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Physical Property Measurements for Symmetric Projectiles

by William P. Aubry, Matthew D. Krassenstein II, Christopher Mermagen, and Paul Weinacht

NOTICES

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14. ABSTRACT
Projectile physical properties such as mass, center-of-gravity location, and axial and transverse moments of inertia are required to perform flight analyses and experimental aerodynamic data reduction. This report documents the theory and processes used at the experimental facilities within the DEVCOM Army Research Laboratory’s Flight Sciences Branch to obtain measurements of the “as-manufactured” physical properties of projectiles. Because of the wide range of sizes and weights of small-caliber through large-caliber projectiles, different processes and measurement machines are used depending on projectile size. Details of the various measurement processes and procedures are provided here to guide users to obtain consistent and accurate projectile physical property measurements.

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1. Introduction

Flight dynamics analyses and experiments for symmetric projectiles require projectile physical properties such as the mass and axial and transverse moments of inertia (MOIs) to be determined. Measured values of these quantities have traditionally been obtained prior to flight test to define the "as-manufactured" physical properties. Modern computer-aided design (CAD) packages can also provide reasonable estimates of these properties provided the drawings are accurate and the material properties are properly selected.

There are several physical property measurement machines located at the U.S. Army Combat Capabilities Development Command Army Research Laboratory's Flight Sciences Branch Transonic Experimental Facility (TEF). These machines support the physical measurements at the TEF and the Flight Sciences Branch Aerodynamics Experimental Facility (AEF). There are two types of physical measurement machines that primarily measure either the center of gravity (CG) or the MOI. For each type of measurement machine, there are various "size" machines tailored to a particular range of projectile weights and sizes. The CG measurement machines use a "moment scale," incorporating high-sensitivity force transducers to measure the mass and CG location of a part or assembly. The MOI machines use a torsion pendulum that oscillates about a fixed axis. The MOI measurement of a part is based on the change in natural frequency of the torsion pendulum produced by the part addition. The longitudinal axis of the projectile can be oriented along the axis of the torsion pendulum to obtain the axial MOI. The longitudinal axis of the projectile can be oriented perpendicular to the axis of the torsion pendulum to obtain the transverse MOI.

Whether measuring physical properties of small- or large-caliber projectiles, the process is similar except for one fundamental difference. For small-caliber projectiles, when obtaining the axial or transverse MOI, a single measured MOI is obtained for the measurement in the axial or transverse orientations. For the measurement of the axial MOI, the projectile is assumed to be rotationally symmetric. With the longitudinal axis of the projectile aligned with the axis of rotation of torsion pendulum, the measured axial MOI represents the axial MOI of the projectile. For the measurement of the transverse MOI for small-caliber projectiles, the projectile's longitudinal axis is oriented perpendicular to the axis of rotation of the torsion pendulum. The projectile's CG is not necessarily aligned with the axis of rotation of the torsion pendulum. (It is helpful to minimize the offset of the CG from the axis of rotation of the torsion pendulum. However, the amount of offset depends on the measurement fixture design. A separate fixture that aligns the axis of rotation with the CG may not be required. Additionally, CG location variations may exist between projectiles within the same projectile type and manufacturing lot; thus, it is unlikely that the longitudinal location of the CG will always be aligned with the axis of rotation.) If the CG is not aligned with the axis of rotation of the torsion pendulum, the measured transverse MOI is then corrected to obtain the transverse MOI about the CG using the parallel axis theorem.

$$I_t|_{cg} = I_t|_{measured} - m\Delta_{CG}^2$$

Here, $I_t|_{cg}$ is the transverse MOI about the CG, $I_t|_{measured}$ is the measured transverse MOI, m is the projectile mass, and Δ_{CG} is the perpendicular distance between the axis of rotation and the CG. The location of the projectile CG is obtained independently using the CG measurement machine. The perpendicular distance between the axis of rotation and the CG is determined by the fixture dimensions.

For MOI measurements of large-caliber projectiles, a series of MOI measurements is made to obtain the projectile's axial or transverse MOI. To obtain the transverse MOI, the projectile's longitudinal axis is aligned perpendicularly to the axis of rotation of the torsional pendulum. A series of MOI measurements is made with the CG displaced at varying distances relative to the axis of rotation of the torsional pendulum. The CG displacements are selected so that there is a mix of CG locations forward and aft of the axis of rotation of the torsional pendulum—typically, around a rough estimate CG measured using a knife's edge or other balancing hardware. Since the CG location may or may not be known prior to the measurements, the displacements of the projectile relative to the axis of rotation of the torsional pendulum are measured relative to a particular location on the projectile such as the projectile base. According to the parallel axis theorem, the measured MOI should vary quadratically with the perpendicular distance between the CG and the axis of rotation of the torsional pendulum as shown below.

$$I_t|_{measured} = I_t|_{cg} + m\Delta_{CG}^2$$

A quadratic curve fit of measured MOIs versus axial locations is then made. The minimum MOI from the curve fit represents the transverse MOI at the CG. The axial location of the minimum MOI is the CG location. Note that the location of the CG could also be determined independently by using the CG measurement machines (e.g., CG-C); however, this alternative procedure is not typically used.

For the measurement of the axial MOI for large-caliber projectiles, two approaches have been used. The first approach is identical to the approach used for small-caliber projectiles. The projectile's longitudinal axis is aligned with the axis of rotation of the torsion pendulum and a single measurement of the MOI is made. The measured MOI is the axial MOI of the projectile about the CG, provided the projectile is rotationally symmetric.

Alternatively, an approach like that used for the transverse MOI of large-caliber projectiles can be applied for the axial MOI. With the projectile's longitudinal axis aligned parallel to the axis of rotation of the torsion pendulum, a series of MOI measurements are made with the CG displaced at varying distances relative to the axis of rotation of the torsional pendulum. The CG locations are selected so that there is a mix of CG locations on either side of the axis of rotation of the torsional pendulum, typically revolving around an estimate of the centerline longitudinal axis. The measured MOI should vary quadratically with perpendicular distance between the CG and the axis of rotation of the torsional pendulum.

$$I_x|_{measured} = I_x|_{cg} + m\Delta_{CG}^2$$

A quadratic curve fit of measured MOIs versus the perpendicular distance relative to the axis of rotation of the torsional pendulum is then made. The minimum MOI from the curve fit represents the axial MOI at the CG. The axial location of the minimum MOI is the CG location. This approach is preferred for large-caliber axial MOI measurements since multiple measurements may improve the accuracy of the measurements. However, examination of the experimental data obtained using both methods showed good consistency between both approaches. Obtaining multiple MOI measurements at various displacements can also identify radial CG offsets and may be required if the projectile has mass offsets from the axis of geometry symmetry.

Although the basic measurement techniques have not changed for several decades, some of the hardware and software used for physical measurements have changed or been upgraded. Additionally, personnel with expertise in physical measurement have departed. This report documents the current process used to obtain the projectile's physical properties and transfers the current knowledge base to future generations of aeroballisticians. A review of the existing measurement hardware and software along with their technical manuals is presented first. The Flight Sciences Branch maintains a central repository of physical measurement data and workbook templates, which are used to process and store the physical measurement data. Finally, the measurement process is discussed. The measurement process has evolved into two classes of measurements: one for small-caliber projectiles and one for medium- to large-caliber projectiles. The need for two processes is based on available equipment and practical considerations resulting from the physical size differences between these types of projectiles. The measurement process for these two classes of projectiles is discussed in two separate sections.

Generally, projectiles weighing less than 200 g are measured with the small-caliber measurement approach, which is driven by the capacity of the available measurement hardware. Projectiles larger than 200 g are measured with the medium- to large-caliber approach.

2. Measurement Hardware

In the past 20 years, there have been upgrades to the Physical Property Measurement infrastructure at the TEF and AEF. In the FY10–11 timeframe, the small-caliber CG and MOI measurement machines were refurbished or replaced. The new MOI machine provides measurement capability for a range of projectile sizes that were previously covered by multiple machines. In FY21, the computer and controller were upgraded. All physical measurement machines can now be controlled with a single controller and computer. The computer upgrade included updating the software (from a DOS-PC–based computer to a current generation Windows-based computer).

There are currently two operational CG measurement machines available (Table 1). The legacy BRL-A CG and BRL-B CG machines are out of service and are stored in the shelves below the physical measurement machine table. The new small-caliber CG machine is capable of measuring projectiles up to masses approaching 300 g (including the fixture), which covers the range of small-caliber and some medium-caliber projectiles. CG measurements of large-caliber projectiles can be measured using the BRL-C CG machine. CG measurements for large projectiles can also be determined using the MOI machines by applying the parallel axis theorem as discussed above.

Table 1. CG measurement machines.

CG measurement machines	Capacity	Model no.	Comments	Barcode	Serial no.
New small-cal. CG machine (BRL-A CG [New])	Label indicates 300-g capacity.	SE300-HS	NA	1294K	20590
BRL-A CG	0–5 lb (small cal.)	CG-A	Out of service	None	8216
BRL-B CG	0–30 lb (40 mm)	CG-B	Out of service	None	8215
BRL-C CG	<300 lb	CG-C	NA	None	8214

There are currently five operational MOI machines (Table 2). The new MOI-AAA machine replaced the older MOI-AAA machine in the FY10–11 timeframe. The new MOI-AAA machine covers the range of the older MOI-AA and MOI-AAA machines (although the MOI-AA still appears to be operational). The new MOI-

AAA machine has a label indicating that the maximum projectile weight is 200 g. (For reference, a typical 7.62-mm projectile is 9.5 g. Many 40-mm projectiles are above the 200-g threshold.)

Table 2. MOI measurement machines.

MOI measurement machines	Capacity (part plus fixture)	Model no.	Comments	Barcode	Serial no.
MOI-C	Large cal.	NKR 450A	NA	None	None
MOI-B	Medium cal.	NKR 40A-MOI B Also listed as NKR 40A-1401B	NA	None	8213
MOI-A	<5 lb	NKR 0.5A (MOI-A)	NA	None	8217
MOI-AA	Small cal.	No label on machine, but identified in software as XKR	Appears to be in-service but not used	None	None
MOI-AAA (Old)	Tiny: flechettes	XKL 0.5A	Appears that this unit was refurbished and returned as the MOI-AAA (new)	None	S8766
MOI-AAA (New)	Labeled with 200-g maximum weight	XKR05F-HS	NA	1293K	20588

The CG-A, MOI-AAA, and MOI-AA machines can all use the same measurement fixture, which allows the CG-A machine to be used in conjunction with either the MOI-AAA or MOI-AA machines. However, the MOI-A machine uses a different fixture than the CG-A.

A survey of projectile measurements over the past two decades indicates that small-caliber and 25-mm medium-caliber projectiles can be measured with the new MOI-AAA machine. This class of projectiles is below the 200-g threshold for the new MOI-AAA machine. Although some 40-mm projectiles may weigh less than 200 g, the MOI measurements for these projectiles tend to be made with the MOI-B machine. It seems possible to use the CG-A and MOI-A machines for projectiles in the 200–300 g range, but there is not much historical precedence for this application.

There is also a Multi-Machine Controller that provides the interface between the CG and MOI machines and a dedicated Windows-based computer that runs the software driving the CG and MOI machines. There are software modules on the dedicated computer that run the two CG machines and five MOI machines.

3. Manuals

Technical manuals for the various physical property machines can be found in the "Range Operations/Physical Properties Spreadsheet" folder on the Flight Sciences Branch share drive.

These manuals provide technical information but also focus on using these machines for general physical measurement. The manuals do not specifically address the process for measuring projectile physical properties. Additionally, some manuals are for similar models (but not necessarily identical) to DEVCOM Army Research Laboratory's machines; therefore, some of the technical details and specifications may differ. The new user should review this document for information on the physical property measurement for projectiles and refer to the instrument manuals for additional details if needed. See Table 3.

Table 3. Instrument manuals.

Manual file name	Manual title	Instrument
02 SE199 CG Instr Manual Rev TPK 8-11-10.pdf [a]	Instruction Manual Model SE199-02 Center of Gravity Instrument[1]	This manual is for a slightly different model (SE199-02) than ARL's new small-caliber CG measurement machine CG-A (SE300-HS)
CG Instr Manual SE199, SE300.pdf [b]	Instruction Manual Models: SE199-02, SE300 Center of Gravity Instrument[2]	Updated to include the SE300 model
10 Operator Manual.pdf	SE9601 WCG-200 Weight and CG Instrument Operator Manual[3]	May be for a unit similar to CG-C, but not exactly the same due to the age of the CG-C machine
GB550AX User Manual v2012.pdf	Model GB550AX Moment of Inertia Instrument Operating and Maintenance Manual[4]	May be for a unit similar to MOI-C, but not exactly the same due to the age of the MOI-C machine
SE9598A C# Software Instruction Manual.pdf	Moment of Inertia SE9598A Software Manual for XKR, XR & GB Instruments[5]	This is the manual for the software that runs the MOI machines
XKR02 XKR05 XKR1.pdf	Instruction Manual Models: XKR02, XKR05, XKR1 Moment of Inertia Instrument[6]	This is the manual for the MOI-AAA XKR05F-HS (and more). Manual says max part weight is 200 g.
XKR02A Rev B (OBS).pdf	Instruction Manual Model XKR02A Moment of Inertia Instrument[7]	This is specifically for the XKR02A, but we are uncertain which machine this is. Manual says max part weight is 90 g. Manual is very similar to XKR02 XKR05 XKR1.pdf.

[a] This manual is for a slightly different model (SE199) than used by ARL (SE300-HS). The instructions are generally applicable between the two types of machines; however, some details may be different (maximum part weight is 100 vs. 300 g for the SE199 and SE300HS machines, respectively). Calibration weights are a 3/8-inch-diameter spherical ball weighing 6.75 g vs. a 3/4-inch-diameter spherical ball weighing 54 g vs. for the SE199 and SE300HS machines, respectively. The weight scales the two machines use a 100-g cylindrical calibration weight vs. a 198.54-g cylindrical weight for the SE199 and SE300HS machines, respectively.
[b] This manual is updated to include both the SE199 and SE300 models. This model specifies the maximum part weights for both models: 100 vs. 300 g for the SE199 and SE300HS machines, respectively. It does not list the specifications for the calibration weights.

4. Data and Information Location

Much of the information on projectile physical property measurement is stored within the "Range Operations/Physical Properties Spreadsheet" folder in the Flight Sciences Branch network shared drive. In this folder, there is a set of subfolders (named by fiscal year), which contain prior physical property measurements for various projectiles. Physical properties for projectiles fired at both AEF and TEF are included here. Other folders are also included—many of which contain legacy information. There is a draft report,[8] which documents the available instrumentation circa 2008 prior to the upgrade.

5. Process of Measuring Physical Properties of Small-Caliber Projectiles

The physical properties measurement process is similar between small- and large-caliber projectiles. However, as discussed above, there is one significant difference in the measurement process between the two types of projectiles. The description presented here focuses on physical measurements for small-caliber projectiles.

5.1 Obtain a Measurement Fixture

Both the CG and MOI measurement machines use fixtures to secure the projectile while measurements are made. There are two different types of fixtures (Figure 1) for measuring the transverse and axial MOIs, which orient the projectile about the appropriate axis while the MOI is being measured. The transverse MOI fixture is also used to measure the CG location.

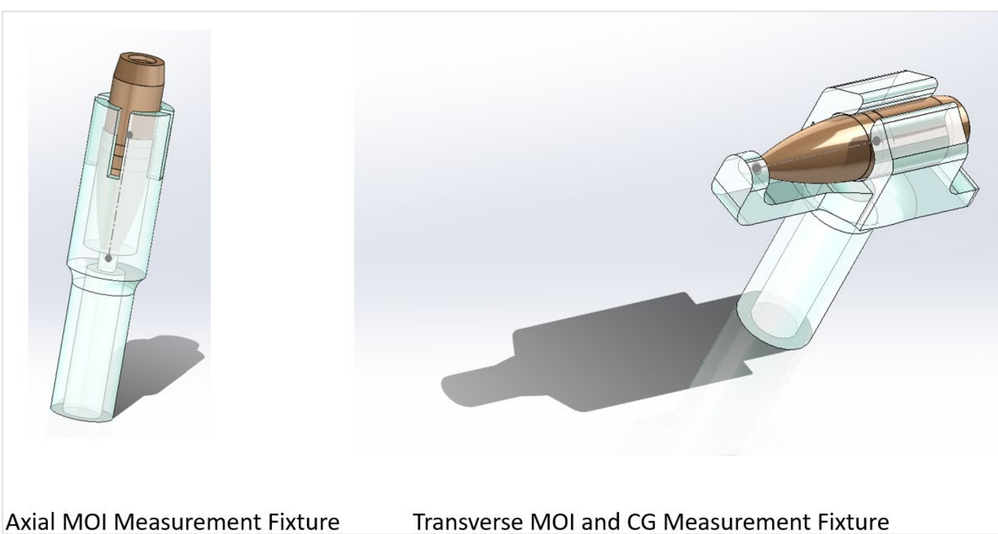


Figure 1. Examples of axial MOI (left) and transverse MOI/CG (right) measurement fixtures.

The key features of the fixtures are 1) the hollow stem used to connect the fixture to the shaft on the measurement machine and 2) the portion of the fixture that holds the projectile. During the measurement process, the fixture and projectile rotate about the centerline of the hollow stem and the MOI is measured about this axis.

Since the transverse MOI used in flight dynamics analyses is about the CG, it is desirable for the projectile CG to be located close to the centerline of the hollow stem (which is aligned with the MOI measurement machine axis of rotation). If the CG is not aligned with the centerline of the hollow stem, the measured MOI can be corrected to obtain the MOI about the CG using the parallel axis theorem. In Figure 1, the projectile is oriented with the nose touching the "stop" on the transverse MOI fixture. It is also possible to perform the measurement with the projectile base touching the "stop." In fact, it appears that many previous small-caliber projectile measurements were made with the base touching the "stop."

When designing a new fixture, it is desirable to locate the "stop" so that the projectile CG would be located close to the centerline of the hollow stem, although this is not an absolute requirement. It is likely that when existing fixtures were designed there was a "preferred" direction for the projectile to be oriented (either nose against the "stop" or the base against the "stop") so that the CG was close to the axis of rotation. Existing fixtures that have the CG offset from the centerline of the hollow stem can be used. If the CG location relative to the axis of rotation is not known, the CG machine can be used to determine the preferred orientation of the projectile nose or base relative to the "stop." Alternatively, two separate MOI measurements can be made with the projectile oriented with the nose and base against the stop. The smaller of the two MOI measurements will indicate which orientation has the CG closer to the axis of rotation. The minimum transverse MOI exists when the CG is aligned with the axis of rotation.

A critical dimension required for the transverse MOI correction is the distance from the stop to the centerline of the hollow stem/axis of rotation for the transverse MOI fixture. This dimension is input into the "Physical Property Measurement" Excel worksheet. This distance can be measured using the optical comparator at TEF. This distance may also be available from the SolidWorks model used to create the fixture; however, SolidWorks models for some of the older fixtures do not appear to be available. The Excel template for physical property measurements made with the new machines uses this measurement to correct the measured MOI for the CG offset. Be sure to use the template for the new machine, which contains the "Distance from Center to Stop" and the "Nose/Base" orientation inputs in the upper right-hand side of the sheet. Measurements prior to FY10–11 did not (apparently) include this data.

There is a box containing fixtures sized to various common projectile diameters. Typically, if the fixture secures the projectile properly, the fixture can be used. There is usually no need to create a new fixture for each projectile type of the same caliber (e.g., the same fixture could be used for 7.62-mm M80 or 7.62-mm M80A1).

If a fixture is not available for the particular projectile that is being measured, a fixture will have to be built. The current process is to create a SolidWorks CAD file of the fixture and use that model to obtain a fixture using rapid prototyping. Rapid prototyping is now available at AEF and TEF; however, it was found that resin-based rapid prototyping found elsewhere in the laboratory produced higher-quality parts. SolidWorks models of various fixtures are located in the “hardware for measurement” subfolder in the “Range Operations/Physical Properties Spreadsheet” folder on the Flight Sciences Branch shared drive and can be used as starting points for modification. The MOI-AAA, MOI-AA, and small CG measurement machines have tapered shafts upon which the stem of the axial and transverse MOI fixtures are mounted. The measured tapered shaft dimensions are shown in Table 4. The transverse MOI fixture needs to fit both the CG-A and MOI-AAA (or MOI-AA) machines since the same fixture is used for the CG and transverse MOI measurements.

Table 4. Measurement machine tapered shaft dimensions and no. 1 reamer dimensions.

Machine	Shaft length (inches)	Diameter at top (inches)	Diameter at bottom (inches)	Taper angle (deg)
CG-A	0.63	0.1605	0.1715	0.50
MOI-AAA	0.6280	0.1595	0.1710	0.52
MOI-AA	0.5600	0.1595	0.1710	0.59
MOI-A	0.4875 fixture shaft depth	0.2490 fixture shaft	0.2550 fixture shaft	0.35
No. 1 reamer	1.6875	0.1447	0.1798	0.597

SolidWorks models of recent fixtures have been dimensioned with a straight 0.171-inch cylindrical hole in the fixture stem that mounts the fixture to the tapered shaft of the measurement machines. In practice, the tolerancing of the rapid prototyped fixtures produced components that have a cylindrical hole that was smaller than the specified dimension. The hole was subsequently drilled out with a 0.152-inch bit. The hole was then reamed to the appropriate dimensions using a no. 1 reamer. To accommodate the no. 1 reamer, the hole had to be drilled completely through the fixture so that the reamer could be inserted deep enough into the fixture shaft to ream the hole to the appropriate dimensions. Existing fixtures can be used to determine the approximate depth that the reamer can be inserted to obtain the proper hole dimensions. Some iterative cutting with the reamer may be required to obtain the desired fit on both the CG and MOI machines. The opening on the bottom of several existing fixtures was nominally 0.162 inch and the fixtures slid down about halfway down the shaft on the CG and MOI machines.

The MOI-A machine uses a fixture with a solid shaft that fits inside the mount on the MOI-A machine. The outer dimensions of the calibration fixture for the MOI-A machine are shown in Table 4. These dimensions can be used to fabricate fixtures for the MOI-A machine.

5.2 Obtain Basic Dimensional Measurements of the Projectile

There are several critical measurements of the projectile that are needed for the physical property measurement. The projectile length and reference diameter should be measured. The axial location where the reference diameter was measured is also recorded. The optical comparator in the Physical Property Measurement room at TEF can be used. If a spin pin is used, the spin pin's dimensions and location may also be measured at this time.

Once the fixture is obtained and the basic dimensional measurements of the projectile and fixture are made, the physical property measurement process can proceed.

5.3 Power Up the Computer, Controller, and Compressed Air

The MOI machines use compressed air to power the units. If the MOI machines are used, the air compressor in the HVAC room off the main hallway of the TEF must be turned on (control box shown in Figure 2). Switches for both Compressors 1 and 2 should be turned on. With the air compressor powered up, the air supply to individual MOI machines is then turned on using the valves mounted on the wall behind the MOI machines (Figure 3).

Figure 2. **Compressor on/off control box.**

Figure 3. **Pressure valve array used to supply compressed air to MOI machines.**

The Multi-Machine Controller (Figure 4) is then turned on using the on/off switch on the front panel of the controller. Powering on the Multi-Machine Controller sends power to the CG-A, MOI-A, MOI-AA, and MOI-AAA machines. There is also an on/off switch toward the back of the base on the MOI-AAA machine that also needs to be turned on if the MOI-AAA machine is being used. Allow each machine to warm up for at least 10 min before operating the instruments.

Figure 4. Multi-Machine Controller.

The Raptor Scientific SuperLogics computer is then turned on using the lighted blue power button below the "Raptor Scientific" label (Figure 5). When turned off, the blue button is not lit and may be hard to find. When the computer is booted up, three icons will appear on the monitor's desktop (Figure 6). The "SE300 CG Measurement Software" icon controls the software for the small-caliber CG measurement machine. The "CGC" icon controls the software for the BRL-C CG machine. The "Multi MOI Controller" icon controls the software for all of the MOI machines. The "Multi MOI Controller" software has embedded modules to individually control the various MOI machines.

Figure 5. Raptor Scientific SuperLogics computer.

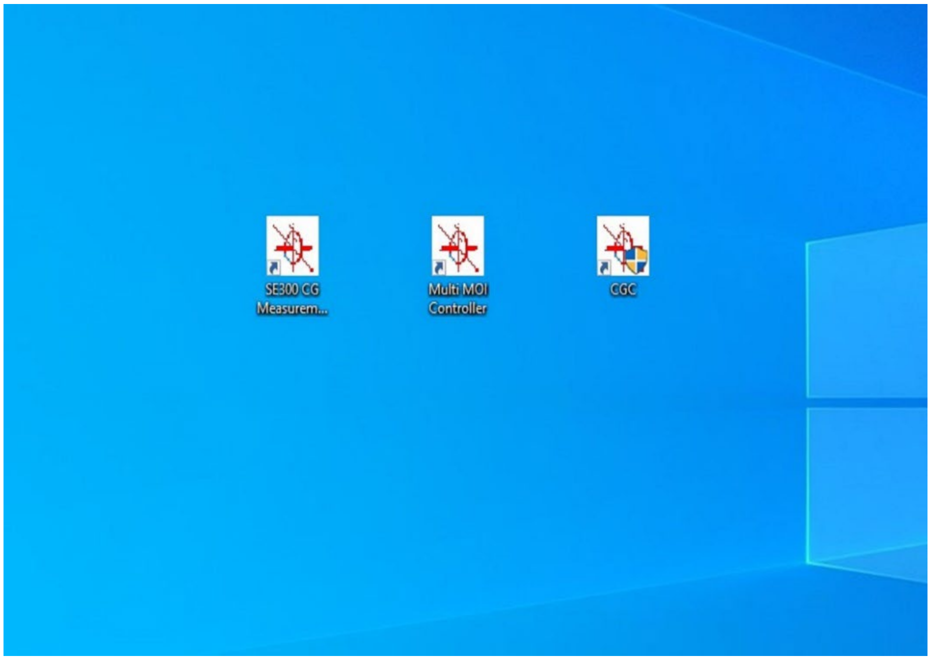


Figure 6. Main screen for CG and MOI measurement software.

5.4 Obtain the CG Location and Projectile Mass Using the CG Measurement Machine

The CG location and the projectile mass are determined using the CG measurement machine. The BRL-A CG machine is used to measure the CG of small-caliber projectiles weighing up to 300 g. The CG measurement machine consists of two components that measure the CG location and the weight of the projectile. The two components of the CG measurement machine appear to interact with each other. When using either the CG balance or the weight scale, make sure the other component is clear of any parts, fixtures, or calibration weights.

The "SE300 CG Measurement Software" module on the stand-alone PC is used to perform the CG and mass measurements. The software will guide the user step by step (with pictures) through the measurement process. There are five main steps in the measurement process:

1) Calibrate,
2) Measure tare,
3) Measure part,
4) Calculations, and
5) Weight scale (Figure 7).

There is also an instruction manual[2] for the CG machine (CG Instr Manual SE199, SE300.pdf), which provides instructions for calibration and measurement. In most cases, users should be able to simply follow the step-by-step instructions shown by the software. The manual also includes instructions for the initial setup of the CG machine, which might be required if the machine is shipped or moved to a different location. The following instructions assume that the initial setup has been completed.

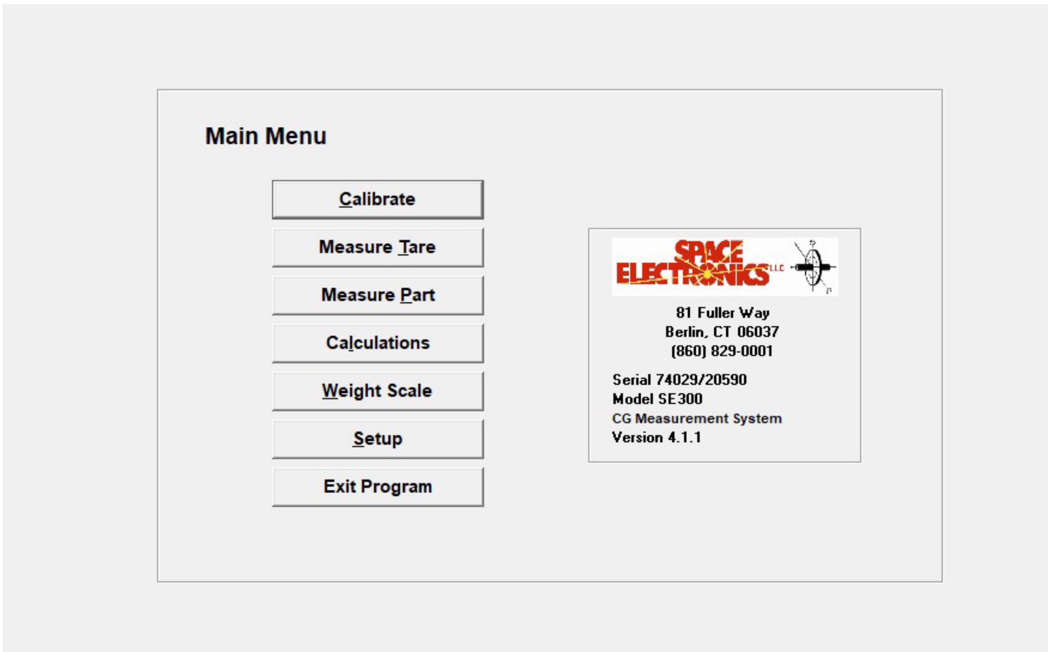


Figure 7. CG measurement main menu.

5.4.1 Calibration

The moment scale should be periodically calibrated for maximum accuracy and to ensure calibration is within specifications. There are two calibration weights for the updated small-caliber CG machine designated as 20590-1 and 20590-2. These can be found in the labeled plastic bags usually located in the boxes with the projectile measurement fixtures (Figure 8). The 20590-2 calibration weight used for the CG balance is a 3/4-inch-diameter spherical ball that weighs 54.02 g. The 20590-1 calibration weight used for the mass scale is a cylindrical disk that is 2 inches in diameter, 0.5 inch thick, and weighs 198.54 g. The 20590-1 disk is marked with the serial number, but the spherical ball 20590-2 does not have any markings. The weight and dimensions of the two calibration weights are included here to ensure the correct identification of the calibration weights. The calibration weights should be placed in the correct bags when calibration is complete (to avoid confusing the calibration weights with other calibration weights used for the other machines).

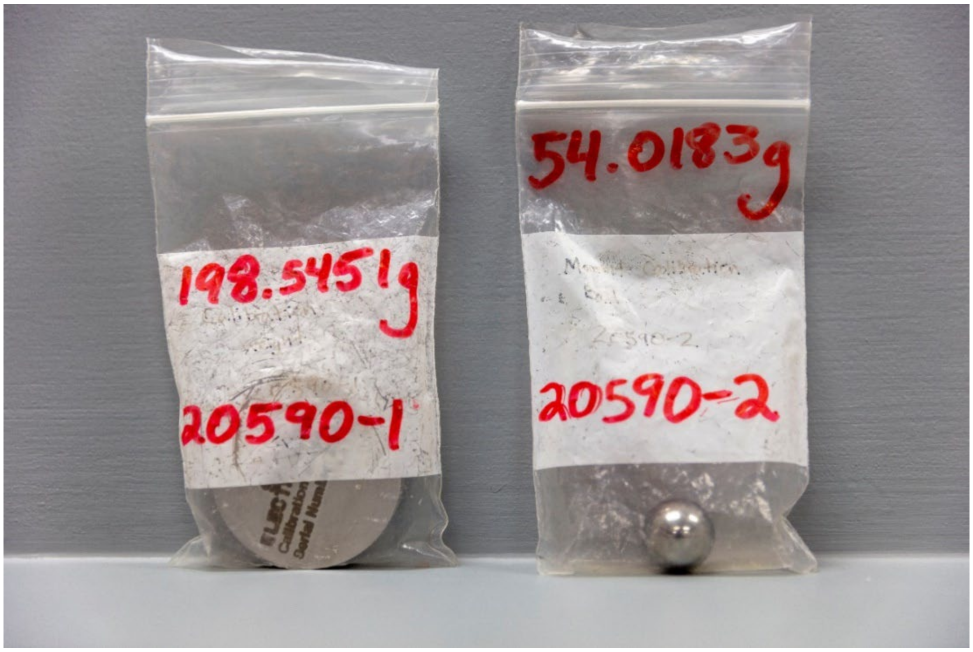


Figure 8. Calibration weights for small-caliber CG machine and mass scale.

The step-by-step calibration procedure is as follows:

1) Click “Calibrate” in the Main Menu of the CG Measurement module to begin the calibration process.
2) Enter Calibration Information. Enter the Operator name under “Enter Information for this Calibration.” Operator initials are often used. Click “Continue” to proceed to the next menu.
3) Instructions state, “Please make sure the Instrument power is on.” Power is hardwired to the instrument through the Multi-Machine Controller; therefore, power should be on once the Multi-Machine Controller is turned on.
4) Per the instructions, place the Calibration Ball 20590-2 in Hole A (i.e., the right hole).
5) Close cover. The cover should be closed to avoid any air movement that may affect the readings. Click “Continue” to begin the measurement. Wait for readings to settle. The user can freeze the data, but this is usually not necessary. The computer will proceed to the next step when the reading is complete. It is not necessary for the user to record the displayed data.
6) Place Calibration Ball 20590-2 in Hole B (i.e., the left hole).
7) Close cover. Click “Continue.” Wait for readings to settle. The computer will proceed to the next step when the reading is computed.
8) User is prompted to “Perform Weight Platform Calibration” (Yes/No). Enter “Yes” if weight calibration is to be performed. In general, it is standard practice to perform the weight platform calibration.

9) Remove Calibration Ball 20590-2 in Hole B. Close lower cover.
10) Ensure that the weight platform is clear. Close upper cover. Click "Continue" to obtain weight platform tare. Wait for readings to settle. When complete, the software advances to the next step.
11) Place Calibration Mass 20590-1 on platform. Close cover. Click "Continue." Wait for readings to settle. When complete, software advances to the next step.
12) Calibration results are displayed on the screen. The results should indicate "Pass" if both calibrations pass. If the calibration fails, the failure of either (or both) the CG or mass calibrations will be indicated. The manual[2] recommends recording the calibration constants so that any significant changes can be noted. Previous calibration constants do not appear to be saved on disk for the CG machine. For reference, recent calibration constants are shown in Table 5.
13) In the event the calibration fails, review the calibration process and try again.
14) Click "Continue" to save the calibration for future measurements and return to the main menu.
15) Remove the calibration weight from the weight platform and close cover.

Table 5. Calibration constants for CG-A machine.

Calibration date	Calibration constant (g-in/count)	Weight calibration (g/count)
1/2/2024	0.002511142	0.0010009

5.4.2 CG Measurement

With the calibration established, the measurement of the CG can be made. First, the measurement of the fixture alone is made (tare), followed by the measurement of the fixture with the projectile. The tare is subtracted from the measurement of the fixture with the projectile to get the CG measurement for the projectile alone.

For the current application, the "fixture" consists of two components: a "permanently" installed component of the fixture and an additional removable fixture that is custom-built to hold the projectile. The manual[2] (p. 11) describes a procedure for installing a "fixture." The installation procedure in the manual refers to the "permanently" installed component of the fixture. This step should have already been completed and can be ignored.

5.4.2.1 Measure Tare

The tare measurement is made next. Note that if a series of measurements for similar projectiles using the same fixture are being made, only a single tare measurement of the fixture is required.

1) Click “Measure Tare.”
2) The “Measure Tare” menu window is opened. Instructions state, “Please make sure power is on” and “The fixture SHOULD be clear (no Part).” Power should be on by default. The removable component of the fixture still needs to be installed.
3) The removable component of the fixture is installed by placing the hollow stem of the removable fixture on the stem of the permanent fixture. The fixture should be aligned such that the “stop” on the fixture points to the right (0°) as shown in Figure 9. Subsequent measurements are made at 90°, 180°, and 270°, with the stop pointed in the direction of the angles denoted on the measurement platform. The user should try to orient the fixture as close as possible to these orientations although there does not appear to be a requirement for the orientations to be made with a particular precision. It is important to maintain the convention of the stop being pointed in the direction of the angles denoted on the measurement platform. The CG measurement will eventually be displayed as a positive or negative number. Using the correct convention will ensure the CG measurement is correctly interpreted. If the correct convention is followed, a positive value of the CG location means that the CG of the projectile is located between the stop and the axis of rotation. A negative value means that the CG of the projectile is located on the opposite side of the axis of rotation relative to the stop.

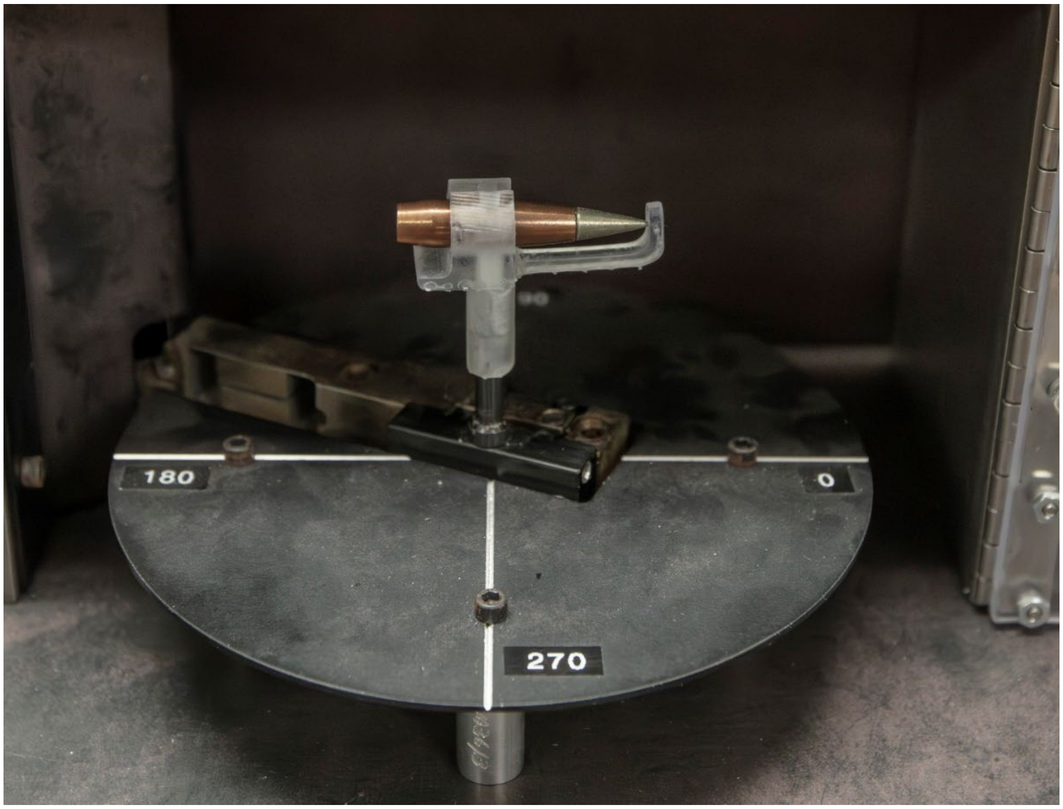


Figure 9. Fixture mounted on CG-A machine and oriented in the 0° position (fixture stop to the right).

4) Once the fixture is installed, click “Continue.”
5) Rotate the fixture to the 0° position if not already done. Click “Continue.” There are two windows that appear prior to advancing to the next step. The first window says, “Waiting for readings to settle . . . ” followed by a “CG Parts Measurement” screen with in-process readings displayed. The user can freeze the readings (usually not necessary). After the software determines the readings are stable, the software will automatically advance to the next step.
6) Rotate the fixture (counterclockwise) to 90°. Click “Continue” and wait for software to advance to the next step.
7) Rotate the fixture (counterclockwise) to 180°. Click “Continue” and wait for software to advance to the next step.
8) Rotate the fixture (counterclockwise) to 270°. Click “Continue” and wait for software to advance to the next step.
9) The “Store Measurement” box appears.
10) Readings for all four angular positions are displayed. The user should enter “Operator” (required, but should be auto-filled from calibration), “Tare ID” (required), “Comments” (optional). Click “Store and Continue” to complete the tare measurement sequence and return to the main menu.

5.4.2.2 Measure Part

The combined measurement of the fixture and part is made next. The process follows the same procedure as for the tare.

1) Click “Measure Part.”
2) The “Measure Part” menu window is opened. Instructions state, “Please make sure power is on” and “The part fixture SHOULD be mounted now.” Power should be on by default.
3) The projectile is placed in the fixture with the nose or tail placed against the stop. The fixture was likely built with a preferred orientation of the nose or tail relative to the stop so that the CG is close to the axis of rotation of the shaft. The fixture is then installed in the measurement machine and aligned such that the “stop” on the fixture points to the right (0°).
4) Mount the part and fixture. Click “Continue.”
5) Rotate the fixture to the 0° position if not already done. Click “Continue.” After the software determines the readings are stable, the software will advance to the next step.
6) Rotate the fixture (counterclockwise) to 90°. Click “Continue” and wait for software to advance to the next step.
7) Rotate the fixture (counterclockwise) to 180°. Click “Continue” and wait for software to advance to the next step.
8) Rotate the fixture (counterclockwise) to 270°. Click “Continue” and wait for software to advance to the next step.
9) The “Store Measurement” box appears.
10) Readings for all four angular positions are displayed. The user should enter “Operator” (required), “Part ID” (required), “Part Serial” (required), and “Comments” (optional). The Operator and Part ID are likely auto-filled from the previous tare measurement. Part serial number needs to be entered and is used to identify individual projectiles particularly if several similar projectiles are being measured. If measuring a series of similar projectiles, be sure to separate the projectiles so that the CG and MOI measurements (performed later) are associated with the correct projectiles.
11) Click “Store and Continue” to complete the part measurement sequence and return to the main menu.

5.4.2.3 Calculation

Once the CG is measured for the fixture alone (tare) and the combined fixture/part, the software can be run to compute the CG for the part alone. If a series of measurements for similar projectiles is being made, the calculations can be done after all the measurements are complete. However, since the calculation process is quick and easy, running calculations after each part measurement can be helpful to determine if measurements are consistent.

1) Click “Calculations.”
2) A “Calculation Information” dialog box with information is displayed. A collection of tare and part measurement data from previous measurements are displayed in a spreadsheet form.
3) Select desired “Part” by clicking the appropriate row of data, which will be highlighted when selected. If the “Use Operator and Part Information from Part Measurement” box is checked (default upon opening), the information from the part measurement is used. The Operator, Part ID, and Part Serial No. information from the part measurement will be auto-filled. Add Comment if desired.
4) Unchecking the “Use Operator and Part Information from Part Measurement” box allows the user to change the Operator, Part ID, and Part Serial No. information.
5) Select the correct “Tare” data at this point.
6) The operator can also weigh the part at this time. The weight information will be stored with the CG measurement. Note that before weighing the part, a weight may appear in the dialog box. Be careful with this. This displayed weight may be from a previous measurement of a completely different projectile. If the user has a projectile weight measurement from a previous measurement, then the weight can be entered here. Otherwise, it is recommended to weigh the part using the CG machine. It is standard practice to weigh the projectile at this time.
7) If the part is to be weighed, click “Weigh Part.”
8) Ensure the scale platform is clear and cover is closed. Click “Zero Reading” to zero the scale. Then, place the part (no fixture) on the scale platform. Close the cover.
9) Part weight appears. When weight reading is stable, click “Continue” to return to main “Calculations” menu. Newly calculated weight appears.
10) Click “Continue” once the correct tare and part combination are selected.
11) A screen with the “Calculations Results” is then displayed. Record the CGX and projectile weight.
12) Click “Save and Continue” to complete the calculations and return to the main menu.
13) Click “Exit Program” when CG measurements and calculations are complete.

The critical data displayed on the “Calculation Results” screen is the CGX, which represents the axial location of the CG relative to the fixture axis of rotation. Using the distance between the stop and the axis of rotation, the axial CG location relative to the projectile nose or tail can be determined. The data also includes the CGY, which is the CG location perpendicular to the longitudinal axis of the projectile. Ideally, CGY should be zero, but a nonzero CGY is common and may indicate a small misalignment of the projectile within the fixture or the fixture itself. If the fixture is designed to locate the CG on the axis of rotation, the CGY may be on the order of the measured CGX since both numbers should be small. A placeholder for CGY data appears in the external spreadsheet used to log the data but this is not used in any calculations and is often not recorded. The "Calculation Results" also display the mass of the projectile. Although the calculation results are stored, the user should manually record the CGX and the mass of the projectile for entry into the external spreadsheet.

5.4.2.4 Weight Scale

The weight scale can also be accessed independently of the CG measurement process. (It is not necessary to re-weigh the part if the part was weighed during the CG measurement process.) To weigh items, the following process is executed.

1) Click "Weight Scale."
2) Ensure the weight scale is empty. Click "Zero Reading." Scale reading should appear as 0.
3) Place the projectile (no fixture) on scale.
4) Scale should show projectile weight.
5) Click "Continue" to return to main menu. Note that the weight scale measurements are not saved on disk. If this measure is to be saved, it must be manually recorded.

5.5 Obtain the Transverse MOI

The transverse and axial MOI measurements are obtained independently and require different fixtures. The order of measurement is not particularly important, and the transverse MOI measurement can be obtained before the axial MOI measurement or vice versa. However, since the same fixture is used for the CG-A and transverse MOI-AAA and MOI-AA measurements, it is probably best to perform the transverse MOI measurement after the CG measurement. The axial MOI does not require the CG location since the projectile rotates about its longitudinal axis during the MOI measurement.

The MOI-A, MOI-AA, and MOI-AAA machines have a cylindrical cap on the top of the machines to protect the mounting stem. Unfasten the two hex bolts on the top of the cap to loosen and remove the cap prior to measurement. Replace the cap when measurements are complete.

The MOI instruments consist of an inverted torsion pendulum that oscillates in a rotational sense, a precision interface surface on which the test part may be mounted, and a means of measuring the exact period of oscillation of the torsion pendulum. The MOI measurement of the test part is based on the change in the natural frequency of oscillation of the torsion pendulum resulting from the addition of the test part. This change in natural frequency is compared with the change in natural frequency that occurs when a calibration weight of known MOI is placed on the instrument.

For the MOI-AAA machine, the rotational motion of the calibration fixture or part fixture must be initiated with a small light twist (i.e., ~10°) of the fixture. Once the part is released, the part should oscillate about the axis of rotation. The motion may damp with time, so the measurement needs to be performed shortly after the rotation is initiated. For the MOI-AA and MOI-A machines, the rotation is initiated by the machine itself as part of the measurement process and no user intervention is needed.

To begin the MOI measurement, select the "Multi MOI Controller" module on the main screen of CG and MOI measurement software on the stand-alone PC (Figure 6). The software will guide the user step by step (with pictures) through the measurement process. (The various steps are also explained in the "Moment of Inertia SE9598A Software Manual.pdf" file starting with the Operating Instructions [p. 3]. In most cases, users should be able to simply follow the step-by-step instructions shown by the software.)

1) Click "Multi MOI Controller." There are several items in the "Multi MOI Controller" module menu (Figure 10). The focus here is the "Measure" module.

Figure 10. Multi MOI Controller menu.

2) Click "Measure" to bring up the MOI measurement menu. There are four steps in the MOI measurement process: a) MOI Calibration, b) MOI Tare, c) MOI Part, and d) MOI Calculations (Figure 11). Each task is a separate box on the Measurement Screen menu. Each box has a red dot that changes to green as each task is completed.

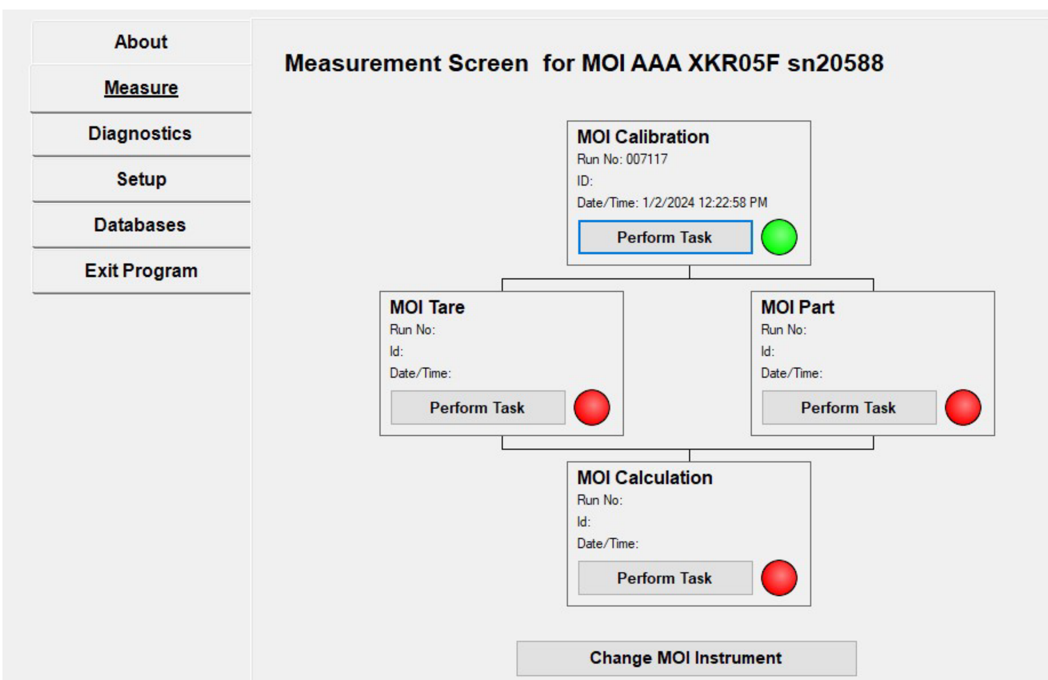


Figure 11. Measurement menu for MOI measurement.

3) Once the “Measure” module is opened, make sure the correct MOI instrument is selected. The machine type will be indicated at the top of the Measure window. To change to a different instrument, select “Change MOI Instrument” at the bottom of the Multi MOI Controller Measurement screen. Use the drop-down menu to select the correct MOI machine from the five listed MOI instruments.

5.5.1 MOI Calibration

The MOI-AAA and MOI-AA machine calibrations are performed with a conical fixture that is placed on the machine spindle on the top of the machine. The calibration weight is placed in the fixture. Figure 12 shows the conical fixture and calibration weight mounted on the MOI-AAA machine. The conical fixture (inset of Figure 12), is 1 inch tall, has a diameter on the top of the cone of 0.91 inch and weighs 2.70 g. The conical fixture has a pink semicircle on the bottom. The conical fixture has no permanent storage location but is typically found near the MOI-AAA machine. The calibration ball is a 1-inch-diameter sphere that weighs 65.88 g. The calibration weight should be in the brown wooden box (Figure 13) with the sheet of identification information on top of the box. The calibration ball serial number is S8207 (not marked on the ball).

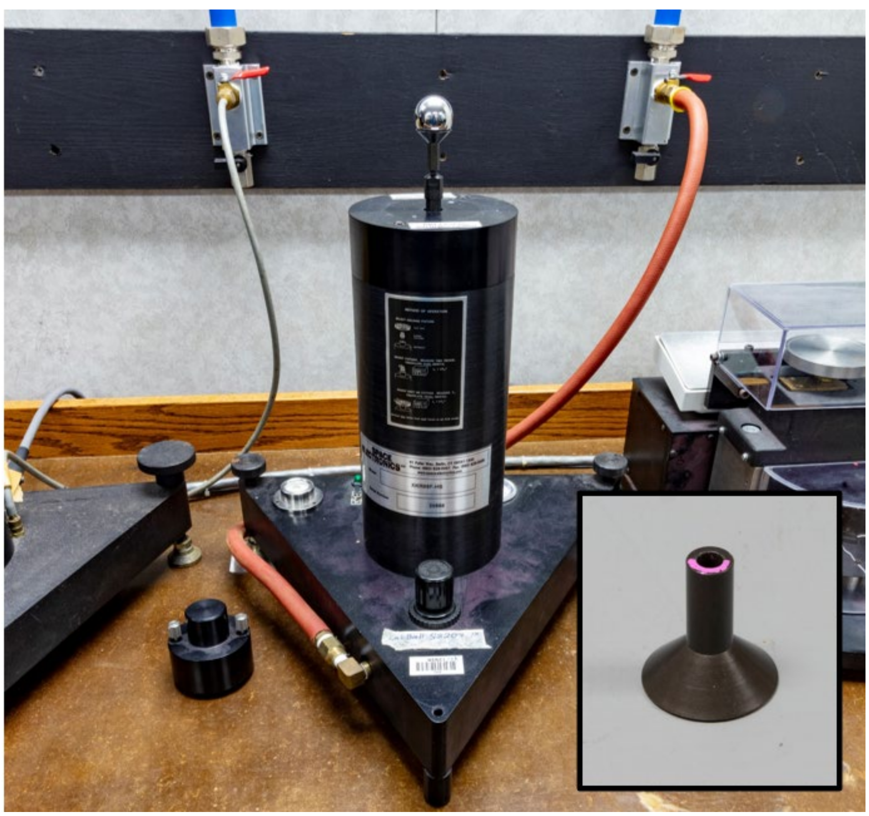


Figure 12. Calibration ball and mounting fixture on MOI-AAA machine (fixture shown as inset).

Figure 13. Calibration weights and mounting fixtures for MOI-A, MOI-AA, and MOI-AAA machines.

The MOI-A machine uses the same 1-inch-spherical calibration weight as the MOI-AA and MOI-AAA machines but a different fixture to hold the calibration weight. Figure 14 shows the fixture with the calibration weight mounted on the MOI-A machine. The MOI-A fixture (inset of Figure 14), consists of two black cylinders on a silver shaft with a cone–cylinder interior. The fixture is 1.7 inches long with a 1-inch inner diameter to hold the 1-inch spherical ball. The fixture weighs 17.35 g. The fixture is stored in the same brown wooden box (Figure 13) with the 1-inch spherical ball. The position in the box is labeled as “1.0 in. CUP.” The fixture shaft fits inside the hole in the mounting shaft on the MOI-A machine.

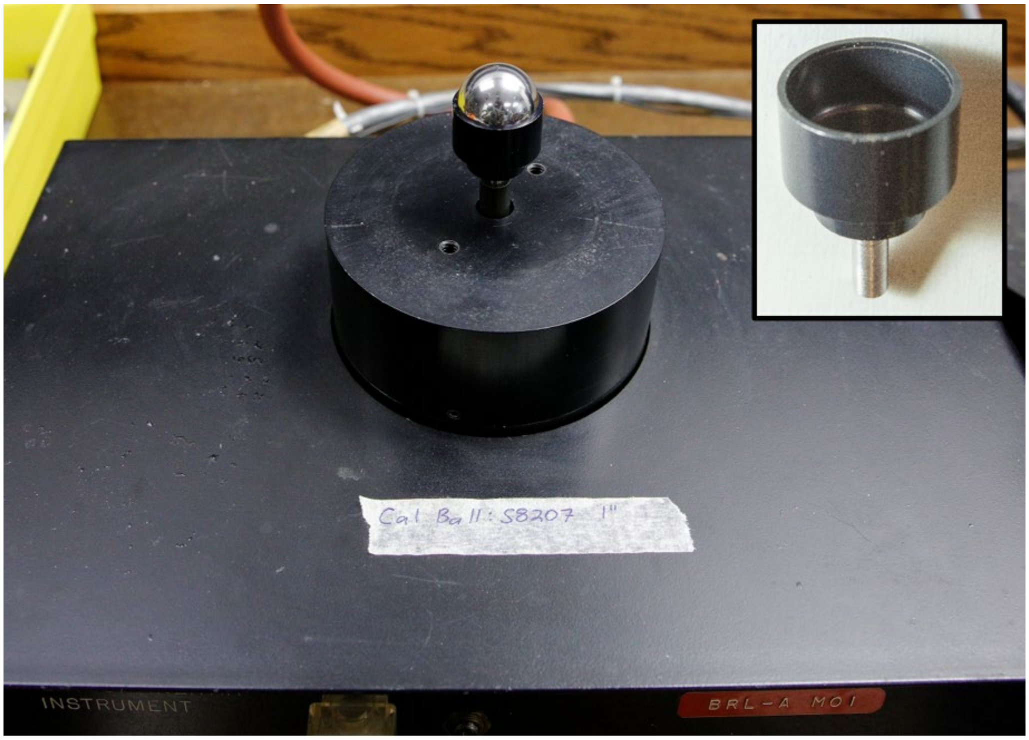


Figure 14. Calibration ball and mounting fixture on MOI-A (BRL-A MOI) machine (fixture shown as inset).

The MOI calibration for the MOI-AAA is performed as discussed below. The process is similar to the process for the MOI-AA and MOI-A machines with only small differences in the instructions displayed by the software. As guided by the software instructions, the oscillations for the MOI-AAA machine are started manually, while the machine initiates the oscillations for the MOI-AA and MOI-A machines. As the oscillations are initiated for the MOI-AA and MOI-A machine, an audible clicking noise will be heard—apparently this is normal. The order of the calibration is to obtain readings with the fixture/calibration weight first and then obtain "tare" readings with just the fixture. This is opposite of the calibration approach for the CG-A machine, which measures the tare first. If an error is encountered in the calibration process, make sure compressed air is turned on to the machine. Also make sure correct 1-inch-diameter calibration weight is used—do not use the spherical 0.75-inch-diameter CG machine calibration weight. At first glance, both calibration weights may appear similar.

1) In the "MOI Calibration" box, click "Perform Task."
2) A "Calibration Selection" menu will appear. Either an existing calibration can be selected or a new calibration can be performed.
3) If an existing calibration is desired, click on the left-most cell in the spreadsheet to highlight the calibration. Click "Select." The user is returned

to the main menu and the red dot by the MOI Calibration turns green (Figure 11).

4) For a new calibration, click "New Calibration." Following the instructions, make sure the machine is powered up and clear of any fixtures. Place the conical fixture with the calibration weight on the machine spindle. Start oscillations. Click "Continue." The computer will analyze the readings and if they exceed preset limits a warning will be displayed. If a warning is displayed, check that the load is freely floating. If using MOI-AAA and a menu appears with reading timer "OFF," make sure the MOI-AAA switch on base is turned on.
5) Remove calibration weight (remove just the spherical ball, leave conical fixture attached). Click "Continue."
6) Start oscillations and click "Continue." When measurements are complete, "Calibration Results" are displayed. Enter Operator (required) and Comments (optional). The computer will calculate and display the MOI calibration constant. The calibration constant is compared with a factory reference calibration constant and must agree within allowable variations or the new calibration will be rejected. The most current calibration constant is always used for calculations.
7) Click "Save and Continue" to save the calibration results and return to the main menu.
8) Note that if the calibration deviates somewhat from the expected calibration (e.g., 302 rather than 309 g-cm^2 for the MOI-AAA machine), the spherical calibration weight and the conical fixture may have been removed in step 5 rather than just the spherical calibration weight. (The calibration may still indicate a "pass" if this occurs, but the accuracy of the calibration will be affected.)

Nominal calibration constants are shown in Table 6 for reference.

Table 6. Calibration constants for MOI machines.

Machine	Calibration performed by Space Electronics (TPK) 4/2023 (g-cm^2/sec^2)	Spring 2024 calibration (g-cm^2/sec^2)
MOI-AAA	309.7487	309.568
MOI-AA	69.818	69.866
MOI-A	561.12	560.69
MOI-B	177251	177305.31657
MOI-C	5308272	5308603.63853

5.5.2 MOI Tare

1) In the MOI Tare box, click "Perform Task."
2) A "Tare Selection" window appears with a list of existing tares.
3) If an existing tare is desired, highlight the appropriate row of data and click "Select" to return to the main menu. For a series of measurements using the same fixture, an existing tare can be used. The red dot by the MOI tare box turns green.
4) If a new tare is desired, click "New Tare."
5) If New Tare is selected, the Tare Measurement window opens. The instructions prompt the user to ensure power is on and the fixture without part is mounted. Click "Continue."
6) The operator will be prompted to start the oscillations. Start oscillations and quickly click "Continue" to begin the measurement of the period of oscillation.
7) When measurement is complete, the Tare Measurement Results window is opened. Enter Operator and Tare ID. There is a drop-down menu for both. Comments are optional. Click "Save and Continue" to save Tare Results and return to the Measurement Screen.
8) The user is returned to the main menu and the red dot by the MOI Tare turns green.

5.5.3 MOI Part

9) In the MOI Part box, click "Perform Task."
10) "Part Selection" window is opened.
11) Select either existing part measurement or "New Part." (In most cases, a new part measurement would be performed, but if a different calibration or tare is to be applied in the final calculation, existing part measurements can be used.)
12) Click "New Part."
13) Part Measurement window opens. The instructions prompt the user to ensure power is on and the fixture with part is to be mounted. Click "Continue."
14) Start oscillations and click "Continue."
15) When measurement is complete, the Part Measurement Results window is opened. Enter Operator, Part ID, and Part Serial. There is a drop-down menu for all three. Comments are optional. Some information may be auto-filled. Ensure these entries are correct. Click "Save and Continue" to save Part Results and return to the Measurement Screen.
16) The user is returned to the main menu and the red dot by the MOI Part turns green.

5.5.4 MOI Calculation

After executing the first three steps, the software can calculate the MOI of the part alone. The MOI of the part is obtained by subtracting the tare MOI from the measured MOI for the combined fixture and part. Note that this MOI is the MOI about the axis of rotation (which may or may not be coincident with the CG). The MOI of the projectile about its CG is later calculated using the auxiliary Excel workbook (a blank workbook template can be found in "Blank_Template_NewMachines.xls").

Calculations are performed based on the previously selected Calibration, Tare, and Part in the "Measure" window. If a calculation based on a different combination of calibration, tare, or part is desired, then those selections need to be made before the Calculation.

1) In the MOI Calculation box, click "Perform Task."
2) "Calculation Selection" window is opened.
3) If the existing calculation data is to be examined, highlight the desired row of data to select existing calculation data. Then click "Select" to open the "Calculation Results" window showing existing calculation data. Essentially, these are the calculation results based on the prior calibration, tare, and part measurements. Only the Operator, Part ID, and Part Serial can be changed here (which do not change the results). Hit "Cancel" if no changes to the data are desired.
4) If a new calculation is desired, click "New Calculation." "Calculation Results" window is opened. Operator, Part ID, and Part Serial is auto-filled for the current measurement sequence. Ensure these entries are correct. The measured/calculated MOI is displayed. There are drop-down menus to access/change the Operator, Part ID, or Part Serial entrees, but this does not change the MOI displayed.
5) Click "Save and Continue" to save data and return to the Measurement Screen.
6) Red turns to Green and calculation is complete.

To measure a new part with an existing tare, open the "Measure" module, select an existing calibration and tare in the "MOI Calibration" and "MOI Tare" steps. This turns the status indicator "dots" in both modules from red to green and allows the user to proceed to the MOI Part and Calculations tasks.

When all measurements and calculations are complete, click "Exit Program" to return to the Main Menu.

In addition to the Measure module, there is also a “Databases” module in the Main MOI menu. Here, previous MOI Calibration History, MOI Tare Measurements, MOI Part Measurements, and Calculation Results can be accessed.

5.6 Obtain the Axial MOI

The axial MOI measurement process is similar to the process used to measure the transverse MOI. A different fixture that aligns the projectile’s longitudinal axis with the MOI machine’s axis of rotation is used for the axial MOI measurement. The same four steps used for the transverse MOI can be used here. It may not be necessary to perform the MOI machine calibration again; although, an existing calibration must be selected. However, the MOI tare for the axial MOI fixture will be different than the MOI tare for transverse MOI fixture. A single axial MOI tare can be used for multiple measurements of a series of projectiles that employ the same axial MOI fixture.

1) Click “Measure” to open the Measure module. Execute the four steps of the MOI measurement process: a) MOI Calibration, b) MOI Tare, c) MOI Part, and d) MOI Calculations. Ensure that the correct MOI instrument is selected.

5.7 Power Down the Computer, Controller, and Compressed Air

1) Remember to reinstall the cylindrical cap on the MOI machines to protect them.

2) Turn off power to MOI AAA machine (on/off switch toward back of machine).

3) Close values to air supply to individual MOI machines.

4) Turn off Multi-Machine Controller using the on/off switch on the front panel of the controller.

5) Turn off Raptor Scientific SuperLogics computer.

6) Turn off compressors in HVAC room.

5.8 Enter the Measured Data into the Appropriate Workbook

Physical property measurements are recorded and processed in an Excel workbook. There are separate templates used for small- or large-caliber projectiles as both projectile classes use slightly different measurement processes. Excel workbook templates used to record and process the measurements can be found in the “Range

Operations/Physical Properties Spreadsheet" folder on the Flight Sciences Branch shared drive.

The "Blank_Template_NewMachines.xls" is the appropriate template to use for small-caliber projectiles. Note there are other templates located in this folder. The "Blank_Template.xls" is an older small-caliber projectile template that appears to have been used with the older (pre-FY11) measurement machines. Most of the existing pre-FY11 data is recorded with this template.

The primary difference between the two workbooks is that the "Blank_Template_NewMachines.xls" has the "Distance from Center to Stop" and the Nose/Base orientation inputs in the upper right-hand side of the "Actual Raw Measurements" tab of the workbook (Figure 15) while the legacy workbooks for small-caliber projectiles do not. The "Blank_Template.xls" does not have embedded calculations to correct the transverse MOI for the offset of the CG from the axis of rotation. (It is assumed that the legacy process corrected the transverse MOI prior to the data being enter in the "Blank_Template.xls" workbook.)

The measured data is entered into the "Actual Raw Measurements" tab in the appropriate Excel workbook template (Figure 15). The distance from the center of rotation to the Stop on the transverse MOI fixture as well as the orientation of the projectile relative to the stop is entered in the upper right-hand corner of the worksheet. The critical measurement data for the physical property measurements are the projectile mass, length, reference diameter, axial location of the CG relative to the axis of rotation (CGX), and the measured transverse and axial MOI.

Projectile Physicals Measurement Raw Data Sheet

Person Performing Measurements:	Technician #1	Distance from Center to Stop	0.3977 inches (choose units)
Date:	10/7/2013	Projectile against Stop: 1 - Nose, 2 - Base	2

Alpha numeric program identifier (up to 42 chars)	7.62mm Commercial Projectile													
Projectile Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**AVG**	**Std. Dev.**	**SD %**
Projectile ID	**(choose units)**											**5 Measurements**		
Projectile Mass	grams	8.74488	8.75194	8.76095	8.76495	8.76443						8.75743	0.0087	0.1%
Projectile Length	inches	1.0712	1.0714	1.083	1.0743	1.0288						1.06574	0.0212	2.0%
Reference Diameter	inches	0.3029	0.31	0.3102	0.3097	0.3106						0.30868	0.0032	1.1%
Ref Diameter location from base	inches	0.193	0.193	0.193	0.193	0.193						0.193	0.0000	0.0%
CG X	inches	0.0009	0.0019	-0.0012	0.0028	-0.0017						0.00054	0.0019	360.2%
CG Y (used only in this sheet)	inches											0	0.0000	0.0%
CG Mag (used only in this sheet)	inches											0	0.0000	0.0%
CG Angle (used only in this sheet)	degrees											0	0.0000	0.0%
Distance from axis to spin pin if any	inches											0	0.0000	0.0%
Distance from base to spin pin if any	inches											0	0.0000	0.0%
Length of spin pin	inches											0	0.0000	0.0%
Diameter of spin pin	inches											0	0.0000	0.0%
Transverse moment of inertia	gm-cm**2	3.1281	3.13717	3.13655	3.13181	3.13758						3.134242	0.0041	0.1%
Axial moment of inertia	gm-cm**2	0.56793	0.57906	0.5756	0.57204	0.56759						0.572444	0.0049	0.9%

Lot Numbers and Additional Comments:	

Figure 15. "Actual Raw Measurements" tab for "Blank_Template_NewMachines.xls" workbook.

The measured reference diameter and axial location of the measured reference diameter are also entered into the "Actual Raw Measurements" tab. These measurements are used in the film reading and aerodynamic reduction process but do not affect the MOI calculations. There are fields for additional supplemental data that can be entered in the spreadsheet, but this data is generally not required and can be omitted.

Data for up to 10 similar projectiles can be entered into the "Actual Raw Measurements" tab. If a group of similar projectiles is measured, the average and standard deviation of the group of projectiles is computed on the right-hand side of the "Actual Raw Measurements" tab and is used to establish the physical properties for the projectile.

The measured data is then used to compute the physical properties in the "Processed Projectile Physicals" tab. The mass and axial MOI are identical to the average measured values. The location of the CG relative to the projectile base and nose is also computed using the measured data.

The transverse MOI about the projectile's CG is then calculated in the "Processed Projectile Physicals" tab of the workbook using the following formula.

$$I_t|_{cg} = I_t|_{measured} - m\Delta_{CG}^2$$

For larger-caliber projectiles, a series of MOI measurements are made with the projectile located at different axial locations normal to the axis of rotation. These axial locations are selected so that the CG is located forward and aft of the axis of rotation. A curve fit of measured MOI relative versus axial locations is made. The minimum MOI from the curve fit represents the MOI at the CG. Because of the small size of small-caliber rounds, this approach may be difficult to execute accurately and the previous process is used.

To preserve measurement data, Excel workbooks for the completed physical measurements should be stored in the appropriate fiscal year sub-folder in the "Range Operations/Physical Properties Spreadsheet" folder on the Flight Sciences Branch shared drive.

There are two additional tabs that pull the processed physical measurement data and organize the data in a form used for film reading from spark range experiments.

6. Measurement of Medium- and Large-Caliber Projectiles

A separate set of machines are used to determine the transverse and axial MOI of medium- and large-caliber projectiles. As a by-product of these measurements, the mass and CG is also obtained. In contrast, for small-caliber projectiles, a separate machine is used to determine mass and CG. The projectile mass can be independently (and easily) obtained by directly weighing the projectile and serves as an independent check on the measurements from the MOI machines. The process used to measure the MOI of medium- and large-caliber projectiles will be very similar to the process followed for small-caliber projectiles as discussed in Section 5.

There are also several templates (i.e., “New Physical Measurement Sheet(2017-03-01).xlsx” and “New Physical Measurement Sheet(2018-08-09).xlsx”) that are used to process the medium- and large-caliber projectile data, which uses a different procedure for MOI measurement than for small-caliber projectiles.

6.1 Obtain a Measurement Fixture

The key features of medium- and large-caliber fixtures include 1) the ability to align on the platform surface relative to the axis of rotation, depending on the machine used and 2) the ability to offset the fixture or projectile on the fixture relative to the axis of rotation of the machine. The MOI-B machine described earlier (Table 1) has a single alignment hole that measures approximately 3/4-inch diameter. The MOI-C and CG-C machines, designed for heavier measurements, have five alignments holes of 3/4-inch diameter, spaced 2.5 and 4.0 inches from center, respectively, providing support for the larger heavier objects. The MOI-B and MOI-C fixture mount hole patterns are shown in Figure 16.

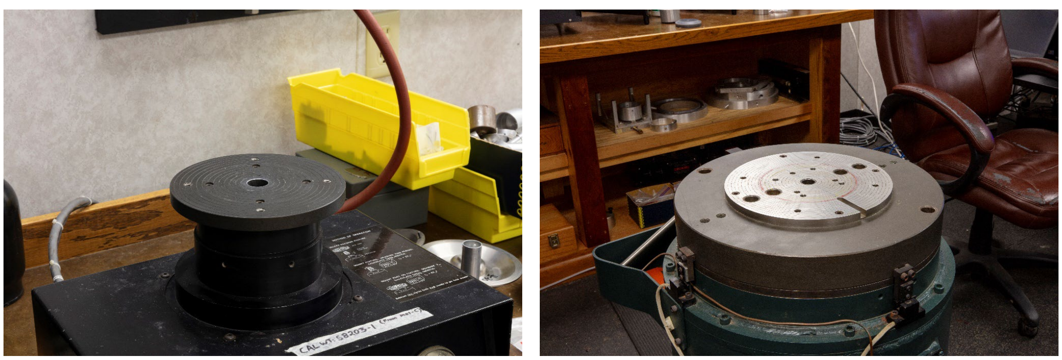


Figure 16. MOI-B (left) MOI-C (right) fixture mount hole patterns.

There are several methods that have been historically used in fixture design—particularly, in the transverse measurement requirement—but the primary goal is to have proper alignment of the object relative to the axis of rotation (parallel or perpendicular to), and the ability to translate the object’s CG across the axis of rotation as described previously. Figure 17 shows several fixtures used for the MOI-B machine. One method is to develop a pattern of holes of known distance on a machined or 3D-printed fixture that can mount and move the object relative to the axis. An example of this is shown by the white plastic fixture shown in the middle of Figure 17. Figure 18 shows an MOI-B measurement fixture employed to measure the transverse MOI for a 40-mm grenade projectile.

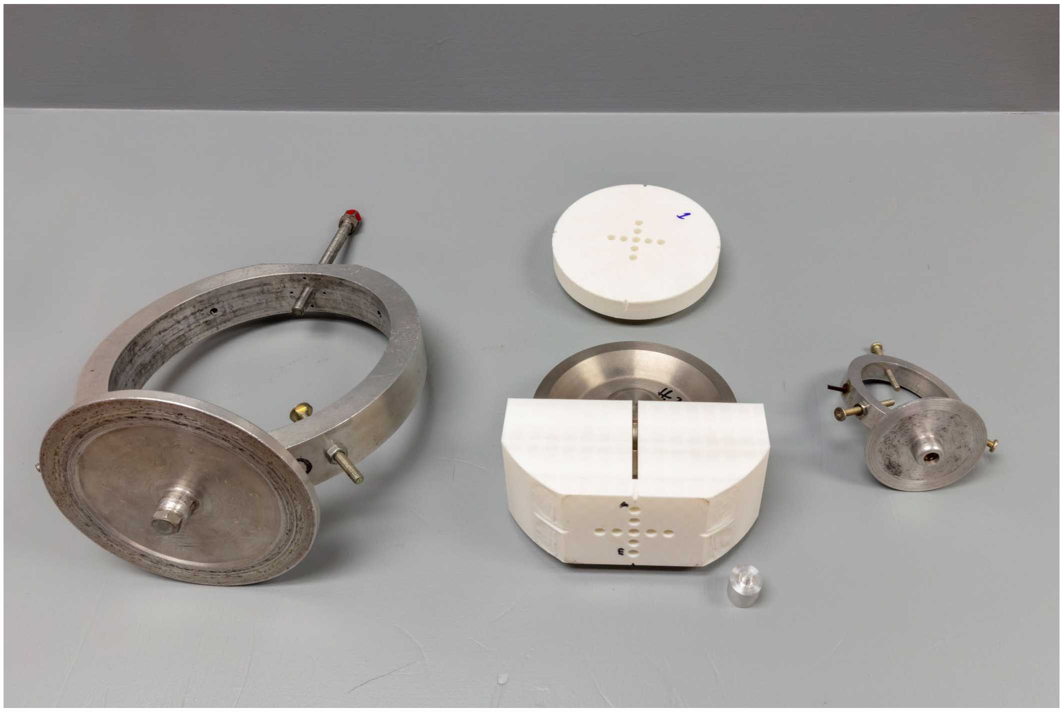


Figure 17. Various MOI-B fixtures.

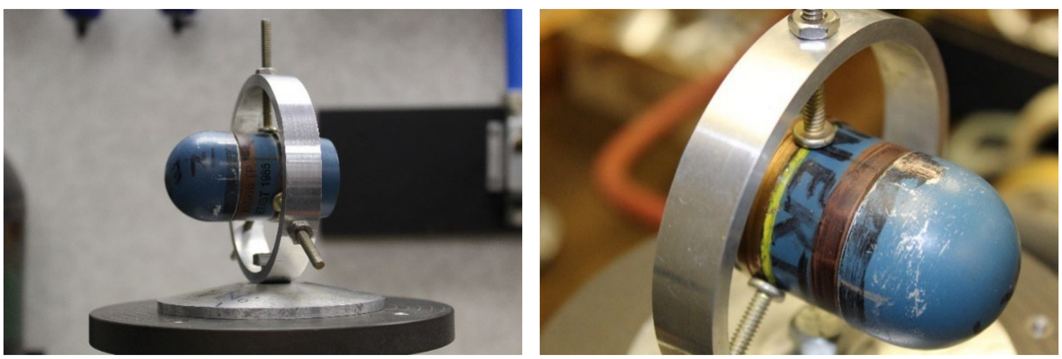


Figure 18. The 40-mm grenade projectile in one type of MOI-B fixture.

Another approach is to have a fixture with measurable sliding movement that can translate the object at known increments while the fixture base is fixed to the rotating platform (Figures 19 and 20).

With all fixtures, the part must be level and either normal to or parallel with the axis of rotation depending on whether the transverse or axial MOI is being measured.

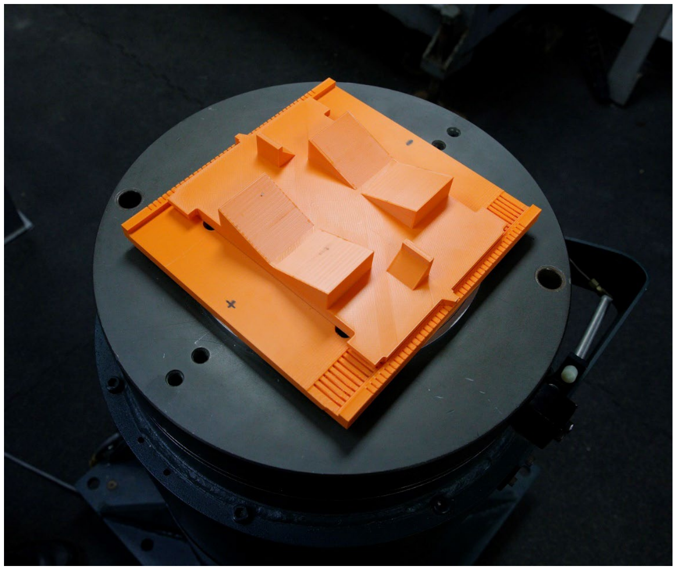


Figure 19. MOI-C with sliding fixture for large-caliber projectiles.

Figure 20. MOI-C with sliding fixture for large-caliber, with 155-mm projectile.

6.2 Obtain Basic Dimensional Measurements of the Projectile

The same measurements referenced in Section 5.2 will also be captured for medium- and large-caliber parts and projectiles, including projectile length and diameter (with the axial length to the measurement recorded) as well as mass, spin pin (if applicable), location, and length.

6.3 Power Up the Computer, Controller, and Compressed Air

This procedure is identical to Section 5.3.

6.4 Obtain the CG Location

Historically, technicians/engineers at TEF use the MOI B or C machine to obtain CG locations through multiple MOI readings at various points along the translation axis. Sections 6.4.1–6.4.3 (below) briefly describe an alternative approach using the CG-C large-caliber CG machine to find the CG location. If the alternative approach is not used, the process described in Section 6.5 produces a CG location and mass as a by-product of the MOI measurement procedure.

6.4.1 Obtain the CG Calibration

1) Run the CGC application from the desktop.
2) Select CG Calibration (red triangle—or green, if a previous calibration was already selected).
3) Select "Measure."
4) Follow the steps on-screen to perform the calibration using the cylindrical calibration weight (Figure 21) with hook, hanging the weight from each side and selecting "Continue" when prompted. Once complete, the software will advise if the calibration is within specification and will ask to Save or Abort.
5) Recent calibrations are shown in Table 7.

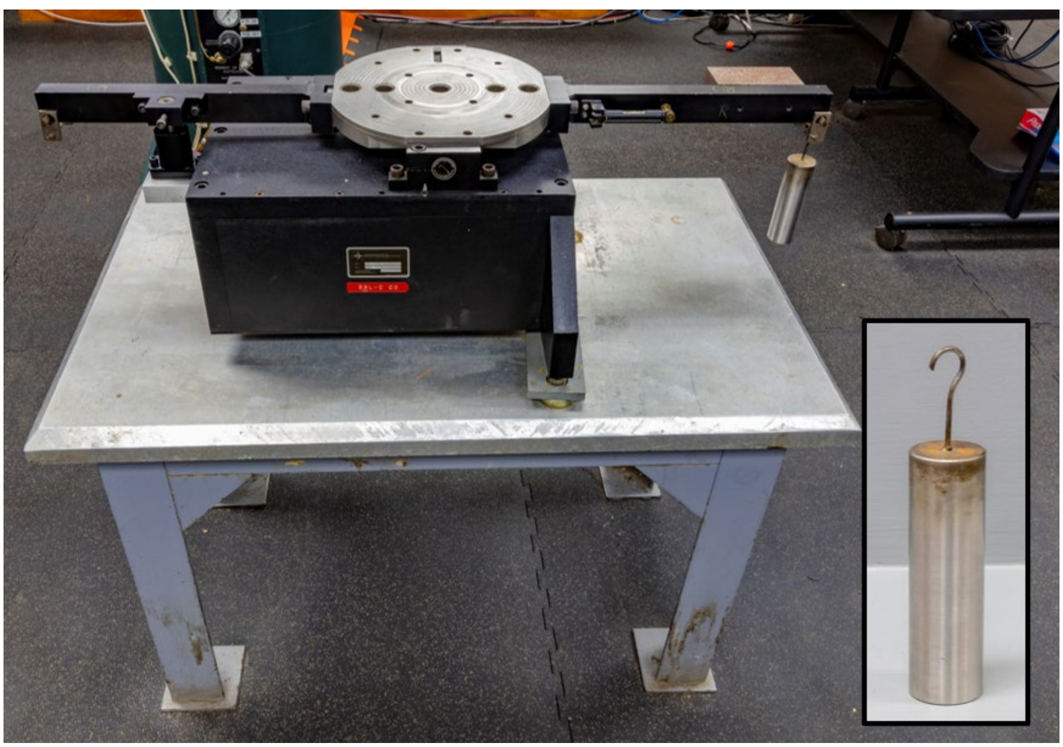


Figure 21. Calibration weight mounted on CG-C machine (calibration weight shown in inset).

Table 7. Calibration constants for CG-C machine.

Position A (g-cm)	Position B (g-cm)
33110	–32770

6.4.2 CG Tare

1) Select CG Tare by clicking the red arrow (or green arrow, if a tare was already selected but needs to be re-run).
2) Select "Measure."
3) Follow the steps on-screen, placing the fixture without any part on the machine surface and selecting "Continue." Once the values have been read, select "Continue." Fill in the fields to name the operator, part_id, and serial; then select "Save."

6.4.3 CG Part Measurement

1) Select CT Part by clicking the red arrow (or green arrow, if a part was recently measured but needs to be re-run).
2) Select "Measure."
3) Follow the steps on-screen, placing the part in the fixture and selecting "Continue." Click "Continue" once the measurements are complete, then fill in the fields and select "Save."

6.5 Obtain the Transverse MOI

The process for obtaining the transverse MOI for medium- and large-caliber projectiles is similar to Section 5.5 for small-caliber parts and projectiles. Other than a different set of machines (MOI B and C machines), the primary difference for medium- and large-caliber projectiles is that a series of MOI measurements are made at locations along the longitudinal axis of the projectile perpendicular to the axis of rotation. From these measurements, the CG location and the MOI at the CG are obtained using the parallel axis theorem. Otherwise, the procedures using the controller software are similar to those used for small-caliber projectiles.

6.5.1 MOI Calibration

Calibration for the MOI-B and MOI-C machines are performed following instructions from the controller software, detailed later in this section. The MOI-B machine uses a large cylindrical weight (labeled "#1-S8203") that fits into the hole on the platform surface (Figure 22).

Figure 22. MOI-B with calibration weight.

Calibration for the MOI-C machine uses a large bar (Figure 23) that screws into the surface top and holds cylindrical weights (labeled "#1-S8203" and "#2-S8204"), on the end of the bars or stacked in the center, depending on the instructions from the software.

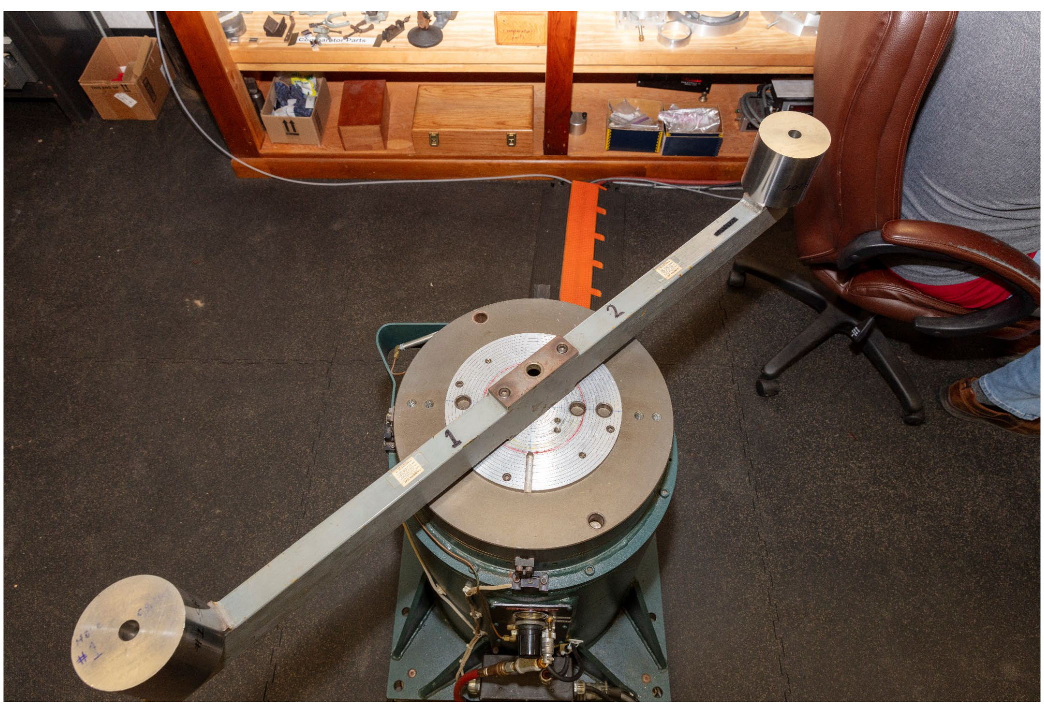


Figure 23. MOI-C calibration bar with weights.

For the MOI-B machine calibration, from the desktop, run the "Multi MOI Controller" application.

1) Select "Measure."
2) On the bottom of the screen, click "Change MOI Instrument" and select "MOI B NKR 40A."
3) Select "Perform Task" under "MOI Calibration," which should have a red dot next to it.
4) Select "New Calibration."
5) Follow the directions on-screen, placing calibration weight "#1-S8203" on the spindle and selecting "Continue."
6) Once complete, remove the calibration weight and select "Continue."
7) Once the calibration is complete, the software will notify if calibration passed.
8) Click "Save and Continue."
9) A recent calibration constant of 177305.31657 g-cm^2/sec^2 was measured.

For the MOI-C machine calibration, from the desktop, run the "Multi MOI Controller" application.

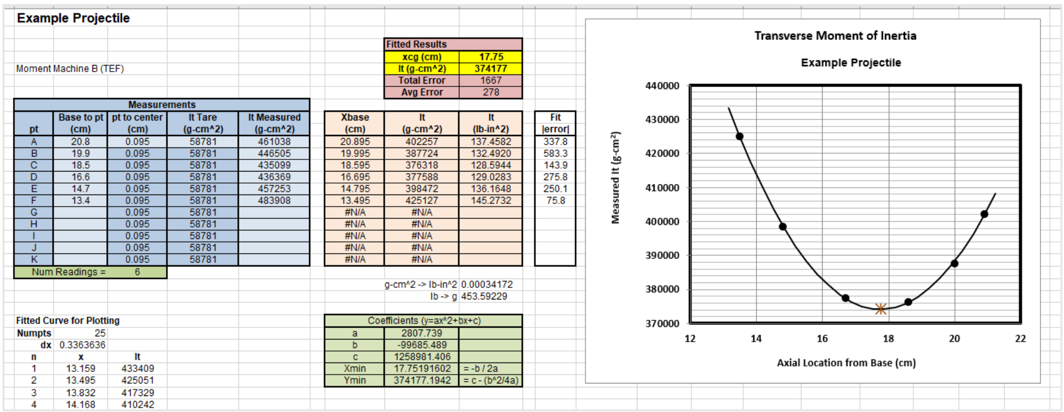
1) Select "Measure."
2) On the bottom of the screen, click "Change MOI Instrument" and select "MOI C NKR 450A."
3) Select "Perform Task" under "MOI Calibration," which should have a red dot next to it.
4) Select "New Calibration" and follow the directions on-screen.
5) Mount calibration beam SE-7888 on the surface plate with two bolts.
6) Place calibration weights #1-S8203 and #2-S8204 in Hole 1 and Hole 2, respectively, located at either end of the bar and click "Continue."
7) Move the calibration weights from Hole 1 and Hole 2 to the center hole and stack them and click "Continue."
8) Once the calibration is performed and passed, fill in the operator and comment field and select "Save and Continue."
9) A recent calibration constant of 5308603.63853 g-cm^2/sec^2 was measured.

6.5.2 MOI Tare, Part, and Calculation

Once the calibration is complete, the MOI Tare, Part, and Calculation steps are completed following the software instructions. The MOI Tare, Part, and Calculation steps are the same as those described in Sections 5.5.2–5.5.4 for small-caliber projectiles.

6.5.3 Calculations to Determine Longitudinal CG Location and MOI at CG

After a series of MOI measurements are made at different (transverse) axial locations relative to the axis of rotation, the measured MOIs are entered in an auxiliary workbook—e.g., New Physical Measurement Sheet (2017-03-01.xlsx). The measured MOI data is plotted versus axial location and a quadratic equation is fit to the measured MOI data. Applying the parallel axis theorem, the axial location where the curve fit of the MOI is a minimum represents the CG location and the MOI at this location is the MOI at the CG. An example of the worksheet is shown in Figure 24.


Example Projectile

Moment Machine B (TEF)

Measurements				
pt	Base to pt (cm)	pt to center (cm)	It Tare (g-cm^2)	It Measured (g-cm^2)
A	20.8	0.095	58781	461038
B	19.9	0.095	58781	446505
C	18.5	0.095	58781	435099
D	16.6	0.095	58781	436369
E	14.7	0.095	58781	457253
F	13.4	0.095	58781	483908
G		0.095	58781	
H		0.095	58781	
I		0.095	58781	
J		0.095	58781	
K		0.095	58781	
Num Readings =		6		

Fitted Results	
xcg (cm)	17.75
It (g-cm^2)	374177
Total Error	1667
Avg Error	278

Xbase (cm)	It (g-cm^2)	It (lb-in^2)	Fit |error|
20.895	402257	137.4582	337.8
19.995	387724	132.4920	583.3
18.595	376318	128.5944	143.9
16.695	377588	129.0283	275.8
14.795	398472	136.1648	250.1
13.495	425127	145.2732	75.8
#N/A	#N/A		
#N/A	#N/A		
#N/A	#N/A		
#N/A	#N/A		
#N/A	#N/A		

g-cm^2 -> lb-in^2 0.00034172
lb -> g 453.59229

Coefficients (y=ax^2+bx+c)		
a	2807.739	
b	-99685.489	
c	1258981.406	
Xmin	17.75191602	= -b / 2a
Ymin	374177.1942	= c - (b^2/4a)

Fitted Curve for Plotting

Numpts 25
dx 0.3363636

n	x	It
1	13.159	433409
2	13.495	425051
3	13.832	417329
4	14.168	410242

Figure 24. Sample worksheet for MOI calculation.

6.6 Obtain the Axial MOI

When using MOI-B and MOI-C machines, a fixture can be used that allows the part/projectile axis to be oriented parallel to the rotational axis of the machine, and the part can be translated perpendicular to that axis. Alternatively, the part can be placed directly on the rotating platform of the machine and translated by hand measurements through the axis of rotation to an axis parallel to it. Note that a TARE measurement needs to be taken when using a fixture, and retaken each time the fixture is moved to translate the projectile axis away from the axis of rotation. The process for obtaining and computing the axial MOI is analogous to the process used for the transverse MOI.

1) Click "Measure" to open the Measure module. Execute the four steps of the MOI measurement process: a) MOI Calibration, b) MOI Tare, c) MOI Part, and d) MOI Calculations. Ensure that the correct MOI instrument is selected.
2) Enter the measured axial MOI data in an auxiliary workbook and determine the CG and MOI at the CG using the parallel axis theorem.

7. Conclusion

The current measurement process for obtaining the physical properties of symmetric projectiles is documented in this report. The theoretical basis for the measurement procedure is the parallel axis theorem, which allows the moment of transverse/axial MOI about the CG to be determined from the measured MOI about an axis parallel to the transverse/axial axis of the projectile using the perpendicular distance between the two axes. Slightly different procedures are used for small-caliber projectiles compared with medium- and large-caliber projectiles. For example, for small-caliber projectiles a specialized machine is used for measurement of the CG location along the projectile's longitudinal axis. In contrast, the MOI measurement process is typically used to determine CG locations for medium- and large-caliber projectiles. The difference in the procedures appears to be necessitated by measurement tolerances associated with the various projectile sizes.

New users should perform preliminary measurements using previously measured projectiles to validate the measurement approach and build confidence in the accuracy of the measurements. Accurate measurements can be obtained with minimal instruction provided care is taken with the measurement process. Computational estimates of the physical properties can also be compared with the measured values, but some differences between the measurements and the computational measurements might be expected if the material density of the individual components is not known with a high degree of confidence or if the as-manufactured parts deviate from the drawings.

8. References

1. Instruction manual model SE199-02 center of gravity instrument. Space Electronics LLC, Berlin, CT; 2021 Sep.
2. Instruction manual models: SE199-02, SE300 center of gravity instrument. Space Electronics LLC, Berlin, CT; 2005 Nov.
3. SE9601 WCG-200 weight and CG instrument operator manual. Space Electronics LLC, Berlin, CT; 2021 Sep.
4. Model GB550AX moment of inertia instrument operating and maintenance manual. Space Electronics LLC, Berlin, CT; 2021 Sep.
5. Moment of inertia SE9598A software manual for XKR, XR & GB instruments. Space Electronics LLC, Berlin, CT; 2021 Sep.
6. Instruction manual models: XKR02, XKR05, XKR1 moment of inertia instrument. Space Electronics LLC, Berlin, CT; 2021 Sep.
7. Instruction manual model XKR02A moment of inertia instrument. Space Electronics LLC, Berlin, CT; 2001 Sep.
8. Guidos BJ, Keppinger RM, Hudler B. ARL Aerodynamics Branch projectile physical measurement inventory. DEVCOM Army Research Laboratory (US); unpublished draft.

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AEF	Aerodynamics Experimental Facility
ARL	Army Research Laboratory
CAD	computer-aided design
cal.	caliber
CG	center of gravity
DEVCOM	U.S. Army Combat Capabilities Development Command
DOS	Disk Operating System
FY	fiscal year
HVAC	heating, ventilation, and air conditioning
MOI	moment of inertia
PC	personal computer
TEF	Transonic Experimental Facility

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