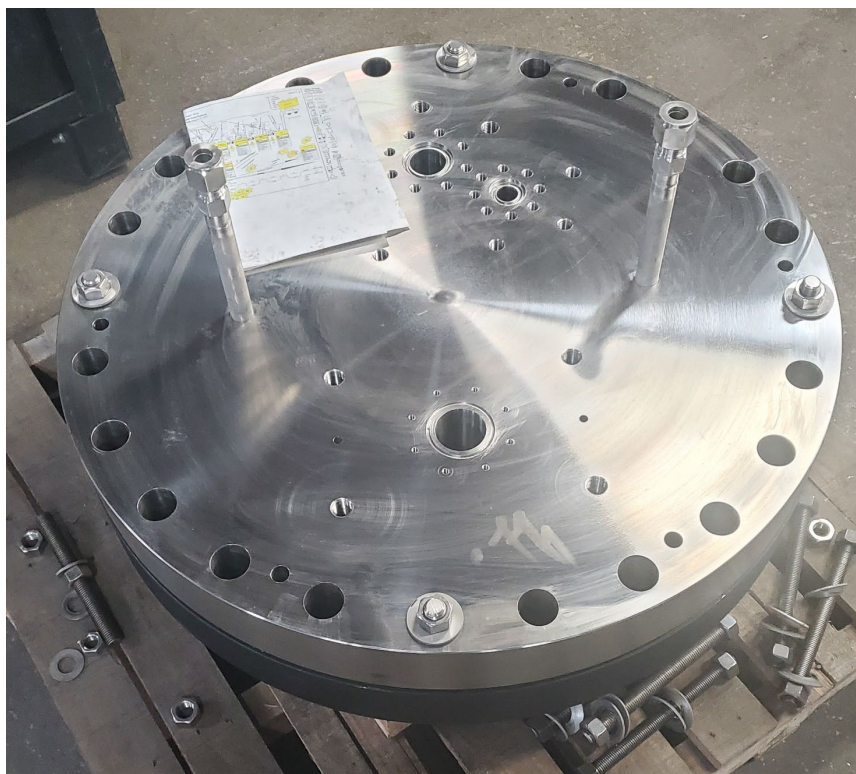


Figure 6: Main flange weldment following inspection and leak check at the manufacturer.



Figure 7: Submerged gearboxes, core socket, bearing support, and other components following inspection at the manufacturer.

3.2. Parker Drive System

The GrTA will have four independent drivetrains to perform the various functions included in the design. All four drivetrains will be powered using Parker rotary servomotors with planetary reduction gearboxes to output the torque required by each line. These systems were used on the GTA project, so the group has previous experience with their programming and operation. The main ball screw drive train and the two auxiliary drivetrains used to rotate the gripper post and actuate the jaws will use inline reduction gearboxes mounted to external gearboxes on support weldments. The load application line will use a rack and pinion system to translate the radial load output of the motors to a linear load output. All four systems have been sized, quoted, purchased, and received at ANL as of April 2023. The following figures show a number of the Parker components.



Figure 8: Parker Servomotors and reduction gearboxes for the main drive (top), rotation function (mid), and jaw actuation (bottom).



Figure 9: Parker servomotor and Stober pinion gearbox for load application.



Figure 10: Parker servomotor drives for all four motors.



Figure 11: Parker ACR motor controller used to coordinate motion between all four drivetrains.

3.3. Preliminary Bearing Assortment

The design of the GrTA uses nineteen different bearings types/sizes with a total of 89 bearings used in each assembly. Nine of the bearing types/sizes will be submerged in the sodium during operation. All of the bearings were selected to use standard bearing dimensions to aid in the procurement process. While the procurement of sodium compatible bearings is ongoing, a preliminary order of standard “off-the-shelf” bearings was made to allow for fit and function checks to be made prior to operation in sodium. The bearings were quoted and purchased at the end of calendar year 2022, and the order was delivered in February 2023. Figure 12 shows a collection of these bearings still in their original packaging.



Figure 12: Assortment of standard bearings to be used in preliminary commissioning in air.

3.4. Instrumentation and Control

Monitoring and control of the GrTA will be managed by a standalone workstation running a purpose built LabVIEW VI. A National Instruments cRIO-9047 with eight available card slots has been purchased and received. The currently available cards are an NI-9213 to read thermocouple data, an NI-9485 solid state relay card that can switch relays to isolate motor power, an NI-9025 voltage input card to read various instrument, an NI-9203 current input card to read instruments, and an NI-9265 current output card that can control variable instruments on the assembly. While the Parker servomotors provide torque outputs from

each system, an inline load cell with a 10,000lbf capacity was purchased from OMEGA to give better data on the load bring applied to the gripper head. Finally, an Inconel sheathed accelerometer was purchased from PCB Pizeotronics that can be submerged in the liquid sodium and has a maximum operating temperature of 650°C. This will be mounted to the submerged gearbox to monitor vibration and aid in detecting mechanical failures. This accelerometer was used in the GTA work and has performed well at temperature up to 250°C. Figure 13 shows the National Instruments cRIO with cards available for this work. Figure 14 shows the OMEGA load cell with corresponding transmitter. Figure 15 shows the high temperature sodium compatible accelerometer with corresponding transmitter.



Figure 13: National Instruments cRIO chassis with several available cards that will cover all needed input/output functions.

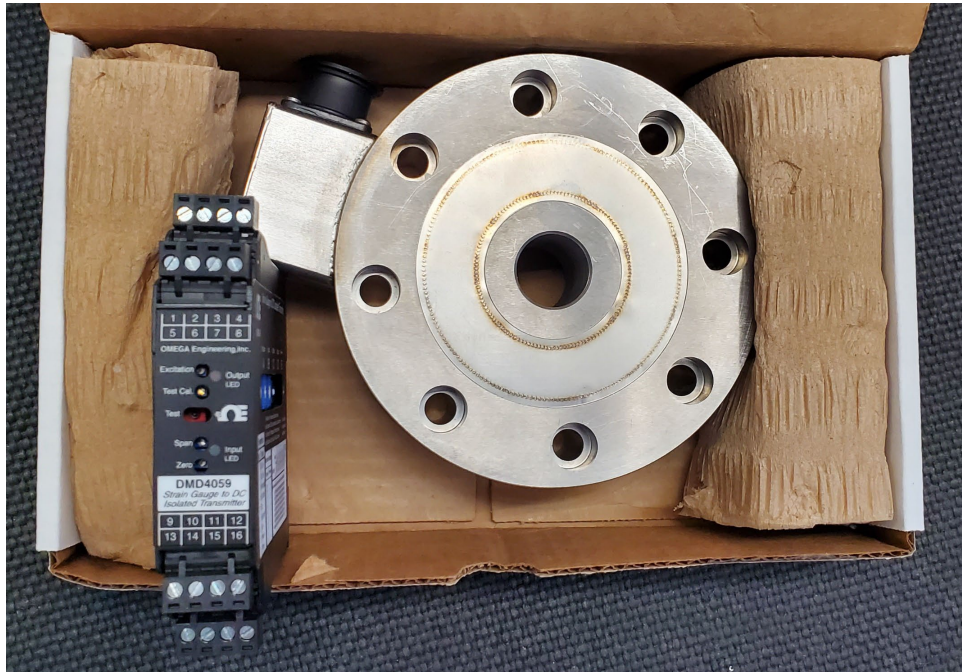


Figure 14: OMEGA load cell with 10,000 lbs capacity including with transmitter.

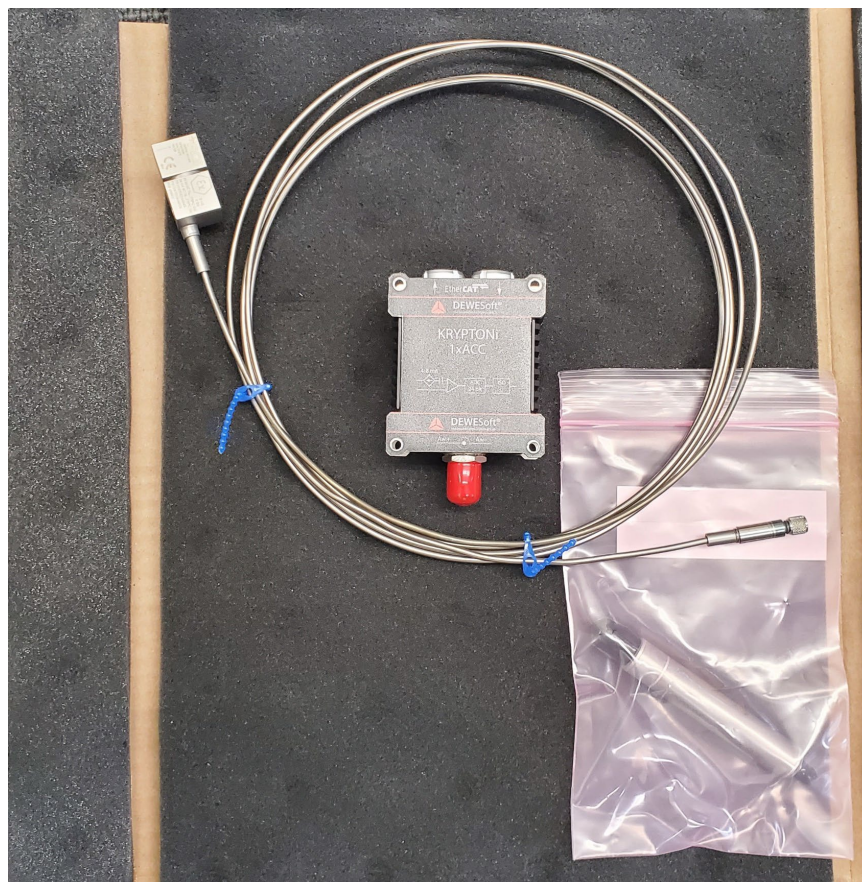


Figure 15: Inconel sheathed accelerometer with amplifier and transmitter.

4. Preliminary Assembly for Commissioning

With the bulk of the materials on hand, the preliminary assembly of the system was started in FY2023. Assembly was started on the sodium side of the flange to demonstrate the function of the sodium side components first. To begin, the flange was mounted to one of the 28-inch Test Stands and the orientation was adjusted so the bottom side of the flange was facing up. Next the welded support column was fastened to the flange and the first section of the submerged gearbox was fastened to the support column. Figure 16 shows a model view of the sodium side assembly for reference. Figure 17 shows the beginning of the assembly of the sodium side.

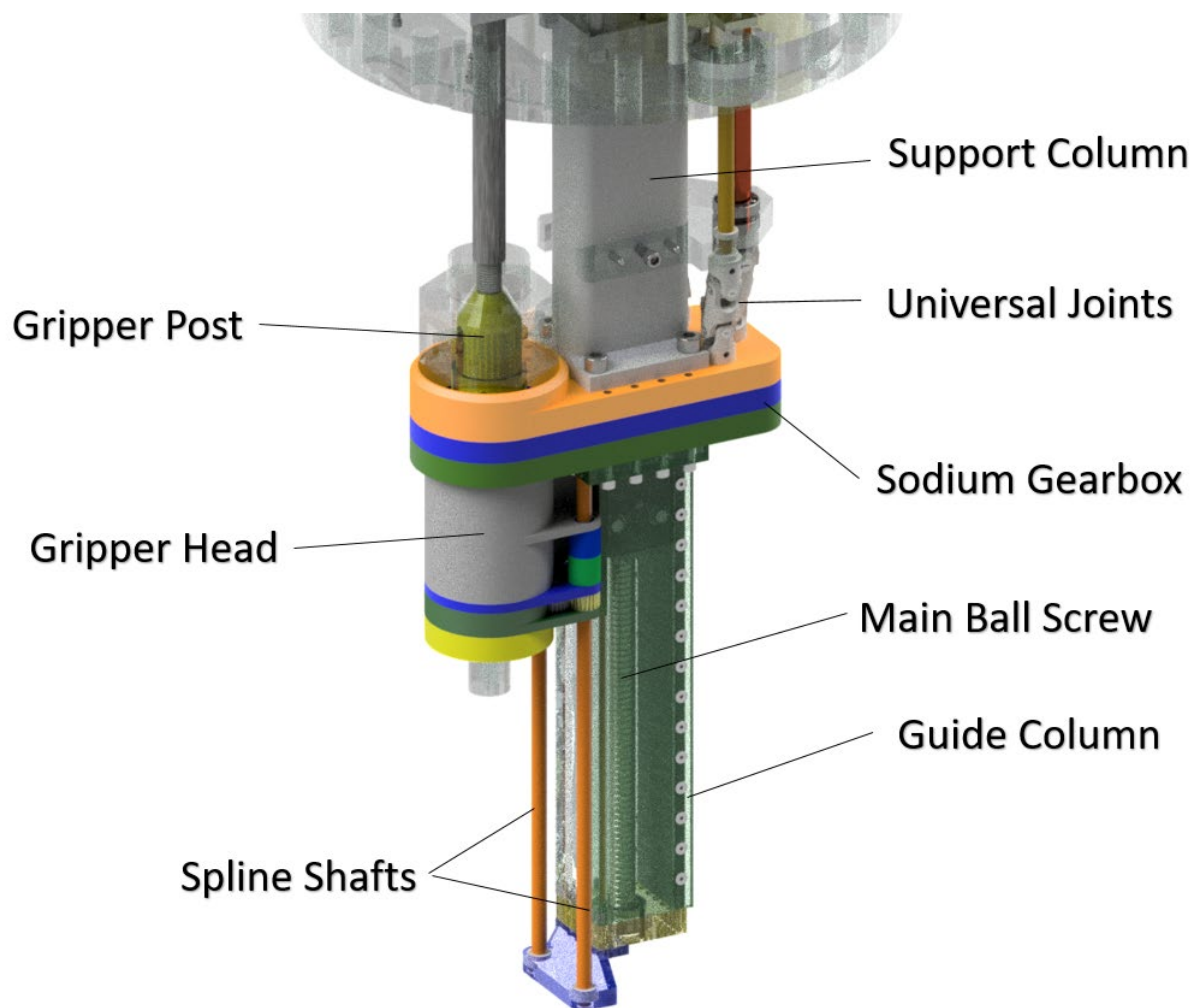


Figure 16: Overview of the sodium side assembly.

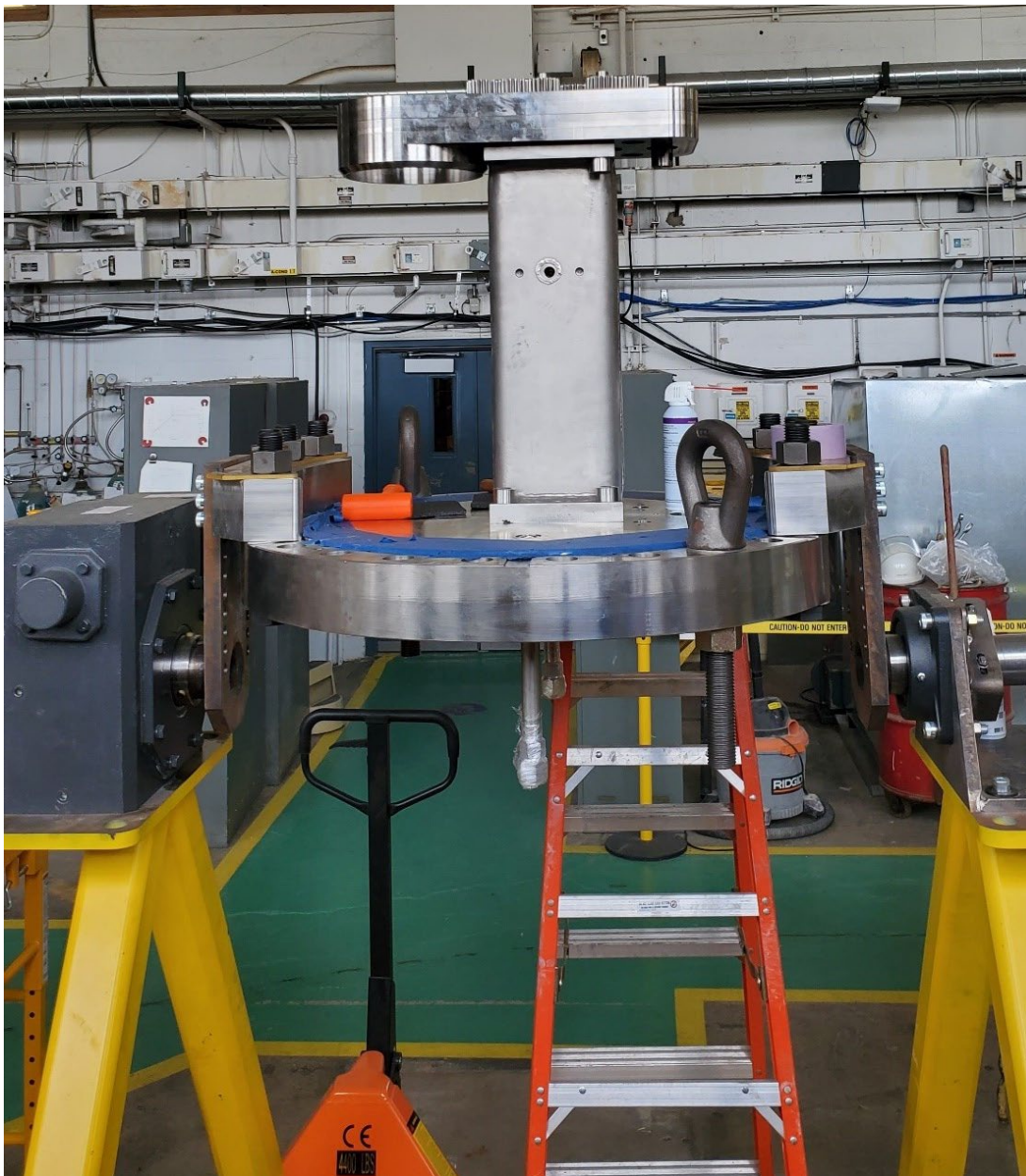


Figure 17: Main flange mounted to the vessel stand, with the support column and gearbox assembly.

A manufacturing issue became clear at this point that required a minor redesign. The welded support column was not aligning with all the holes in the flange and support gearbox. This likely was the result of warping of the components due to the required welding, and as this column aligns all the sodium side components with the air side components a new column was needed. To avoid the warping that occurs during welding, the new column was designed to use multiple components that are fastened together. Figure 18 is a comparison of the designs of the original welded support column and the new fastened support column.

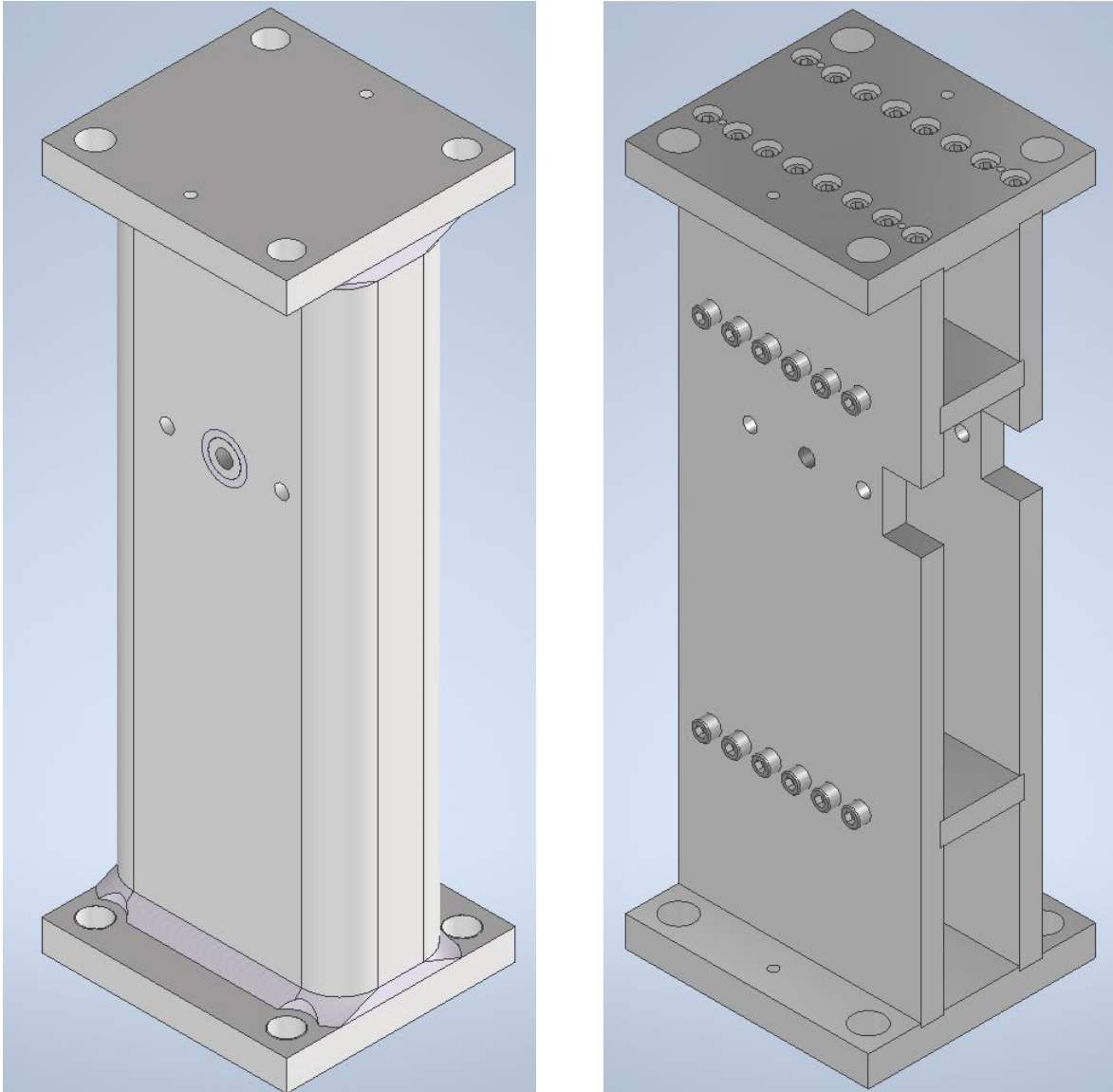


Figure 18: Welded support column (left) and new fastened support column (right).

While the fabrication of the fastened support column was underway, the gripper head components were assembled on a benchtop to assess fit and tolerances. The gripper head houses several bearings, gears, both spline nuts, the gripper post, and the smaller ball screw. All these components have tight fits and often required some minor sanding and refinishing to allow for assembly. Additionally, bearings and dowel pins were sometimes frozen using a freezer and spray to give enough clearance for the required tight fits. Figure 19 shows the gripper head as delivered from the fabricator. Figure 20 shows two of the gripper head gearbox plates during installation of the bearings. Figure 21 shows the gripper post during bearing installation, along with the gripper jaws prior to installation. Figure 22 shows a nearly complete assembly of the gripper head, not including the gripper post.

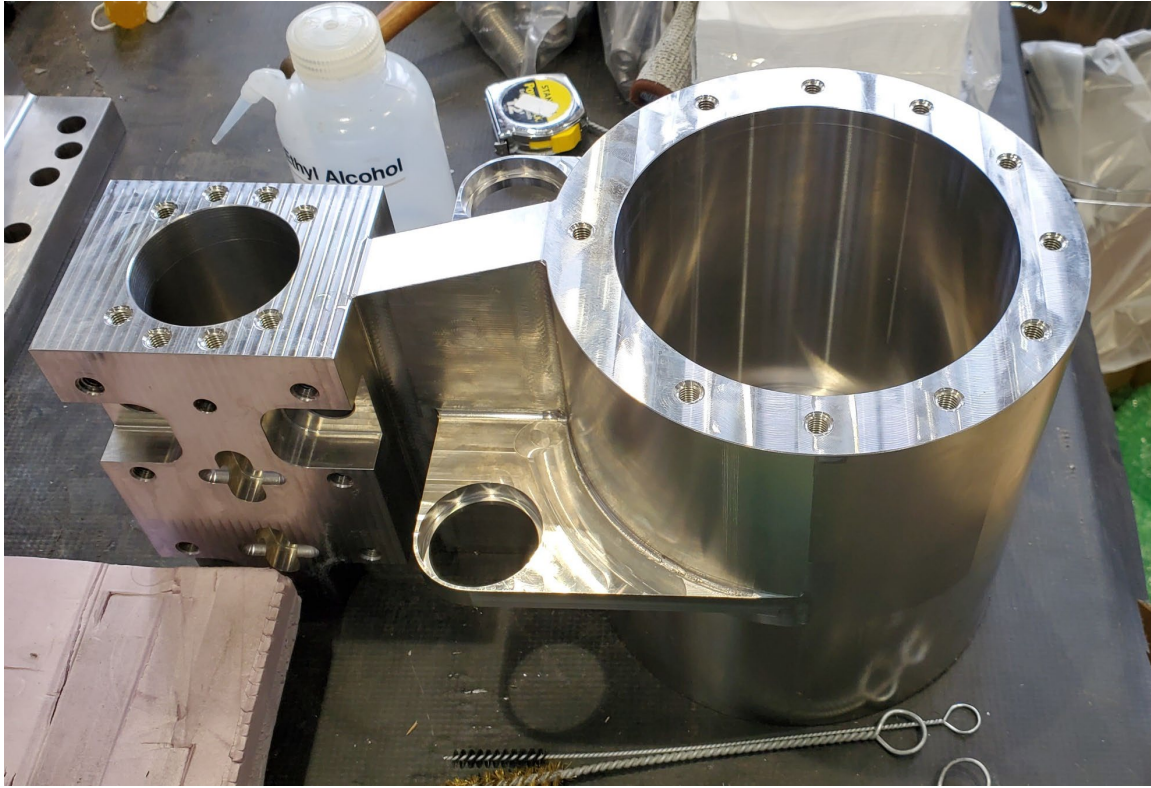


Figure 19: Gripper head with no installed components.

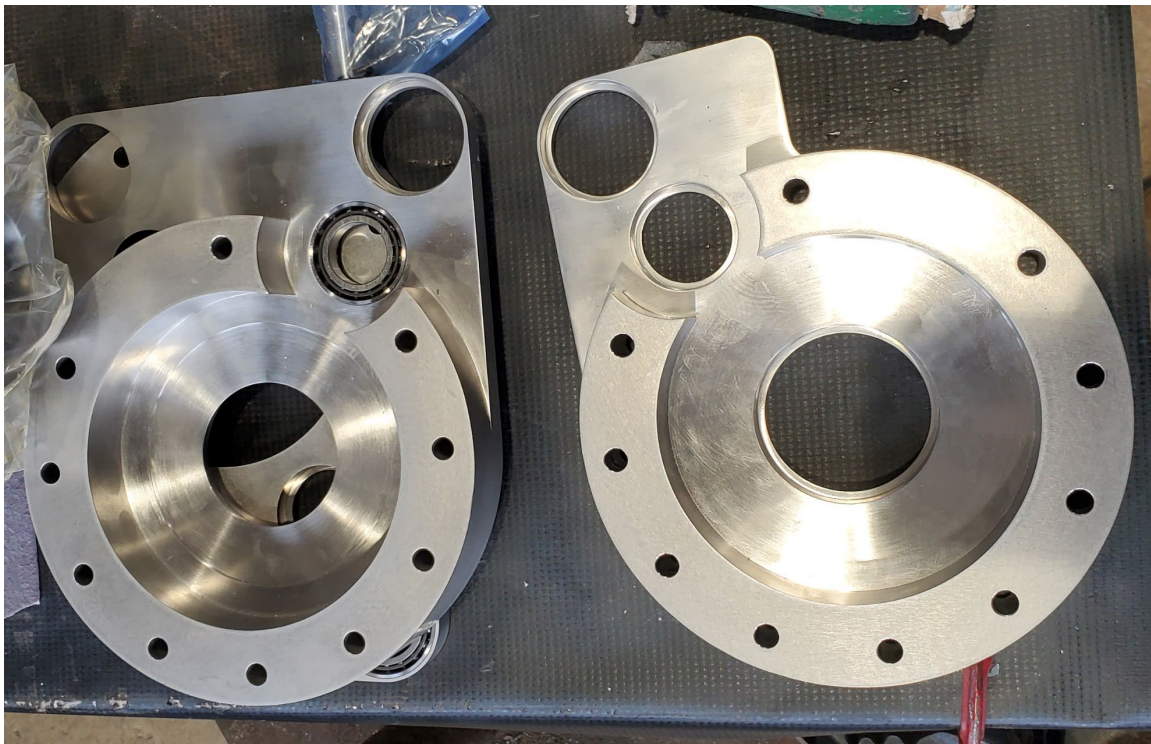


Figure 20: Two of three gripper head gearboxes with bearing install started.



Figure 21: Gripper post with bearing installed and other gripper head components during fit check prior to assembly.



Figure 22: Gripper head with fully assembled gearboxes following fit check.

Following the preliminary benchtop assembly of the gripper head, assembly efforts were moved back to the flange using the original support column as a base. This was due to the lack of benchtop space and support for the assembly of the main gearboxes. Assembly proceeded with the installation of the main sodium gearbox plates on the welded support column. The main sodium gearbox houses several bearings, three gear trains, the main ball screw support, and both spline shaft supports for the GrTA. This section again required some minor sanding/filing/refinishing of the various components to allow for proper assembly and function. Once fully assembled, each gear train was able to rotate freely so the assembly efforts moved forward. Figure 23 shows the fully assembled sodium gearbox mounted to the welded support column.

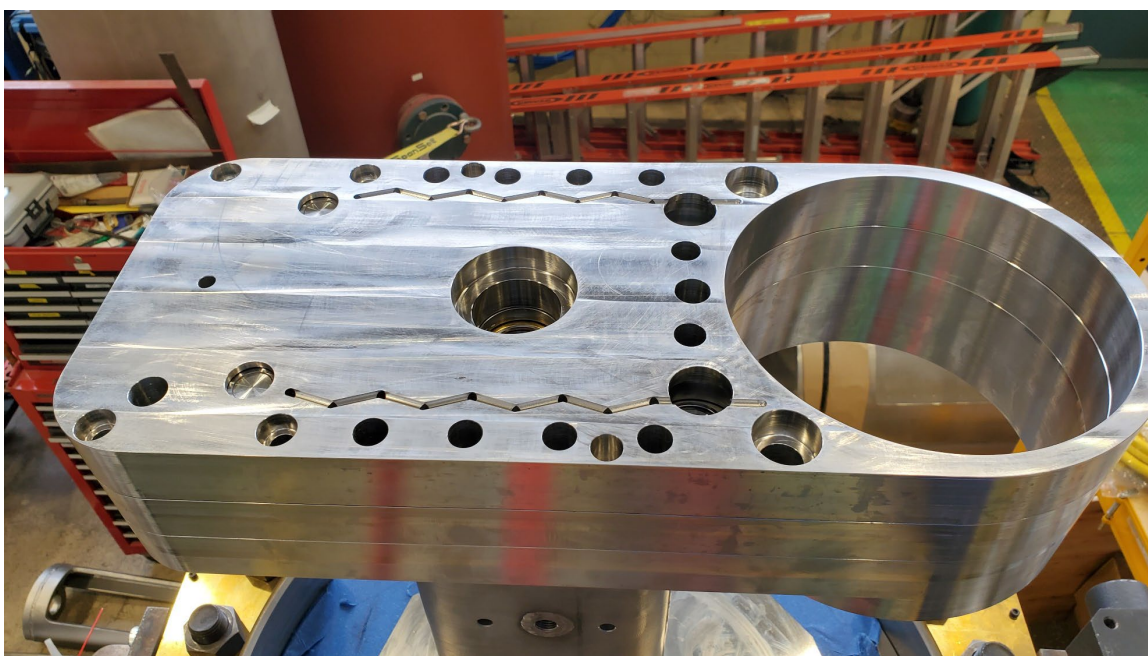


Figure 23: Fully assembled sodium gearbox on the original welded support column.

Following the assembly of the sodium gearbox, the gripper head guide column was assembled on the benchtop then installed on the sodium gearbox. With the guide column in place, the gripper head could be installed in the guide. The gripper head is supported in the guide column using several roller bearings that allow for the head to translate axially within the column. The movement of the head is controlled using the main ball screw. Figure 24 shows the guide column assembled on the benchtop prior to installation on the gearbox. Figure 25 shows the gripper head being installed in the guide column using the overhead crane. Figure 26 shows the gripper post being installed in the gripper head using the overhead crane. Figure 27 shows the nearly complete assembly of the gripper assembly prior to functional check.

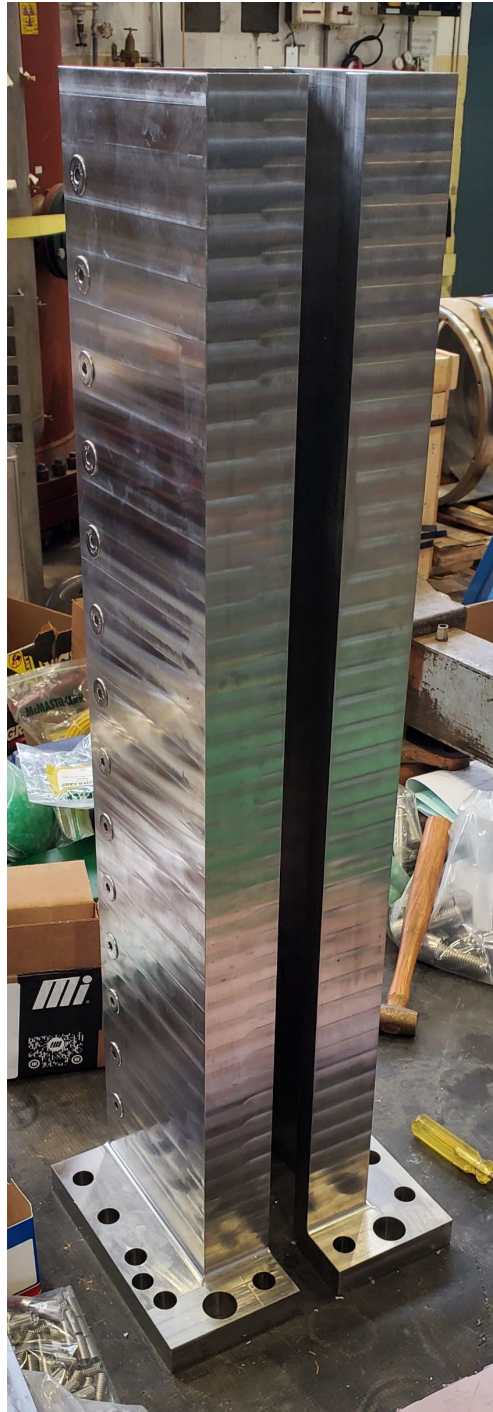


Figure 24: Guide column for the gripper head during benchtop assembly.



Figure 25: Installation of the gripper head in the guide column fastened to the sodium gearbox.



Figure 26: Installation of the gripper post in the gripper head.



Figure 27: Sodium side assembly prior to function check.

Following the completion of the gripper assembly, each of the three primary functions were checked. Rotating the main ball screw successfully moved the gripper head axially inside the guide column with negligible interference. The gripper post was successfully rotated using one of the auxiliary drive lines that rotates the corresponding spline shaft. Finally, the jaws were successfully actuated, both in a locked and unlocked position, using the second auxiliary drive line.

At this point the fabrication of the fastened support column was complete, so the system was disassembled then reassembled to incorporate this new component. The fastened support column exhibited a much better fit to both the main flange and the sodium gearbox. All assemblies and testing moving forward will use this fastened support column. Figure 28 shows the new fastened support column installed on the main flange. Figure 29 shows a nearly complete gripper assembly mounted on the new support column.



Figure 28: Fastened support column installed on the main flange.



Figure 29: Reassembled sodium side with the new fastened support column.

All three primary functions were successfully tested following the reassembly, so the assembly efforts could progress to the air side. This required that the vessel stand rotate the assembly 180° so the top face of the flange faced upwards. The mounted position of the flange on the vessel stand was first rotated 90° such that the support column was in the best orientation to support the load of the sodium side assembly as the

vessel stand rotated the whole assembly. The gripper assembly is well balanced, and this allowed for it to be picked as a whole using the overhead crane instead of fully disassembling it to perform this flange reorientation. Once the flange was rotated 90° on the vessel stand, the gripper assembly was reinstalled on the support column and the entire assembly was flipped 180° to put the GrTA in its proper orientation. Figure 30 shows the gripper assembly being installed back onto the support column using the overhead crane after rotating the flange 90°. Figure 31 shows the entire assembly in the new orientation prior to the 180° flip. Figure 32 shows the assembly halfway through the flip. Figure 33 shows the GrTA in the current orientation, with the top face of the flange facing upwards.



Figure 30: Gripper assembly being placed back on the support column after rotating the flange 90° on the mounts.



Figure 31: Assembly prior to rotation.

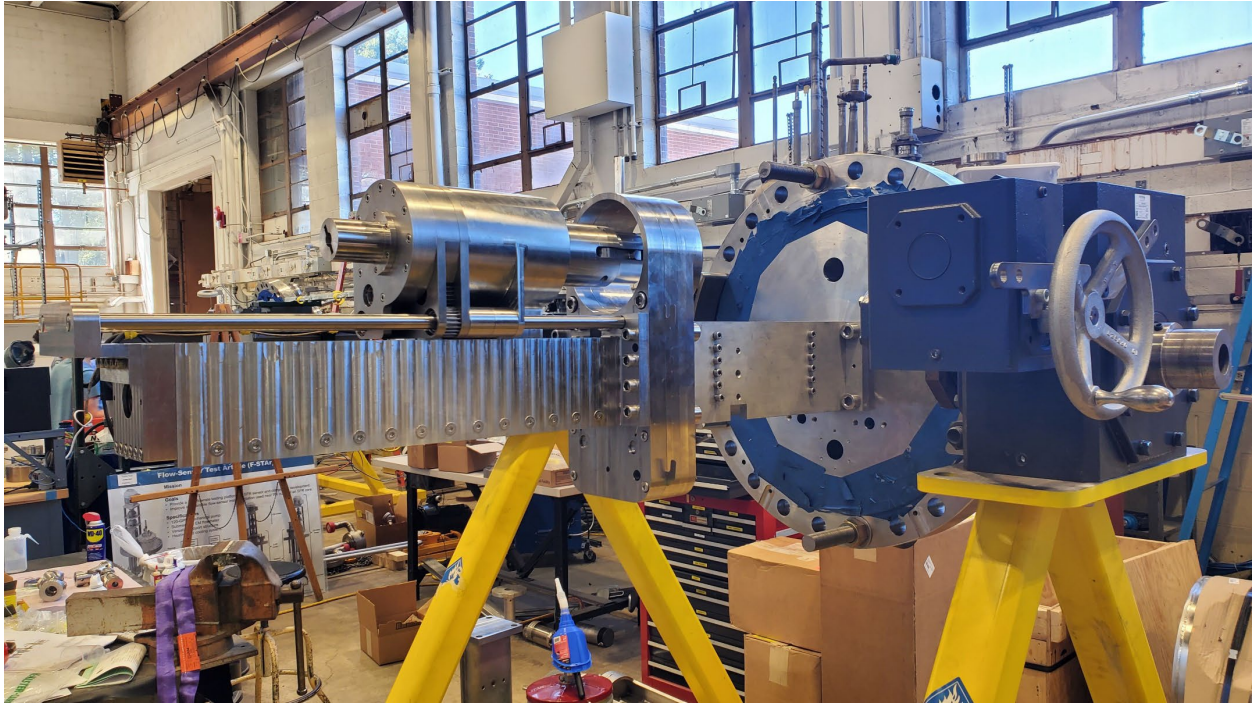


Figure 32: Assembly during rotation.



Figure 33: Assembly after rotation, now in normal orientation

With the assembly in this new orientation, component installation could progress towards the air side of the GrTA. The universal joints were installed on their respected gear shafts, and the drive shafts that extend to the air side were installed on the other side of the joints. Then the welded standoffs that support the external gearboxes and Parker motors were installed on the top of the flange. The current status of the assembly work involves fitting the gears/bearings/shafts of the external gearbox assemblies, as well as the load application components. Once this is complete, the parker motors can be installed and preliminary testing in air can commence. Figure 34 shows the completed installation of the universal joints. Figure 35 shows the installation of the upper welded standoff and the beginning of the gearbox installation. Figure 36 shows the various gearbox plates, gears, and bearings that are being fitted for the external gearbox assembly. Figure 37 and Figure 38 show the test fitting of the external graphite shaft seals.



Figure 34: installation of drive shafts and universal joints.



Figure 35: Installation of upper support weldments.



Figure 36: Preparation of external gearboxes.



Figure 37: Preparation of auxiliary drive graphite shaft seals.

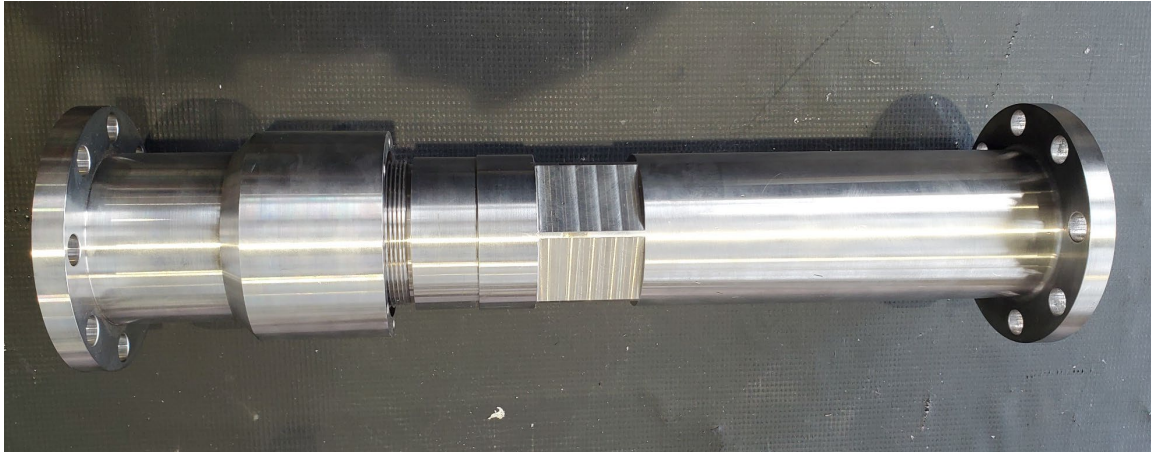


Figure 38: Preparation of main drive graphite shaft seals.

5. Function Check

As mentioned in the previous section, the function of the GrTA sodium side was checked after the preliminary assembly. The axial translation of the gripper head inside the guide column using the main ball screw and drive train was successfully checked with the gripper head under no load. The rotations of the gripper post inside within the gripper head by rotating one spline shaft on an auxiliary gear train was successfully check under no load as well. Finally, the extension and retraction of the gripper jaws within the gripper post by rotating the second spline shaft on an auxiliary gear train was successfully completed as well. The following figures display each of the functions over their full range of motion.



Figure 39: Demonstration of the axial movement of the gripper head.

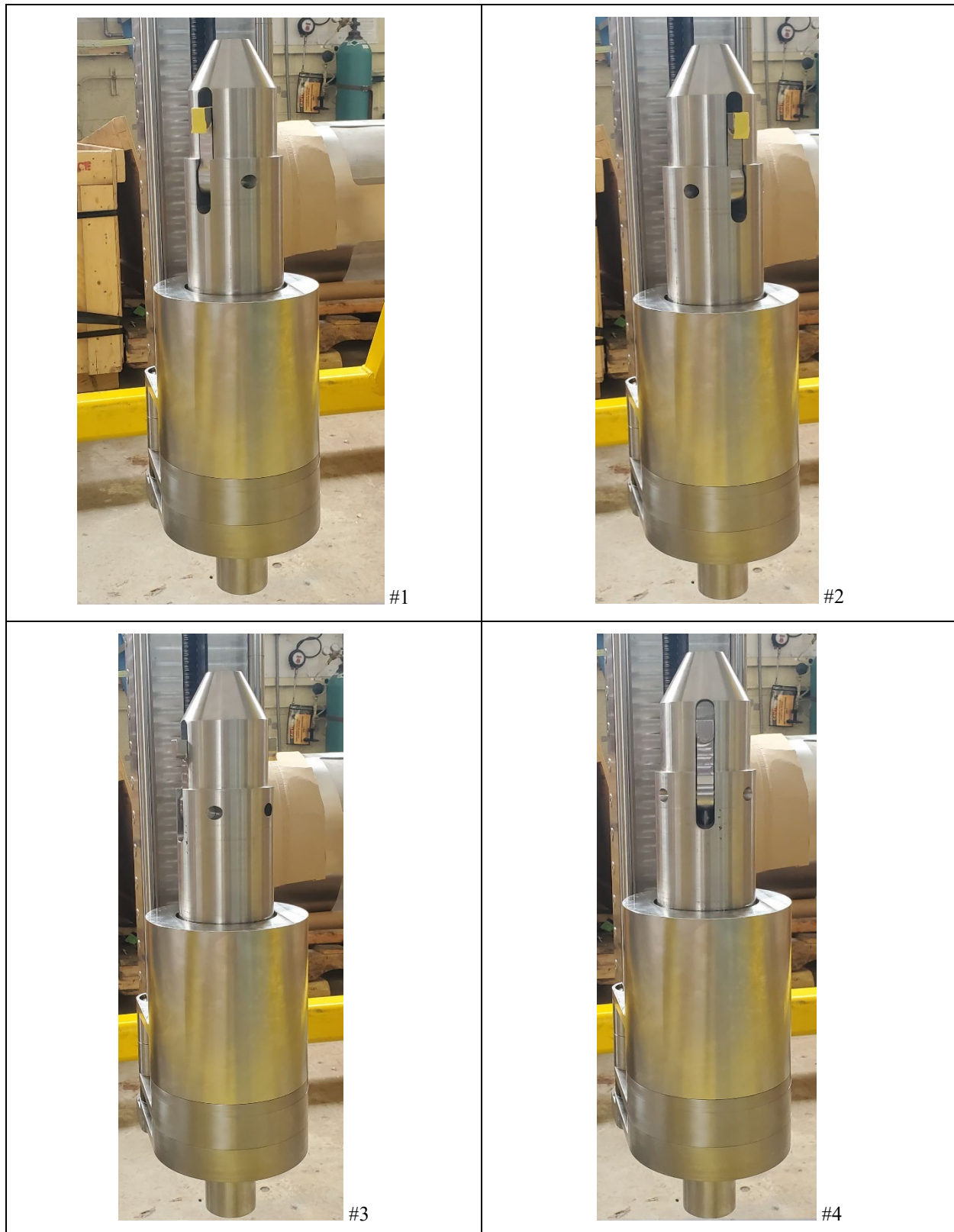


Figure 40: Demonstration of the rotation of the gripper post. Gripper post is rotating counter clockwise. Images are numbered in order.

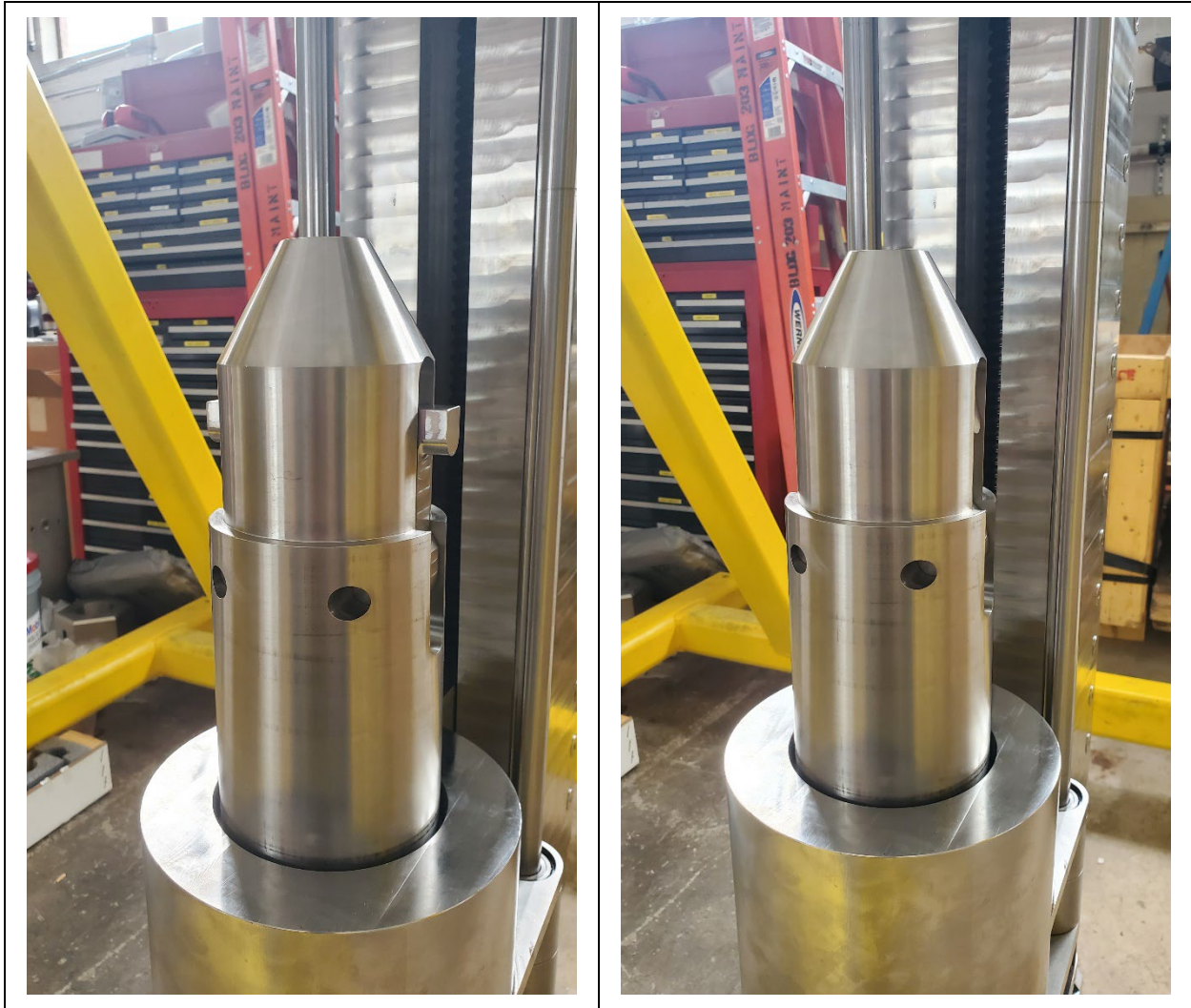


Figure 41: Demonstration of the extension (left) and retraction (right) of the gripper jaws.

6. Path Forward

6.1. Assembly

We will continue to assemble the air side of the GrTA to complete the fit/tolerance checkout of the whole system. The upper gearboxes will be assembled to allow for the gripper functions to be driven by the Parker servomotors. Then the load application side of the air assembly will be built to test the rack and pinion system that will apply a variable load to the simulated core socket. Once all components are fitted and each of the primary functions can be driven using the Parker motors, the various instruments will be installed and tested for function. Then final programming can be completed prior to sodium operations.

6.2. Sodium Ball Screws

The ball screws currently installed in the GrTA have polymer components or coated components that will not survive the high temperature liquid sodium environment, so compatible models are still needed. A

preliminary set has been purchased that will be fabricated in alloy steel and not include any polymers or coatings that are typically used in these systems. A second more robust system has also been purchased that will include an Inconel screw, Stellite bearing balls, and a stainless steel nut. This system has a significant lead time so the first in sodium test may use the alloy steel versions. Additionally, the smaller ball screw that is used in the jaw actuation may be changed to an ACME nut/screw as the loads are relatively low and the manufacture and operation of a custom ACME screw system in advanced materials is simpler.

6.3. Sodium Spline Shafts

The spline shafts currently installed in the GrTA also use polymers and coatings that are not compatible with liquid sodium. We have purchased a set in alloy and stainless steel that should be able to survive the harsh environment. An alternative path is also being pursued where a custom spline nut with no moving parts will be cut from Inconel or some other compatible material that will replace the reciprocating ball spline nut.

6.4. Sodium Bearings.

Sodium bearing procurement has been a difficult process, as previously experienced in the Gear Test Assembly project. We have identified three of the nine sodium bearing types that will experience the greatest load and set them as priority for fabrication in advance materials. We are in contact with several manufacturers regarding this project, but we are still waiting for the initial quotes. An alternative approach to meet the need for these sodium bearings is to disassemble the off-the-shelf bearings and reassemble them in full-complement form where the cage is removed. The cage material of roller bearings is often made of sheet metal, brass, or some polymer that are not compatible with the liquid sodium. By removing the cage, all that is left is the bearing steel races and balls/rollers. This material is compatible with the sodium, but does soften at high temperatures. Many of the bearings in the GrTA are under minimal load, and this full-complement approach will likely be sufficient. For the higher load bearings, the current alternative approach would be to again remove the cage of the off-the-shelf bearing and install balls/rollers in harder materials. It is easier to buy bearing balls and rollers alone than it is to buy full bearing assemblies. In addition to adding the harder balls/rollers, we may attempt to heat treat the off-the-shelf races. DOE has also has awarded at least two SBIR contracts with vendors to develop bearings suitable for sodium applications.

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