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Implementation of a conformal pressure measurement system for small arms

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Summary

Chamber pressure and its measurement are of paramount importance for the evaluation of the safety and the understanding of the functionality of a firearm. In a rudimentary way, this may be accomplished by proof loads, the concept and the use of which for the proofing of firearms are therefore briefly explained. This leads to definitions on the maximum service load for different calibers and the use of chamber pressure measurements as part of the safety and functionality evaluation procedure for ammunition. Following this is a review of methods for measuring chamber pressure during firing and an overview of standards and standardization bodies for deciding on the suitability of a specific cartridge, or a lot of cartridges, for a firearm. Then, the implementation of a conformal sensor method, to be put into service at FFI, is described. The next two chapters are the user manuals for calibration and measuring, respectively, with the FFI system. The impatient reader, who just wants to perform a chamber pressure measurement with the conformal pressure sensor method should skip directly to there. The final two chapters discuss the results of a calibration effort and a shot-by-shot comparison of chamber pressure measurements. The many appendices contain peripheral information on piezoelectric sensors, a schematic calculation on cartridge expansion, a short primer on statistical methods and a list of parts and materials.

Sammendrag

Kammertrykk og måling av dette er av betydning for evaluering av sikkerhet og forståelse for funksjoneringen til et skytevåpen. Det forklares overordnet hvordan våpenprodusenter forsikrer seg om at kammertrykket ikke er for høyt. Dette fører til definisjoner av maksimalt kammertrykk for forskjellige kalibre og bruk av kammertrykkmålinger som en del av en evalueringsprosedyre for ammunisjon. Det gis en gjennomgang av metoder for måling av kammertrykk under skyting, og en oversikt over standarder og standardiseringsorganer. Deretter beskrives implementeringen av et målesystem med konforme trykkmålere, som skal tas i bruk hos FFI. De neste to kapitlene er brukerhåndbøkene for henholdsvis kalibrering og måling med FFI-systemet. Den utålmodige leser, som bare ønsker å utføre en kammertrykkmåling med konforme trykkmålere, bør hoppe direkte dit. De to siste kapitlene diskuterer resultatene av en kalibrering og en sammenligning av trykkmålinger. Vedleggene inneholder informasjon om piezoelektriske sensorer, en skjematisk beregning av patronutvidelse, en kort innføring i statistiske metoder og en liste over deler og materialer.

Contents

1 Introduction

During firing, a firearm develops high internal pressures that for a too large load or too weak weapon may make the weapon to fracture or fragment. This may lead to injury for the shooter and bystanders. In order to avoid such events, both cartridges and firearms are subjected to strict control and testing before being put into service. This leads to definitions of a maximum chamber pressure for cartridges and a proof load for proofing the firearm. The proof load is a cartridge that develops substantially more pressure than a normal service load for the caliber. Besides being a part of the procedure for verifying ammunition, methods for measuring internal pressure are deployed for developing ammunition and weapons, as well as being a diagnostic tool for problem-solving. Both in the US and in many European countries, decisions on pressures for both service and proof loads are relayed to standardization organizations. In Europe, the Commission Internationale Permanente pour l'Épreuve des Armes à Feu Portatives (Permanent International Commission for the Proof of Small Arms) (C.I.P.) sets the standards. In the US, the Sporting Arms and Ammunition Manufacturers' Institute (SAAMI) decides on standard values. Besides these two civilian organizations, there are also NATO standards. The C.I.P. and the SAAMI are not quite equal in the way they operate. While the C.I.P. is a nation membership organization, the SAAMI is a voluntary organization for manufacturers. All of the organizations mentioned above decide on values for maximum chamber pressure developed by a service load. However, the values are not directly comparable due to the use of different measurement methods. The SAAMI uses a piezoelectric pressure sensor that is pressurized by the outer surface of the cartridge. The C.I.P. and NATO use pressure sensors that are pressurized by the propellant gases through a short channel, either through a hole drilled in the cartridge or just in front of the casing.

The main part of this work was done 2014 to 2017, mainly by Bjørn Hugstedt, until his retirement, and later continued by Andreas Schiller. The weapons and ammunition were handled by Lasse Sundem-Eriksen and Andreas Haugland, which also were instrumental in following up on production and fitting of different parts. Sven Ivar Holm constructed, made the drawings and got the high pressure calibration unit built. Morten Huseby had the original idea for the work, and also programmed the LabView calibration and measurement software. This report is made available to the international small arms community now, in the hope that it may be of help to others, in a field where most such documentation remain internal to government labs.

2 Methods

Figure 2.1 shows a typical pressure versus time graph of the internal pressure inside a cartridge after firing. The measurement has been performed with the conformal method, to be discussed later, and shows the pressure as measured by a piezoelectric pressure sensor that is mounted such as to appear as a part of the chamber wall. The pressure is actually the pressure of the casing onto the sensor, and the casing itself is internally pressurized by the burning powder. The zero time in this recording is somewhat after the bullet is pushed out of the cartridge case. From such a measurement, one often extracts one single value, the maximum pressure. This conformal method is just one of several methods for obtaining either a pressure history or just a measure of the maximum value. Some of the other methods will be explained below.

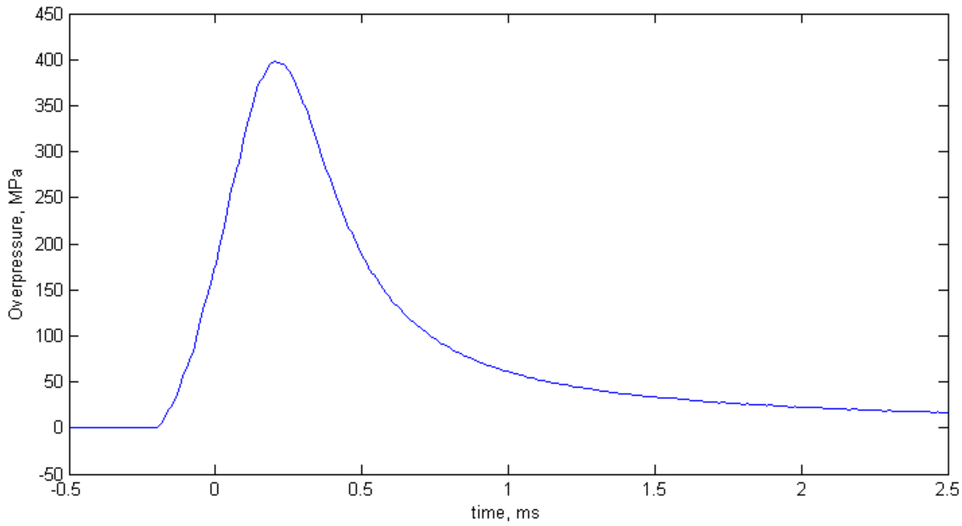

Figure 2.1 Typical pressure versus time graph.

2.1 Copper crusher, lead crusher

This method is based on the deformation of a copper cylinder that is compressed by a piston. The piston runs through a hole drilled into the chamber or bore of the weapon and transfers the gas pressure to the copper cylinder that is crushed against an anvil. The principle is shown in Figure 2.2. The unit of measure is Copper Units of Pressure (CUP) and for smaller pressures one may use Lead Units of Pressure (LUP). For the latter, the more easily deformed lead is used in place of copper. The fabrication and deformation measurement of the copper cylinders must be done with precision. The measured deformation after firing is converted to pressure units, either psi or Pa. With the introduction of piezoelectric pressure sensors in the 1960s, manufacturers abandoned the copper crusher method in favor of piezoelectric sensors.

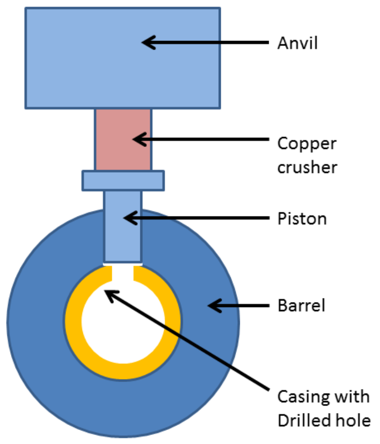

Figure 2.2 Schematics of copper crusher measurement.

2.2 Piezoelectric pressure measurement through drilled casing

Within this method, the piezoelectric pressure sensor is mounted in the chamber wall. Each cartridge is drilled before being inserted into the chamber and the cartridge is aligned so that the combustion gas has direct contact with the sensor. Normally, the sensor is mounted recessed and a protective grid is used. The principle is shown in Figure 2.3.

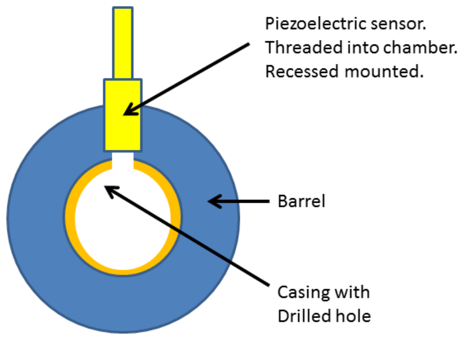

Figure 2.3 Schematics of piezoelectric measurement with drilled casing.

For a recessed mounted transducer, the gas volume is somewhat increased. As an example, consider that the mounting instructions for the Kistler model 6215 [11] piezoelectric pressure sensor requires a minimum 4-mm-long channel with maximum diameter of 5 mm. Using these numbers, the channel from the chamber to the diaphragm of the sensor has a volume of 79 mm^3. For measurements through a drilled casing, the sensor will normally be protected by a thermal protective shield and plate. These parts will also add to the extra volume, but we have no numbers, so we assume that the total added volume may be close to 80 mm^3. According to the table given in Reference [08], the volume of a .308 Winchester casing is 3.54 cm^3 such that the gas volume increases by approximately 2.3%. If we assume that the pressure buildup happens so quickly that there is no or little transfer of thermal energy to the chamber wall, we may calculate the pressure in the increased volume as an adiabatic expansion, see e.g. Reference [30] pages 158 to 159. Hence, if the gas pressure was 400 MPa in a 3.54 cm^3 volume, it will be reduced to 388 MPa in the 80 mm^3 increased volume. With these values, the pressures measured with a recessed mounted sensor may easily be 3 % on the low side. This example calculation is somewhat of a worst case scenario for this caliber, and the measurement standards, to be discussed below, require geometries that typically minimize extra volume. Also, these calculations does not consider the volume of the gunpowder gas after the projectile has started to move, expanding the volume, hence reducing the significance of the added volume of the sensor channel. On the other hand, for a smaller cartridge case, like 9 mm, the increased volume is larger relative to the case of the cartridge case, potentially leading to a larger than 3 % difference. Summarized, the main thing might be to be aware that the measured pressure might not be exactly the same as the pressure before modification of the chamber.

2.3 Piezoelectric pressure measurement in front of casing

Another option is to place the sensor in front of the cartridge case mouth. The mounting of the transducer is similar to the drilled casing method, but the loading of the cartridge is greatly simplified as no special treatment is needed. In this case, the combustion gases will not pressurize the sensor until after the release of the bullet. As for the drilled casing, the sensor is mounted recessed and protected by a grid. Also similar considerations regarding extra volume and diminished pressure readings apply. Figure 2.4 shows a recording of the pressure during firing of a round. The caliber is the 7.62 x 51 mm NATO caliber and the measurement has been done with the Kistler model 6215 pressure sensor.

When the pressure transducer is mounted in front of the casing, the pressure buildup on the sensor is abrupt. This may excite the resonance frequency of the transducer itself, but more likely, it will excite resonances in the gas column in the channel leading from the barrel to the membrane. In Figure 2.4, we may observe an overshoot of the recorded pressure at zero time and oscillations out to 0.7 ms. If we look at the oscillations visible at the pressure maximum, the period is about 26.7 μs giving a frequency of about 37 kHz. Both Kistler and PCB [24] give formulas and numerical examples for the resonance frequency of a gas column or a channel filled with a liquid. The expression for the resonance frequency is $f_r = \frac{v}{4l}$, where f_r is the resonance frequency, v is the speed of sound and l is the length of the channel. Using a speed of sound of 900 m/s which is due to the assumed temperature and pressure conditions, Kistler [11] estimates the resonance frequency to be 75 kHz for a 3-mm-long channel and 25 kHz for a channel of 9 mm length. These values are given in Section 6.3.2. "Influence of a Long Measurement Bore". In our case, the channel from the bore to the protective grid is 2.1 mm, and the protective grid itself (Kistler model 6567) adds two millimeters. If we calculate the resonance frequency of a 4.1-mm-long channel and use 900 m/s as the speed of sound, we obtain about 55 kHz as a resonance frequency. The observed frequency of

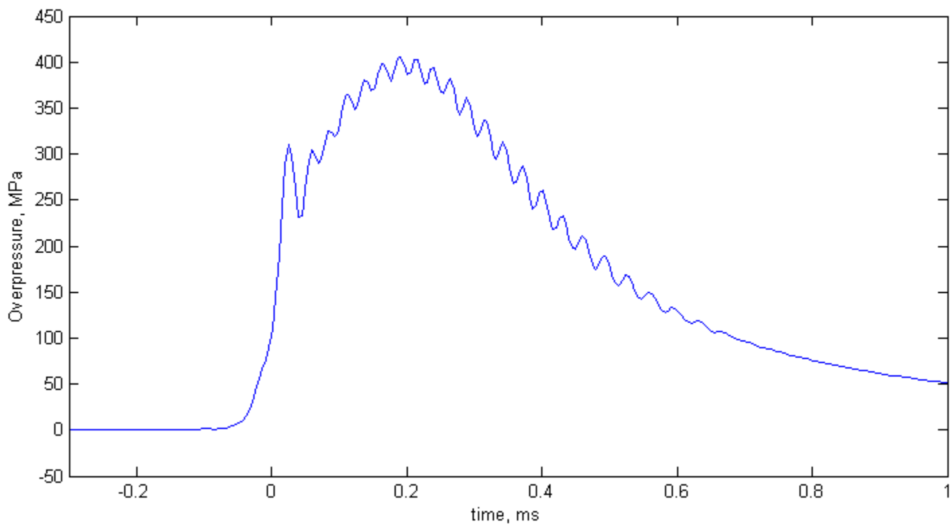

Figure 2.4 Pressure recording using recessed sensor in front of the casing.

37 kHz does not quite agree with the calculation. Our estimate of the length of the channel may be wrong, Kistler's value for the speed of sound may not be correct for our measurement, or they may both be in error.

2.4 Conformal piezoelectric pressure measurement on casing

This method involves a specially shaped, i.e. a conformal sensor that is mounted such as to appear as a part of the chamber wall. No special treatment of the cartridge is needed. The principle is shown in Figure 2.5.

When the round is fired, the cartridge expands until it makes contact with the chamber and the pressure sensor. The initial pressure of expanding the cartridge is not registered by the sensor. Due to this, such a method requires an elaborate calibration process, and furthermore, the calibration must be done for each type of cartridge to be used for the measurements. Figure 2.6 displays simultaneous measurements done with a conformal sensor and a sensor in front of the casing as comparison.

We may again do a guiding calculation for the .308 Winchester casing. The details are given in Appendix B, where the pressure required to expand the casing until it makes contact with the chamber wall is estimated to be 22 MPa. Thus, the pressure measured by a conformal sensor will be 22 MPa lower than the actual pressure inside the cartridge. In this crude calculation, we have assumed that the brass casing does only expand elastically and that the casing length is not restrained. Again, Appendix B gives more details. This model also assumes that the conformal sensor does exactly follow the inner surface of the chamber. In reality, it is difficult to fulfill this requirement and a slightly recessed sensor is preferred. With these assumptions, and an inside pressure of 400 MPa, the pressure measured by a conformal sensor is some 5.5% lower than the internal pressure. This effect is not visible in Figure 2.6. Here, the measurements done in front of the casing and by the conformal sensor seem to agree.

For the conformal sensor, the effect of the casing may be removed by a specific calibration

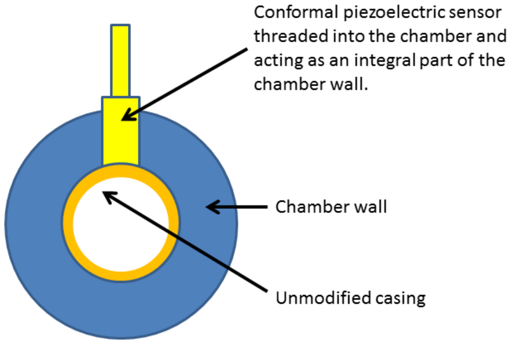

Figure 2.5 Schematics of conformal piezoelectric measurement on the casing.

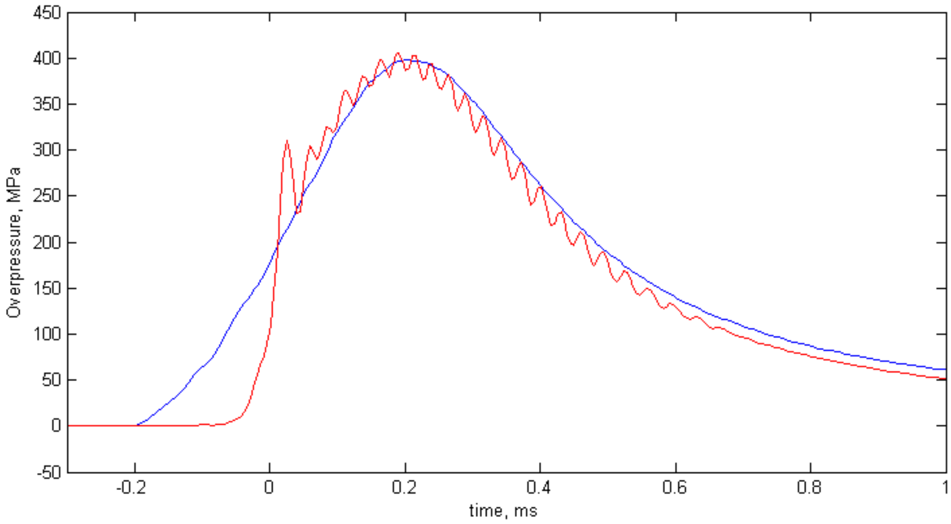

Figure 2.6 Pressure recording using conformal sensor (blue) and sensor in front of the casing (red).

method. The method is explained in Reference [27] and also in Chapter 5 of this document. It involves the use of a high pressure hydraulic pump and a special calibration adapter. The adapter has the same internal shape as the chamber of a weapon for the actual caliber and allows for inserting an empty, but unfired cartridge casing. The casing is internally pressurized up to the calibration pressure while simultaneously the internal pressure as well as the pressure registered by the conformal sensor are monitored. Due to inevitable variations in the casing dimensions and materials, this calibration must be performed for each lot of ammunition which is to be tested.

2.5 Strain gauge placed outside chamber

A strain gauge is an electromechanical measurement device widely used in structural testing. Normally, it consists of a number of parallel metal leads glued onto a polymer backing. When the strain gauge is stretched, the resistance changes proportionally to the strain. For the purpose of measuring chamber pressures, the strain gauge is glued onto the outer chamber wall, where it measures the expansion of the chamber when a round is fired. The deformation of the chamber outer wall is a measure of the inside pressure. This method has the advantage that it neither demands severe modifications of a weapon nor does it require the precision tooling that is needed for mounting piezoelectric pressure sensors. Another advantage is the directionality of strain gauges. They are sensitive to deformation in one direction only. In principle, it is possible to differentiate between elongation and circumferential expansion of the chamber.

3 Standards

At least three organizations publish and maintain standards for measuring chamber pressure (and more). We have already mentioned SAAMI and C.I.P., but also the North Atlantic Treaty Organization (NATO) does publish their own standards. In addition, there may exist measurement procedures and standards derived from or referring to the above. E.g. US military Small Caliber Ammunition Test Procedures (SCATP). Much of our information on this subject is taken from Wikipedia [39].

3.1 ANSI/SAAMI

The Sporting Arms and Ammunition Manufacturers' Institute (SAAMI) maintains and publishes several standards that also are standards maintained by the American National Standards Institute (ANSI). SAAMI was formed in 1926 at the request of the federal government. As stated on the web page, its main tasks are:

- Creating and publishing industry standards for safety, interchangeability, reliability and quality.
- Coordinating technical data.
- Promoting safe and responsible firearm use.

Currently, SAAMI has 28 voting members and 11 supporting members.

The standards are described in several documents that may be viewed and downloaded from the SAAMI homepage [32]. The documents available there contain minimum chamber and maximum cartridge drawings as well as maximum chamber pressures for different calibers, both when a copper crusher and when a piezoelectric transducer is used. This information is contained in Section I - Characteristics. As stated in Section 1 of Reference [34]: *SAAMI recognizes two pressure-measuring systems. The preferred system is the piezoelectric transducer system with the transducer flush-mounted in the chamber of the test barrel.* For the transducer method, the Standard dictates the use of a conformal sensor and specifies the placement of the sensor for different calibers. Transducer placements are given in Section III – Equipment, in the Subsection 'Standard Velocity and Pressure Test Barrels'. For instance, for the .308 Winchester (7.62 mm) one shall use a 1/4 inch (6.35 mm) transducer, which is placed with its centerline 0.175 inch (4.44 mm) behind the shell case shoulder. Furthermore, SAAMI specifies in this case a PCB Model 117B44 transducer or equivalent. Observe that the 1992 version of the SAAMI standard document [33] has now been superseeded by the 2015 document [34].

SAAMI specifies the Maximum Probable Lot Mean (MPLM) as the maximum pressure for a particular caliber. Based on experiment and statistical evaluation, SAAMI has established the Maximum Average Pressure (MAP) to be used as the loading limit and this is also the value that should be reached by pressure measurements. The MAP is defined to be two *standard errors* (definition follows) below the MPLM. SAAMI uses specific definitions for the standard deviation and standard error. Also the units foot (ft) and pounds per square inch (psi) are used throughout the document of this US based organization. The standard deviation is based on a *Coefficient of Variation* of 4%. According to this, a sample with a MAP of say 62 kpsi (427 MPa) will have a standard deviation of 4% of 62 kpsi or 2.48 kpsi (17 MPa).

The *standard error* as defined by SAAMI is the standard deviation divided by the square root of the sample size (with a typical sample size of 10). Mathematically, this is the standard deviation

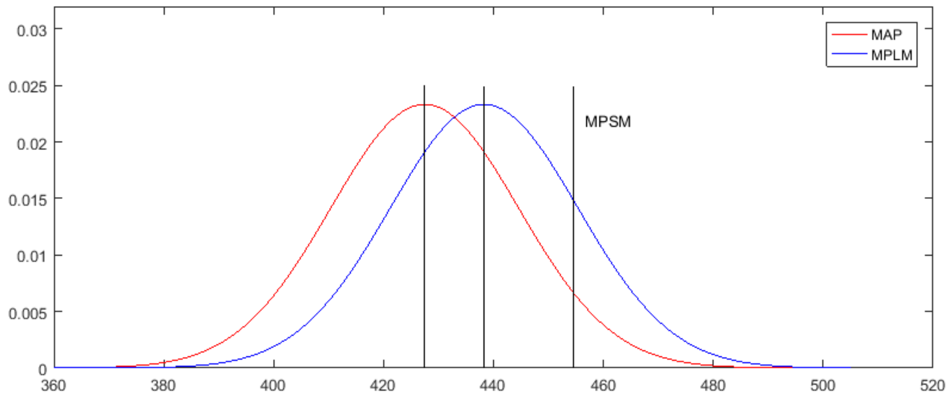

Figure 3.1 The relation between Maximum Average Pressure (MAP), Maximum Probable Lot Mean (MPLM) and Maximum Probable Sample Mean (MPSM). For details, see text.

of the mean as explained in Appendix C, Section C.2. With these definitions, the aforementioned relationship between MPLM and MAP assures that there is a 97.5% probability that the MPLM pressure is not exceeded. For further explanations, see the discussion of the 68-95-99.7 rule in Appendix C, Section C.2. For the .308 Winchester, the MPLM is 63.6 kpsi (439 MPa), while the MAP is 62.0 kpsi according to the tables to be used with the transducer (conformal method). The standard deviation (4%) of the MAP is 2.48 kpsi. This gives a standard error of 0.784 kpsi (5.41 MPa) for a sample size of ten. The MAP of 62.0 kpsi plus twice the standard error of 0.784 kpsi gives, as expected, 63.6 kpsi, when rounded to the nearest tenth. Finally, a Maximum Probable Sample Mean (MPSM) is defined as three *standard errors* above the MPLM, hence five *standard errors* above the MAP. The relationship between these values are shown in Figure 3.1.

SAAMI members supply definitive proof loads for some calibers. Briefly put, the proof loads produce a maximum pressure between 1.3 and 1.4 times the MPLM pressure. Values are given both for the conformal sensor and the copper crusher. It is further stated that the proof cartridges are loaded with the heaviest bullet for the particular cartridge. Also, the slowest burning powder that meets the pressure values shall be used.

3.2 C.I.P.

La Commission Internationale Permanente pour l'Épreuve des Armes à Feu Portatives (The Permanent International Commission for the Proof of Small Arms) was formed in 1914 and has its headquarters in Brussels, Belgium. The C.I.P. is a member organization for nations and as of 2015 the members are the national governments of 14 countries, out of which 11 are European Union members. The C.I.P. proof-tests all firearms sold to civilians in the member states. The front page of the C.I.P. website reads: *FUNCTION OF THE C.I.P. In compliance with the 1969 Convention, its Rules and Regulations, and C.I.P. Decisions, every small arm together with all highly stressed component parts must undergo lawful testing in the Proof House of the C.I.P. Member State in which the manufacturer is located or, for imported weapons, in the Proof House of the Member State into which they have been imported for the first time. The same applies for commercial ammunition.*

For the purpose of measuring the chamber pressure, C.I.P. uses a drilled casing to expose the piezoelectric pressure sensor directly to the propellant gases. When it comes to the dimensions of cartridge and chamber, these values are given in C.I.P. Tables of Dimensions of Cartridges and Chambers (TDCC). The tables may be downloaded from the C.I.P. homepage [02]. The tables give maximum cartridge and minimum chamber dimensions as well as the location of the pressure sensor. The latter is designated by the capital letter M. Values are given in mm and the measure is from the breach face. For the .308 Winchester (7.62 x 51 mm NATO caliber), the TDCC specifies that the pressure sensor is to be mounted 25 mm from the breach face. The maximum pressure p_{max} is given as 4150 bar, i.e., 415 MPa. The information given on the C.I.P. homepage is far from exhaustive, but a member state may have access to more detailed descriptions. As the C.I.P. delegates proofing of firearms and ammunition testing to the proof houses of the member states, more information may be found e.g. from the Birmingham Proof House [29] or the Worshipful Company of Gunmakers. Under the heading 'Proof House' the Gunmakers state that depending on the gun, the proof charge should exceed the maximum service load by between 25% to 50%. At Birmingham, from the menu item 'Proof Memoranda', one may find the Rules of Proof 2006. This document specifies the proof load to be such as to produce a pressure that is 30% higher than the pressure developed by the service load. Also, for the sake of pressure tests, the number of cartridges to be tested are between 20 and 50 depending on the size of the lot. It is simply stated that: *Pressure values must not exceed those laid down by the C.I.P.*

3.3 NATO (EPVAT)

NATO maintains and distributes several standards among member nations and others. Several unclassified NATO documents are publicly available. Procedures for measuring chamber pressure for 5.56 mm, 7.62 mm, 9 mm and 12.7 mm cartridges are contained within the document MULTI CALIBRE MANUAL OF PROOF AND INSPECTION (M-C MOPI) [01]. This is a document of approximately 450 pages and contains among others, the Sections 'NATO Reference Cartridges', 'Link Test Procedure', 'Smoke and Flash Test Procedure', 'Terminal Effects Test Procedure', 'Precision Test Procedure', as well as information on mounting and calibration of transducers, preparing the test barrel and much more. Procedures for pressure measurements are described in Section 12 'Combination Electronic Pressure Velocity & Action Time (EPVAT) Test Procedure'. We have not been able to locate the M-C MOPI document among NATO's publicly available documents [16], but it is available internally at FFI. The EPVAT test procedure requires the use of piezoelectric pressure sensors, either the Kistler model 6215 or model 6203 sensor. The model 6215 is to be used with 5.56 mm, 7.62 mm and 12.7 mm cartridges and also for new 9 mm designs. The Kistler model 6203 is to be used for production testing of 9 mm cartridges of existing NATO qualified designs. The charge amplifier shall have a frequency response that ranges from direct current (DC) to 100 kHz. To numerically suppress gas column oscillations, one shall use a Butterworth [40] type low pass filter with a cut-off frequency of either 20 kHz or 22 kHz for the calibres 5.6 mm, 7.62 mm and 9 mm. For 12.7 mm ammunition, a cut-off frequency of 10 kHz shall be used. Drawings for the mounting of transducers are provided in Section 6 of the M-C MOPI. For the 7.62 x 51 mm caliber, the transducer mounting details are given in Drawing 12-(7.62mm)-2. The center of the transducer is 54 mm from the breach face, i.e. in front of the case mouth.

As discussed in Section 2.2, the recessed sensor increases the volume of expansion of the gas. The EPVAT specifies a very short and narrow channel that widens out in front of the Kistler model 6215 sensor. This channel and the widening section amounts to a volume of about 18 mm^3.

According to the instruction manual for the Kistler model 6215 sensor [11], the dead volume due to a slightly recessed membrane in the sensor face itself is about 10 mm^3, while the four holes in the model 6567 sensor's protective plate add about 6 mm^3. In total, the EPVAT mounting arrangement adds around 34 mm^3 to the casing volume. For a .308 Winchester cartridge, if the maximum pressure without any added volume was, say, 400 MPa, it will be reduced to 394 MPa due to the sensor mounting arrangement. I.e. the EPVAT measurements will be 1.5% on the low side due to the added volume.

The EPVAT procedure requires testing at 21°C, 52°C and -54°C. At each temperature, a sample of 30 rounds from the lot shall be fired. The standard specifies warming shots, firing of reference ammunition, and cleaning and re-torquing of the transducer before and between the firing of the test samples. At 21°C, testing 7.62 mm ammunition and using the case mouth mounted Kistler model 6215 sensor, the EPVAT gives the value of 445 MPa as the *Maximum Corrected Mean Case Mouth Pressure + 3 SD for 21°C sample*. The Standard Deviation (SD), or better, the corrected standard deviation shall be calculated with the formula given in Equation C.2 in Appendix C. The addition of three times the corrected standard deviation makes it difficult to compare the limit to the limits given by SAAMI and C.I.P., but we may, in order to be able to perform such a comparison, use the corrected standard deviation obtained from the 10 fired shots given in Table C.1 of Appendix C, which is 7.42 MPa. The mean of these 10 shots amounts to 384 MPa. The corrected standard deviation is in agreement with the values given in Reference [08] in the Tables 3A and 3B of Chapter 14 'Pressure Measurements'. Here, the standard deviations are 10 MPa and just above 6 MPa, respectively, each calculated from the values of 5 single shots measured simultaneously with two Kistler model 6203 sensors. The sample given in Table C.1 has a mean + 3 SD value of close to 406 MPa. Thus, the sample shown in Table C.1 is well below the EPVAT limit of 445 MPa, but nevertheless does not fulfill EPVAT demands since only 10 shots out of a required number of 30 shots have been fired. For a comparison between SAAMI, C.I.P. and NATO standards, see Table 3.1.

3.4 US military SCATP

United States Armed Forces define additional standards for maximum chamber pressure [39]. The document MIL-C-46931F specifies this for the 7.62 mm caliber. Measurements may be done using the copper crusher method or the EPVAT test method. The document is dated 29 March 1991 and we were able to retrieve it from www.everyspec.com. There also seems to be a few documents available at a fee from www.globalspec.com. Otherwise, further information on the SCATP is scarce. Measurements shall be performed at three different temperatures, which are 70°F, 125°F and -65°F, which translate to 21°C, 52°C and -54°C, respectively. Note that the temperatures are the same as for the EPVAT procedure. For the maximum pressures we may cite the MIL-C-46931F document. *3.7.1.2 Chamber pressure measurement at 70°F by EPVAT test method. The average chamber pressure of the sample cartridges conditioned at 70°F shall not exceed 365 MegaPascals (MPa) (52,940 psi). The average chamber pressure plus three standard deviations of the chamber pressure shall not exceed 400 MPa (58,016 psi). The chamber pressure of an individual sample cartridge shall not exceed 400 MPa (58,016 psi).* The assessment of the measurements is somewhat comparable to the procedures of the EPVAT, but the maximum pressure plus three standard deviations is about 10% lower. We have not been able to retrieve any further information on the SCATP.

3.5 Comparison of the standards given by SAAMI, C.I.P. and NATO (EPVAT)

The different standards dictate measurement methods that are not easily comparable. Therefore, also the maximum chamber pressure for a specific caliber will depend on the method of measurement and the statistical procedure used to assess the measurements. Table 3.1 lists some of the published pressures for the 7.62 x 51 mm NATO caliber. The values found in the standards and reproduced here are Maximum Average Pressures (MAPs) as calculated from a sample of measurements. The EPVAT does not directly give a limit on the MAP itself. Instead, the MAP + 3 standard deviations are tabulated. We estimate a value for the MAP by subtracting 3 times 7.42 MPa. This is a value for the standard deviation obtained by our own measurements. When we use this value, the three organizations are not that different. The values (for the transducer methods) are 415 MPa, 423 MPa and 427 MPa, for the C.I.P., EPVAT and SAAMI, respectively. The difference between the largest and the smallest value is about 3%. We may recall that the recessed sensor mounting (C.I.P. and EPVAT) is expected to give measurements on the low side, while a properly calibrated conformal sensor measurement (SAAMI) will reflect the internal pressure of an unmodified cartridge. With this consideration in mind, one might say that the SAAMI pressure limit is the highest one.

7.62 mm cartridge	Organization		
	SAAMI	C.I.P.	EPVAT
Sample size	10	20 . . . 50[1)]	30[2)]
p_{max}, crusher	358 MPa		
p_{max} + 3 SD, case mouth			445 MPa
p_{max}, case mouth			423 MPa[3)]
p_{max}, drilled case		415 MPa	
p_{max}, conformal	427 MPa		

Table 3.1 Comparison of SAAMI, C.I.P. and EPVAT sample size and Maximum Average Pressure values.
1) The C.I.P. requires a sample size that increases with lot size, see [29] for details.
2) The EPVAT requires 30 rounds each at three given temperatures.
3) Calculated value by assuming a standard deviation of 7.42 MPa.

4 Development of a conformal measurement system

The principle of using a conformal sensor is shown in Chapter 2, Figure 2.5. The sensor face is shaped such as to follow the curvature of the chamber wall. For tapered cartridges, this also implies a specific orientation of the sensor. When an unfired cartridge is placed in the chamber, there is a clearance to the chamber wall. This is necessary for an easy extraction of the cartridge after the round is fired. The same applies for the calibration adapter, that is made to the same dimensions as the weapons chamber. When the pressure in the cartridge increases, there is a pressure range where the cartridge expands before it touches the conformal sensor and any pressure is applied to it. As shown in Appendix B the cartridge wall will most likely be stressed into the regime of plastic deformation. When this is the case, the metal will not return to its original shape when the pressure is released. Altogether, the conformal measurement method requires an elaborate calibration where the influence of the casing is determined and later added to the measured results. PCB Piezotronics [28] seems to be the sole supplier of equipment for calibration and measurements with the conformal sensor method. Thus, the information released by PCB is the authoritative guide to the use of conformal sensors.

Figure 4.1 Cut-out model of a PCB conformal calibration adapter.

4.1 Principles of the conformal sensor calibrator

Section 2.4 gives an overview of the special calibration method that should be used with the conformal pressure measurement method. Figure 4.1 shows the central part of such a system, i.e., a cut-out model of a calibration adapter. As mentioned, this must be fabricated for each caliber and the internal cavity is an exact copy of the chamber of the firearm used for firing the cartridge. The inlet of the adapter (not shown in the cut-out model) is connected to a hydraulic high pressure pump with a reference sensor to measure the oil pressure. Simultaneously reading off the conformal sensor and the oil pressure sensor will create a calibration table that relates the pressure measured by the conformal sensor to the internal pressure inside the casing.

4.2 Design and implementation of the conformal sensor calibrator

As the conformal pressure sensors are produced by PCB Inc., we decided that we just as well use the PCB calibration adapters. These adapters are fabricated with the correct mounting for the particular pressure sensors to be calibrated. The calibration adapters contain four major parts, which are the chamber, the cartridge case retainer, the chamber adapter, and the retaining nut. Calibration adapters for several calibers were obtained from PCB Inc. [28]. The high pressure pump is fabricated by the Prototype Workshop (PTV) at the Norwegian Defence Research Establishment (FFI).

All solutions seem to base their pressure pumps on a pressure cylinder where a rod is pushed into a volume of pressurized hydraulic oil. Looking through the pressure limits given by SAAMI, the highest Maximum Average Pressure tabulated is 65 kpsi or about 450 MPa. Based on this, we decided that a maximum pressure of 500 MPa would be sufficient for the calibration high pressure pump. The valves, tubing, fittings and indicators must be of equal or better pressure rating. Valves and fittings, as well as the central manometer were obtained from Valnor [38]. The producer is the US based 'High Pressure Equipment Company' [07]. A list of parts for the calibration pump station is given in Appendix D.

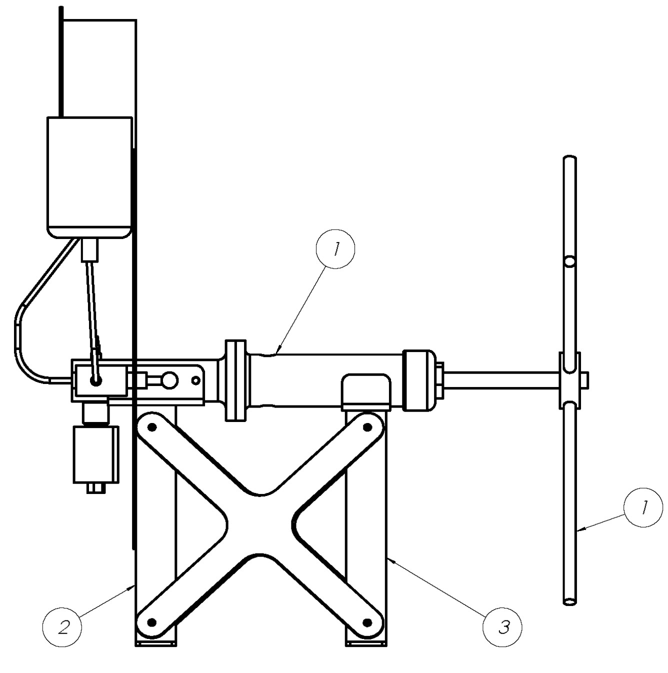

Figure 4.2 Complete system for conformal calibration, side-view.
1 - plunger housing, 2,3 - table stand, 1 - pump handle.

The central plunger of the high pressure pump is 6 mm in diameter. When it forces the oil out of the cylinder, it will have to withstand a force of about 14 kN, which is about the weight of a mass of 1.4 metric tons. There is a concern whether or not the rod needs to be fabricated out of hardened steel. By experiment we found out that it does not need to be - barely. With careful use, we may get by with a silver steel rod. During the first test, the target pressure was reached on the first attempt, but the next attempt failed and the piston rod was bent. We believe that this happens when a great force is applied and the rod has a long free length. Later on, we obtained a hardened steel rod from 'Form og Stanseteknikk' [05]. During several pressure tests up to 500 MPa, no tendency for the rod to bend was observed. The construction drawing reproduced in Figure 4.2 shows the side-view of the completed system, while Figure 4.3 shows the same construction seen from the back. The

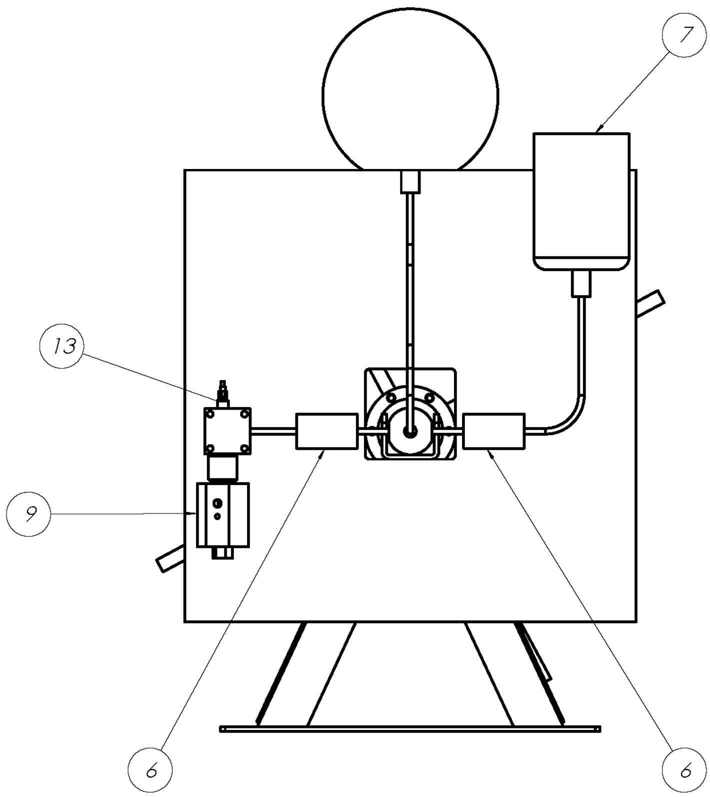

Figure 4.3 Complete system for conformal calibration, back-view.
6,6 - high pressure valve on chamber side and reservoir side, 7 - reservoir for hydraulic oil, 9 - calibration chamber, 13 - reference sensor.

different parts are pointed out. The high pressure valve visible on the chamber adapter side has later been removed. The complete calibration system has maximum dimensions of (W x D x H) 50 cm x 75 cm x 80 cm.

4.2.1 First test of the complete calibration system

Once assembled, the calibration system failed to reach the target pressure of 500 MPa. Actually, we did only reach about 200 MPa. Operating the piston several times with the reservoir valve open forced some air out of the system and we were able to reach 500 MPa with both valves closed. Following this, we opened the valve on the chamber side to the calibration chamber and managed to reach about 400 MPa. At that point, there was a small, but sudden drop in pressure. Some leakage around the piston was observed, but this does not explain why we could not obtain sufficient pressure with the calibration chamber connected. There was also some leakage around the retaining nut that connects the calibration chamber to the chamber adapter. Whether this is from the mount to the pressure manifold or from the chamber adapter itself is not known. During disassembly it was discovered that there was very little oil in the calibration chamber, although it was topped off before being pushed onto the calibration adapter. Hence, we cannot rule out the possibility that there was some amount of air trapped in the cartridge case inside the calibration chamber. More likely, we sucked oil out of the chamber while extracting the piston. On disassembly, we observed that the O-ring on the chamber adapter was badly scarred. This seal probably needs to be replaced each time the chamber is removed from the chamber adapter.

After this not so successful event, we tightened the packing nut inside the pump housing. Further instructions for maintaining the high pressure pump is given in Section 5.3.6. Tightening compresses the PTFE (teflon) tube that is the sealing part around the piston. At this point, the calibration chamber and reference sensor had been removed, and the valve to the reference sensor and calibration chamber was closed. Now it was no problem to take the pressure up to 500 MPa.

4.2.2 Second test of the complete calibration system

Once again we mounted the calibration adapter with a torqued of 25 Nm and the O-ring replaced. We started by sucking some oil into the pump with the reservoir valve open and the calibration chamber side valve closed. Then, with the reservoir valve closed and the calibration chamber side valve open, we turned the handle clockwise to pump some oil until it started dripping for the chamber adapter. Now, we topped off the calibration chamber, casing inserted, with oil and pushed it onto the chamber adapter. Then, we filled up the threaded hole for the reference sensor and mounted the Kistler model 6213BK pressure sensor with a torque of 20 Nm. We then closed the valve to the calibration chamber and opened the one to the reservoir. We turned the handle counter-clockwise to the outermost position, closed the reservoir valve, opened the valve to the calibration chamber and turned the pump handle clockwise. We had obtained only 350 MPa, when the pump handle had reached the inner position.

This did not look good, but we nevertheless performed three more attempts, without removing the chamber. In all three attempts, we now reached the target pressure of 500 MPa. Going from zero to 500 MPa takes about one minute. There were the usual leaks from the piston seal, we also saw some oil at the top of the calibration chamber valve and some on the top of the calibration chamber itself.

4.2.3 Third test of the complete calibration system

In an attempt to get the piston seal somewhat tighter, we arranged for polishing the hardened steel piston. The procedure for replacing this part is quite cumbersome. After replacement, but without the calibration chamber, we took the pressure up to 500 MPa without any problems. The piston was still not fully inserted. Hence, by turning the handle to counteract the pressure loss through leakage, we could maintain a pressure of 500 MPa for a while. Nevertheless, there was still some leakage from the piston, or nearby. We cannot obtain a better piston so we must consider tightening the compression nut to obtain a tighter seal with the PTFE packing.

As a guide to estimate the required torque to produce a tight seal, we may assume that the pressure in the PTFE packing needs to be at least equal to the desired pressure of the hydraulic oil. We call this the packing pressure p_{pack}. At this pressure, the force on the face of the packing nut is $F_{\text{pack}} = A_{\text{pack}} p_{\text{pack}}$ where A_{pack} is the face of the bolt which compresses the PTFE packing. Turning the nut advances it by a distance d_{thread} per revolution. The work done on the packing will be $F_{\text{pack}} d_{\text{thread}}$. If we neglect friction, this should be equal to the work done on the handle of a torque wrench when tightening the nut. Given the force on the handle F_{hand} and the length of the wrench R_{hand}, the work done is $F_{\text{hand}} 2\pi R_{\text{hand}}$. Equating this with the previous expression produces

$$F_{\text{hand}} R_{\text{hand}} = \frac{1}{2\pi} p_{\text{pack}} A_{\text{pack}} d_{\text{thread}}, \tag{4.1}$$

which is the torque needed to obtain the given pressure in the PTFE packing. The packing sleeve has an outer diameter of 14 mm with a central hole for the plunger of 6 mm diameter, so the area of its face is $40\,\pi$ mm^2. With a desired pressure of 500 MPa and a thread pitch of 1.5 mm, we end up with a torque of precisely 15 Nm. This number is probably way too low as we have not included any friction. The effect of friction must be so large that the nut is not pushed out by the packing. We can therefore use this value only as a rough guide for the required torque to tighten the packing.

Inspired by this, we tightened the packing nut to a torque of 30 Nm. Without pressure, the handle still turned without any noticeable resistance. We closed the valve on the calibration chamber side and with the valve to the reservoir open, we pulled the plunger to the outmost position. Now we closed the valve to the reservoir side and were easily able to take the pressure up to 500 MPa. Continued turning of the handle to counteract pressure loss through leakage, we kept the pressure at 500 MPa for nearly 5 minutes. There was a small amount of oil on the plunger seal, maybe a drop or two. Our impression is that the high pressure pump itself is capable of maintaining the required pressure over a time long enough to take measurements.

While we were at it, we also tightened the gland nut on the high pressure valve on the calibration chamber side. We had no suitable torque wrench available, so we used a 26 mm wrench and turned the nut 1/12 or 1/6 rotation. It actually felt quite tight, but the force to turn the valve handle was about the same as always.

4.2.4 Fourth test of the complete calibration system

The conformal pressure sensor had been removed meanwhile, so we remounted it. The same shims ring (0.33 mm) gave a correct seating of the sensor in the calibration chamber. We also noted that a slice of the O-ring was still inside the chamber. Again, we inserted an empty cartridge with primer cap fired in the calibration chamber and tightened the nut until it seated flush against the inner surface. Then, we pushed the calibration chamber onto the adapter, following the now familiar procedure. Turning the handle quite fast, we managed to reach 490 MPa within 1 minute. We still saw some drops of oil on the plunger seal and there was still some oil leaking from the calibration chamber side high pressure valve. Nevertheless, we nearly reached the desired pressure with a new cartridge in the first try. This performance would be sufficient for a calibration run as the expected gas pressure, as shown in e.g. Figure 2.6, is just below 400 MPa.

We then released the pressure by operating the handle and eventually opening the reservoir valve. Without removing the cartridge casing, we operated the valves and the handle to start a new pressure cycle. This time, we reached 500 MPa within 1 minute and by continuing turning the pump handle, we maintained the pressure at this level for 2 minutes. As there are still some leaks, we may consider to further tighten the seal compression nuts, both on the central plunger and the calibration chamber side high pressure valve.

4.2.5 Fifth test of the complete calibration system

Previously, we had tightened the gland nut on the calibration chamber side high pressure valve. The handle was then quite hard to turn. Further tightening will make the valve impossible to operate. We also saw some leaks from the plunger, so we tightened the packing nut to 45 Nm. Still, the pump handle operates easily. With both valves closed, we easily reached 500 MPa. By continuing turning the handle, we maintained the pressure for 12 minutes which is when the handle reached the innermost position. It seems that the packing nut must be retightened regularly. Also, we must consider removing the high pressure valve on the calibration chamber side. During normal operation, it hardly has any function as it is always open.

4.2.6 Removing the high pressure valve on the calibration chamber side

Although we had tightened the packing on the high pressure valve on the calibration chamber side to the point were the handle is hard to operate, there are still leaks from the valve. We believe this is because the packing has to take the full pressure when the valve is open and the calibration chamber is pressurized. This valve has hardly any function at all during normal operation. The valve on the reservoir side is of the same model, but when closed, the pressure is working against the inner needle mechanism and the packing is not pressurized. We have never seen any leaks from this valve. Photographs of the complete system with the calibration chamber side pressure valve removed are shown in Figure 4.4.

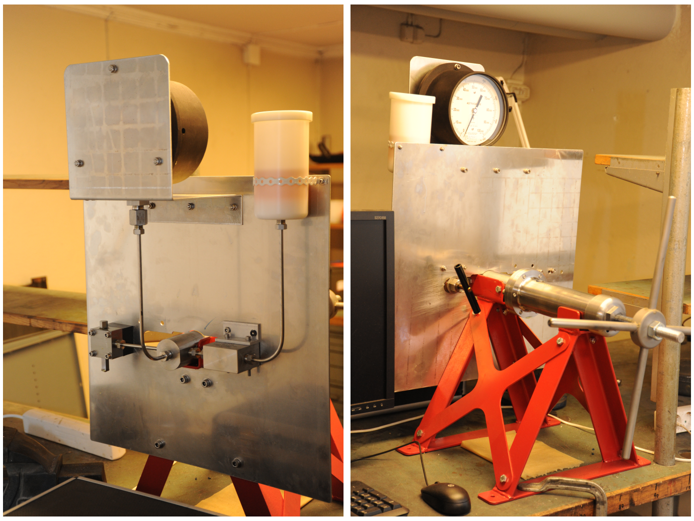

Figure 4.4 Photographs of the complete system for conformal calibration. Left: backside view with oil reservoar on top right. Right: front view with pressure meter on top, pump handle with plunger and valve handle to the left of the plunger.

Removing the high pressure valve on the calibration chamber side does create one problem, however. Now, there is no simple method for testing the high pressure pump by itself. To allow for this, we fabricated plugs to seal the mounting holes for the chamber adapter as well as the Kistler model 6213BK pressure sensor. For the chamber adapter plug, we simply use the same steel seal ring as the actual adapter. For the plug on the sensor side, we did not produce such an elaborate sealing system as Kistler uses, but assumed that we would get a good enough seal with a metal washer. This seems not to be the case, as a brass washer did only seal up to around 300 MPa, even when mounted with a torque in excess of 20 Nm. We also tried a 6 x 10 x 1 mm soft copper ring from Otto Olsen [21], with the same result. As a consequence, the plug on the reference sensor port can only be used for protection and testing at lower pressures.

4.2.7 Additional use of high pressure pump

While the calibration system is primarily intended to be used with the conformal calibration adapters, there is also an option to use it for a quasi static comparison between two pressure sensors. The pressure port where the PCB calibration adapters is to be mounted is the same as a *standard mounting port* for PCB models 118A, 108A, 119A and 109A pressure sensors. These sensors could be mounted without any alterations. To make the high pressure calibrator available for more than the calibration adapters of the PCB model 090B series and the listed PCB sensors, we fabricated adapters that fit onto the same port, but allow for mounting e.g. the Kistler model 6215 pressure sensor.

4.3 Data acquisition during calibration

As explained above, the readings of the reference and conformal pressure sensors shall be done simultaneously and at several predefined pressure values. Since the operator will be fully occupied with the high pressure pump, it is most convenient that an automated computer program does the data acquisition and at the same time, checks that the pressure never decreases - with the exception of possible noise, hence there is a (very small) maximum accepted temporary pressure decrease. Also, the system ensures that the measurement time is well below the charge amplifier time constant.

We may use the information given in Reference [25] as a starting point for designing the data acquisition system for calibration purposes. The manual describes an improved technique for calibrating a conformal sensor by not only providing a single sensitivity value, but instead producing the slope and offset value for a displaced calibration line. The examples given seem to have up to ten measurement points. We may also mention that the usual calibration chart for the PCB model 117B44 sensor has measurements for six separate pressure values.

Using a computer based system, there is no problem handling even more points, but this will be of little value as the conformal sensor nonlinearity is around 1.5%, while the claim for the reference sensor (Kistler model 6213BK) is to have a nonlinearity of 0.3%. Still, acquiring more values at each calibration point will give the possibility to even out noise and also to provide a measure of the noise level. The operation manual [23] recommends using intervals of 5000 psi (35 MPa) for sensors with a full scale range of 40000 psi (276 MPa) or less. For sensors with a full scale range above 40000 psi, intervals of 10000 psi (69 MPa) are recommended. As a starting point, we may use calibration points at 10 MPa intervals, but this should be a configuration setting. During calibration, the values obtained may also be safeguarded, so as to reject the calibration when outlier values are encountered and when an unreasonably wide distribution is seen.

As explained in Appendix A.2, the amplifier to be used with a piezoelectric sensor is a very low input impedance, current-integrating amplifier. The output voltage is proportional to the charge that equalizes the surface charge of the sensing quartz crystal. The combination of such a sensor, a cable and the amplifier will not retain the integrated charge for eternity, rather the charge will slowly leak away. The amplifier will normally have a selector for the time constant, but the longest obtainable time constant is given by the insulation resistance and the drift of the system. Such measurements are regarded as quasi-static. For the Kistler model 6213BK, the instruction manual [10] gives some advise on the drift of the output signal of the amplifier. The Subsection "4.4 Measuring quasistatic phenomena" contains: *With an insulation resistance of* $10^{13}\ \Omega$ *and 0.03 pC/s sensor drift current, using a high-pressure sensor there is an error of 1 bar/minute. With a measuring range of 1000 bar the resulting error is thus ~1% if the measurement lasts 10 minutes.* We must take these values to be representative and since we aim at reaching a pressure of 500 MPa (5000 bar), the error due to leakage and drift may be neglected if a calibration run is completed within, say, 1 minute.

Following the above consideration, we find that within at most 1 minute the pressure on the reference sensor has to increase from zero to 500 MPa, i.e. by a rate of at least 8.3 MPa/s. There may be some variation in the rate of pressure increase, with an estimated maximum rate of, say, 25 MPa/s. Under this assumption, we need to save values in 0.4 s intervals, corresponding to 10 MPa pressure intervals. In order to locate a value within 1 MPa, we must perform 25 measurements each second, i.e. one measurement each 0.04 s. The details of how to collect data during calibration will probably need some experimentation.

The dataset stored for each calibration run should in addition to the actual measurements contain the date, time, operator, reference sensor type and serial number, conformal sensor type and serial number, conformal adapter type and serial number and the high pressure pump type and serial number. The settings of the charge amplifier should be recorded as well. For conformal calibration, the cartridges used are an integral part of the calibration, so the lot number of the ammunition (and probably more) must also be stored. Also, the version number of the software could be of interest at a later time, so this should better be stored as well. In addition to the calibration values themselves, all data used for the calculations should be stored.

During pressure buildup, there is no time for pauses. So when a single operator is to perform the calibration, it is favorable that the data acquisition is done automatically. Preferably, the user interface should be large and at least the most important information should be readable from a distance. Possibly, there should also be audible alarms for error situations. Critical decisions shall not depend on the operator being able to differentiate red and green as red-green color blindness is the most common color vision deficiency; it affects 5% of European males.

Figure 4.5 gives a block diagram of the inner workings of the LabView based data acquisition system. Figure 5.2 of Section 5.4 shows the Graphical User Interface (GUI) of the LabView program to be presented to the user during calibration.

4.4 Mounting pressure sensors in test barrels

In order to obtain results which are comparable to those obtained at other test centers, we need to closely follow the instructions given in the documents made available by the standardization bodies. These are the NATO STANAG in the case of the EPVAT procedure and the ANSI/SAAMI documents in the case of the conformal sensor. We will also need to follow instructions given by the sensor manufacturers (Kistler, PCB), but in cases where the standards and the manufacturers disagree, we will need to follow the standards as close as possible.

4.4.1 The 7.62 x 51 mm NATO caliber Sig-Sauer

We decided to mount both a Kistler model 6215 as well as the conformal PCB model 117B44 pressure sensor in the test barrel. The barrel of choice was Sig-Sauer match grade chambered in 7.62 x 51 mm NATO, with serial number W50428. The mounting of the PCB model 117B44 sensor was done according to the instructions given in the ANSI/SAAMI document [33] and the "Installation and Operating Manual" for the PCB conformal sensor [25]. According to the SAAMI document, Section III - EQUIPMENT, Subsection TRANSDUCER LOCATION on page 134, the center line of the transducer shall be 35.0 mm from the bolt face. At that time we used the 1992 version of the ANSI/SAAMI standard. This has later been superseded by the 2015 revision [34]. In

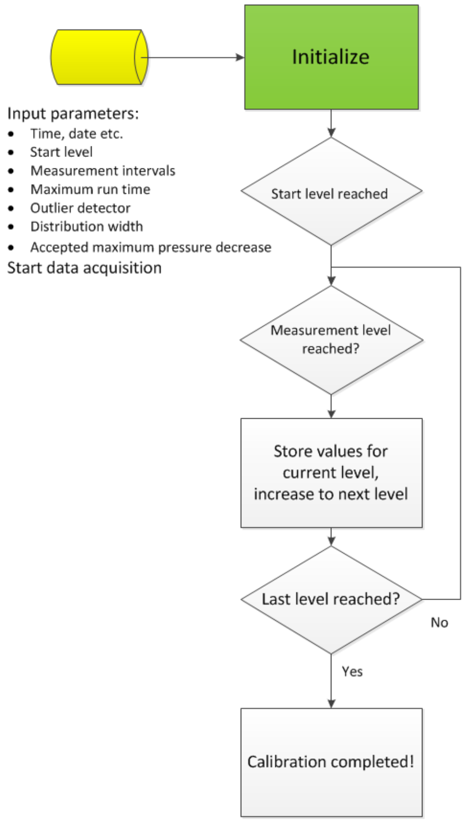

Figure 4.5 Schematic algorithm for the data acquisition software.

the 2015 version, the transducer location is specified as 35.03 mm from the breech bolt face with a tolerance of 0.25 mm. The same position is also shown in Drawing 11504 of the PCB manual. The Kistler model 6215 sensor was mounted according to Section 6 (NATO Testing - Equipment and Drawings) of Reference [01], specifically Drawing 12-(7.62mm)-2 (Barrel, Test, EPVAT, 7.62mm). We also followed the instructions given in the Kistler datasheet [12]. When these instructions disagreed with EPVAT, the latter took precedence.

The intention for mounting two sensors in the same barrel is to be able to compare the results shot by shot. Ironically, the pressure measured on the cartridge by the PCB sensor will be somewhat lowered by the extra volume of the channel to the recessed Kistler sensor, compared to only using the PCB sensor. However, both sensors should still measure the same lowered pressure, which should be equal to the one measured if only the recessed Kistler sensor were installed. For both sensors the location of their centerlines is given with reference to the boltface. We believe this is convenient when an EPVAT or a SAAMI test barrel is to be used, but in our case, we used the Sig-Sauer barrel with 7.62 x 51 mm NATO caliber. Without a cartridge in the chamber, the breech was not fixed at all, so using this as the reference point is not possible. With a cartridge in the chamber the breech was tight, so we decided that measuring from the end of the cartridge casing is the best option.

The fabrication drawings and the machining itself were performed at the "Prototypeverksted" (PTV) of the FFI. On delivery, the dimensions seemed to be spot on and even the depth of the mount hole for the conformal calibrator was so close to the one of the calibration adapter that the same shims ring also seated the sensor correctly in the chamber.

4.4.2 The 9 x 19 mm caliber Luger

Only one barrel of this caliber has been fitted with a conformal sensor and the position of the sensor is according to Reference [35]. In this document, the cartridge and chamber dimensions are shown in Section I - CHARACTERISTICS, Subsection "Cartridge and chamber drawings" under the Heading "9 mm Luger / 9 mm Luger +P" on page 27. The position of the sensor is shown in Section III - EQUIPMENT, Subsection "Standard Velocity and Pressure Test Barrels" under the Heading "9 mm Luger / 9 mm Luger +P" on page 141. Information on placement of the sensor as well as thread dimensions and surface finish are given in Drawing 117-2250-90 of the PCB document "Model 117B25 CONFORMAL BALLISTIC PRESSURE SENSOR Installation and Operating Manual".

4.4.3 The 4.6 x 30 mm caliber HK

Only one barrel of this caliber has been fitted with a conformal sensor. There seems to be no SAAMI specification for this caliber, so the mounting is done according to Drawing 29439 of the PCB document "MODEL 117B69 CONFORMAL BALLISTIC PRESSURE SENSOR Installation and Operating Manual". The location of the sensor (0.775 inch (19.18 mm) from the boltface) is confirmed in Drawing 29375 of the PCB document "Model 090B275 CALIBRATION ADAPTER Installation and Operating Manual".

4.4.4 Sensors for other calibers

In addition to the mentioned conformal sensors, 117B44, 117B25 and 117B69, the measurement system also consists of conformal sensors for other calibers (refcalsensad). Measurements with these are not described in this report. The PCB 117B204 is for 7.62 x 35 mm (often called 300 BLK). The PCB 117B30 is for 5.56 x 45 mm NATO. The PCB 117B229 is for 8.6 x 70 mm (often called .338 Lapua Magnum). We also note that the 117B44 may also be used for .260 Remington, and presumably other calibers of similar design.

5 User guide – calibration

5.1 Calibration checklist

1. Make a record in the logbook.
2. Power on all electronics so as to reach a stable operating temperature.
3. Check and if needed, set the computer time.
4. Select the correct calibration adapter for the given caliber.
5. Open the oil reservoir valve so not to suck air into the high pressure pump.
6. Mount the calibration chamber adapter and reference sensor.
7. Check that the conformal sensor is correctly seated in the calibration chamber with the yellow dot towards the case mouth.
8. Check that the unfired cartridge casing is empty with the ignition cap fired.
9. Insert the casing in the calibration chamber and tighten the end bolt.
10. Replace the calibration chamber adapter O-ring.
11. Check that there is some oil dripping from the chamber adapter.
12. Fill the calibration chamber with oil using a syringe.
13. Push the calibration chamber onto the calibration chamber adapter. Tighten the nut firmly by hand.
14. Connect the pressure sensors to the charge amplifier.
15. Check the charge amplifier settings with the ICAM control or ManuWare.
16. Check that the calibration LabView program settings are correct.
17. Fully extract the plunger by rotating the handle counter-clockwise.
18. Close the oil reservoir high pressure valve. It does not need force.
19. Check that the calibration LabView program is running.
20. Increase the pressure by rotating the handle clockwise until 'stop measure' is reached.
21. Release the pressure by opening the reservoir high pressure valve.
22. Fully extract the plunger by rotating the handle counter-clockwise.
23. Check that the central manometer shows zero pressure.
24. Remove the calibration chamber; open and force out the casing.

5.2 Calibration hardware in detail

All calibration runs, maintenance on the calibration system and especially all problems and failures should be recorded in the calibration logbook. When working with high pressure systems, one should stay in front of the shield that isolates the high pressure side. When working on the high pressure side, one should use safety goggles at least until the reservoir-side high pressure valve has been opened and the central manometer shows zero pressure. Better be safe than sorry.

Any leakage of charge across the piezoelectric sensor and cable leads to a drift at the amplifier output. The impedance of the sensor itself is in the 10^{12} Ω range. Therefore, the connectors should be kept clean.

5.2.1 Tools and materials needed for assembly of calibration system

- Torque wrenches with a range from 10 Nm to 30 Nm will cover all mounting requirements for the piezoelectric sensors and the pressure chamber adapter.
- An 8 mm long socket for the Kistler model 6213BK pressure sensor.
- A 5/16 inch open end wrench for the PCB model 117Bxx. Due to the guiding pin, a socket cannot be used here. An open end wrench adapter for use with a 1/4 inch torque wrench has been fabricated.
- A 7/16 inch open end wrench for the PCB chamber adapter mount onto the high pressure port. Due to the fastening nut and plate, a socket cannot be used here. An open end wrench adapter for use with a 3/8 inch torque wrench has been fabricated.
- Grease for the threads of the sensors and for holding the seals in place during assembly. Kistler recommends using Klüber grease type 1063. This seems to be a Kistler product delivered in dispenser tubes of 5 g.
- Silicon grease or hydraulic oil for the PCB chamber adapter O-ring. We have been using the same oil as for the pump itself.
- Hydraulic oil for the high pressure pump. We have been using the Shell Tellus S46 hydraulic oil. This may be found in a 200 l barrel at the PTV.
- The Kistler insulation tester model 5493 or equivalent should be used periodically for checking the insulation of sensors and cables.
- Solvent for cleaning connections and plugs. Normally, there is no regular cleaning required, but if needed Kistler recommends the use of benzine and PCB recommends the use of isopropanol followed by baking for 1/2 hour at 250°F (120°C). We believe that baking is a way to get rid of possible water contamination of the isopropanol and suggest to try without baking. Additionally, we recommend to check the insulation with the Kistler insulation tester.
- Occasionally, one will need an angled 6 mm hex key to loosen the hex bolts holding the pump housing parts together. The seal compression nut is 27 mm. The end cap of the housing has a 40 mm nut for unscrewing and the handle itself is fixed by two 20 mm nuts.
- Rather unlikely, but one may need to adjust the packing gland nut of the high pressure valve on the oil reservoir side. The nut is 1 inch. Here, one also needs to hold the valve body while tightening the nut. The body is $1\frac{1}{2}$ inch times $2\frac{1}{2}$ inch (38 mm x 67 mm). A 38 mm open end wrench will fit nicely onto the valve body.

5.3 Order of assembly

Before anything is mounted, one should assert that the high pressure pump is in working order. Get rid of trapped air, close the oil reservoir valve and take the pressure to 500 MPa. If there are problems with obtaining high pressure, the PTFE seal most likely needs to be tightened, see Section 5.3.6. The next step will be to determine what calibration adapter to use. For first time assembly, we recommend that the PCB chamber adapter should be mounted first and then the hydraulic oil should be forced through from above to flush out air bubbles. However, the Tellus S46 oil is not that viscous, so it runs quite slowly. Also, one should fill up the mounting hole for the Kistler model 6215 sensor, so that it can be threaded down without leaving any air pockets. It is very important to check the O-ring on the chamber adapter; it must be in good condition and most likely will be in need of replacement each time the adapter is mounted. Finally, the assembled calibration chamber, with cartridge casing inserted, may be mounted.

5.3.1 Selecting the correct calibration adapter for the caliber

The PCB calibration adapters and conformal sensors are of the model 090Bxx and 117Bxx series, respectively. Table 5.1 shows which conformal sensor and adapter is to be used for a given caliber. A few lines have been left open to fill in by hand whenever a new calibration adapter is needed.

Caliber	Sensor type	Adapter type	ANSI/SAAMI
4.6 x 30 mm HK	117B69	090B275	N/A
.223 Rem	117B30	090B30	Z299.4 2015
.308 Win	117B44	090B44	Z299.4 2015
9 mm Luger	117B25	090B201	Z299.3 2015
.300 AAC Blackout	117B204	090M153	Z299.4 2015
.338 Lapua mag	117B229	090B274	Z299.4 2015

Table 5.1 PCB conformal sensor and adapter type to be used for a given caliber.

5.3.2 Chamber adapter mount to pressure port

The mount should follow closely the instructions given in the PCB model 090B44 Calibration Adaptor Installation and Operating Manual [23]. Remember to slide the nut over the chamber adapter with the threaded part first. Thread the chamber adapter onto the pressure port using a model 065A06 seal ring. As hydraulic oil is everywhere, no further lubrication is needed. Ready the special open ended 7/16 inch extension adapter to be used with a 3/8 inch torque wrench. When the extension adapter is at right angle to the wrench handle, the torque will be approximately correct. PCB recommends to tighten the adapter to approximately 20 ft. lbs. (27 Nm) of torque. In our first attempt, we applied approximately 20 Nm. Since there seemed to be some oil leaking, in our next attempt, we applied 25 Nm of torque. Do not exceed the recommended torque as the chamber adapter or the seal could be damaged.

5.3.3 Mounting the Kistler model 6213BK pressure sensor

FFI keeps a Kistler model 6213BK pressure sensor. This model is an improved version of the Kistler model 6215 sensor, with equal geometry but better specifications. In principle, this makes the two models interchangeable. However, FFI's policy is to keep the model 6213BK sensor as a calibration tool in a condition as pristine as possible. This includes only gentle use and excludes contact with hot gasses. Hence, the instructions provided here are intended for mounting the Kistler model 6213BK pressure sensor as the reference sensor in the calibration system. For other mounting conditions, see the Instruction Manual [10].

Check that the sensor and especially the electric connector are clean. If the connecting plug is dirty, it may be cleaned with rectified benzine and a clean paper tissue. We believe, that one may also use isopropanol in place of benzine. Ready the Cr-Ni steel ring, Kistler model 1100, that is the seal ring at the sensor front. In the unlikely event that the model 6213BK instead of the model 6215 sensor should be mounted in a test barrel, the model 1181 thermal protective plate, the model 6563A thermal protective shield and a second seal ring should be used. **These parts shall not be used when mounting the model 6213BK into the calibration system.** The seal ring should be fixed with a small amount of Klüber grease type 1063 to hold it in position while fastening. The seal ring may be used a number of times over. To ensure equal friction conditions on the thread and optimal preload force, the threads must always be greased before fastening using Klüber grease type 1063. Try to get rid of air in the system by topping off the receiving part with hydraulic oil. When the maximum expected pressure is below 500 MPa, as is the case for the conformal calibration, a torque of 20 Nm should be sufficient. For the full range of 1 GPa, 40 Nm torque must be applied.

5.3.4 Mounting the PCB model 117Bxx conformal sensor

The following list is close to an exact copy of the PCB installation manual [25].

1. The forward direction of the sensor is indicated by a yellow dot. This may be of little concern unless the cartridge is heavily tapered, but we suggest, that the yellow dot always is at the high pressure inlet side of the adapter.
2. Loosen, but do not remove completely the slotted clamp.
3. Select the intermediate thickness (.014 inch, 0.36 mm) spacer from the set of nine (models 065A19 or 065A27) which are supplied and place it around sensor barrel. It is difficult to keep track of the rings, so you may want to have a measurement tool available. We measured the ring thicknesses to be 0.25, 0.28, 0.30, 0.33, 0.35, 0.38, 0.41, 0.43 and 0.45 mm.
4. Start by threading the sensor clamp nut onto the threaded mounting port and sliding the slotted clamp fore and aft as needed to allow the guide pin to fully enter the hole. Continue to thread the clamp nut into the hole by hand or use a 5/16 inch open end wrench. Do **not** tighten when the sensor bottoms.
5. Now tighten the screw closing the slotted clamp.
6. Using the open end wrench, tighten the sensor clamp nut. Note that it is not necessary to apply a large amount of torque on this nut since it is not intended to provide a pressure seal. Approximately 5 to 10 ft. lbs. (6.8 to 13.6 Nm) of torque is sufficient. We applied a torque of 10 Nm.
7. Now inspect whether the sensor head is flush with the inside surface of the calibration chamber. This may be accomplished visually in most cases. If the sensor head protrudes into the calibration chamber, select a thicker spacer and repeat the mounting procedure. If the sensor head is too deeply recessed, select a thinner spacer and remount. Once the proper spacer thickness is found to produce a flush mount, the sensor may be removed and reinstalled using the same spacer. A flush mount will be achieved every time. In our first attempt, we found the 0.30 mm washer to be too thin, the sensor head was slightly protruding into the calibration chamber. The 0.33 mm washer gave a slightly recessed mount, so this is our choice. According to the PCB Ballistic Pressure Reference Guide [27], a flush mount is preferred, but a recessed mount is acceptable. An offset or protruding sensor head is not acceptable.

5.3.5 Calibration chamber assembly and mount to chamber adapter

The cartridges to be used for calibration must be selected from the lot to be measured later by firing. The bullet and powder must be removed and the firing cap must be fired. Inspect the casing mouth and deburr for any sharp edges inside. The O-ring of the chamber adapter must slide inside the casing mouth without any damage. Insert the casing into the calibration chamber and tighten the casing retainer nut. Use a 3/4 inch wrench to tighten the nut until it bottoms against the calibration chamber inner surface. The casing retainer has a protrusion in the middle that pushes against the fired primer cap and it may take some force to get it fully seated. Now, inspect the O-ring on the chamber adapter. If there is any damage, the O-ring should be replaced. The sealing surfaces must not be scratched, so better use a wooden tool for removing the old O-ring, e.g. a toothpick. Fill the calibration chamber with oil, open all valves, wait for some oil dripping from the adapter and push the chamber upwards onto the adapter. The holding nut should be tightened by hand, but as firm as possible.

5.3.6 Tightening the plunger PTFE (teflon) seal ring

The piston slides through a compressed sealing tube made of PTFE. This part does degrade and needs to be compressed by tightening the packing nut. As the nut is inside the pump housing, we need to open the pump to gain access. Make sure the piston is **not** at its outermost position, so it will not accidentially be pulled out. Loosen the 6 hex bolts that hold the outer part of the pump housing and wriggle the housing to open up a bit. Turn the handle to follow up when the housing is pulled slightly away from the cylinder. Only a little clearance is needed to reach the nut with a wrench or spanner. The dimension of the seal compression nut is 27 mm. Currently, we tighten the compression nut with a torque of 45 Nm. When retightening, less than 1/6 turn will normally be sufficient to get a reasonable seal.

5.3.7 High pressure valve packing gland adjustment

This procedure was intended to be used on the valve on the calibration chamber side, since we have always observed leaks at that valve. The valve on the calibration chamber side has now been removed and leaking will probably not happen on the valve on the oil reservoir side. That valve is mounted such that the packing box will not experience any pressure. For the valve on the calibration chamber side, the seal had to take the full pressure when the valve was open and the system was pressurized. Nevertheless, according to the manufacturer, the sealing nut on the model 100-**XF4 series valves shall be torqued to a minimum of 60 ft. lbs. (81 Nm). This information may be found on the manufacturer's home page [07] under the tab "Tech Support" and following the link "Recommended Torque". The nut is a 1 inch nut, but in a pinch, a 26 mm wrench could be used here. For adjusting the packing gland, the system should **not** be pressurized. Also, the instructions say that the valve should be removed and placed in a vice, but this is way too cumbersome, so we keep the valve mounted. For the adjustment, fully open the valve stem and loosen the packing gland locking device. Tighten to the recommended torque for the valve and reinstall the locking device. We found that a 38 mm open end wrench can be used to hold the valve body, but pay attention so that the valve itself is not rotated within the assembly.

5.4 The calibration software user guide

Start all electronics in good time before a calibration run, so that temperature dependent mechanisms stabilize. This time may be used for checking cable connections and general tidyness around the workplace. This may also be a good time to check that all software is actually available and running.

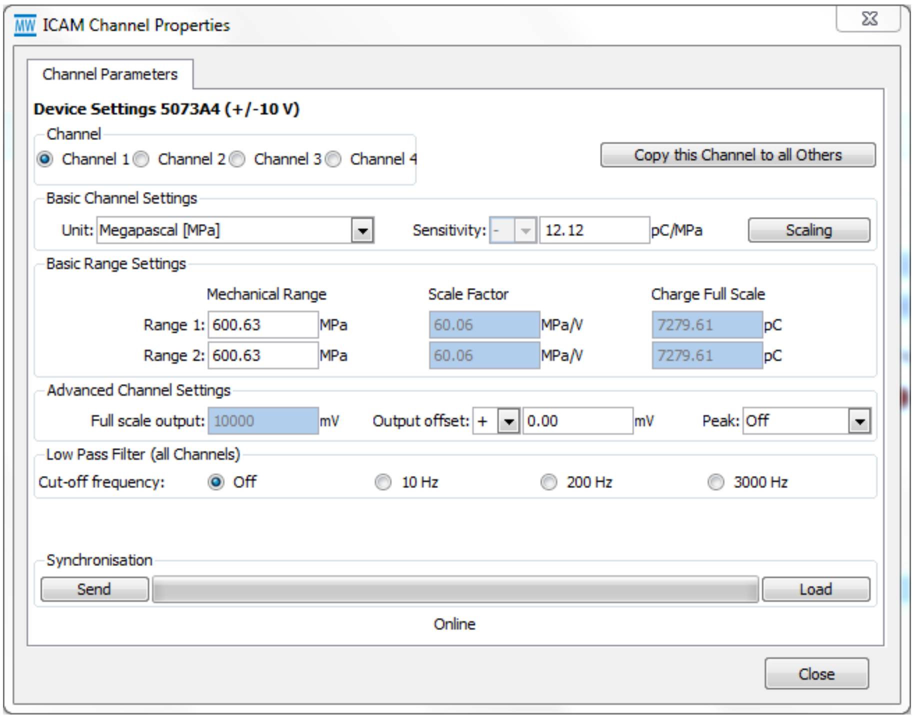

Figure 5.1 Graphic user interface of the ManuWare control of the charge amplifier.

Make a new entry in the calibration logbook. Write down the date and time and the serial numbers of both the reference sensor, the calibration adapter and the sensor to be calibrated. The logbook shall also contain records of any changes and maintenance performed on the calibration system itself. All failures and problems shall be recorded in the logbook.

5.4.1 Setting the charge amplifier

Make sure that both reference and conformal sensor are actually connected to a charge mode input on the amplifier. Set a sufficiently long time constant for both sensors. Based on the sensitivity of the reference and conformal sensor, select a suitable output level for the amplifier. For the Kistler model 5073A sensor, the settings may be adjusted by a dedicated control program, either ICAM control or ManuWare. The ICAM control was the original program delivered with the amplifier, but seems to have been superseeded by ManuWare. Figure 5.1 shows the ManuWare settings panel for one of the four channels of the model 5073A4 amplifier.

5.4.2 Conformal sensor calibration software

The calibration software requires a few values to be set initially. Also, a blue signal is visible. Once started, the program continuously monitors the reference sensor reading and starts storing values

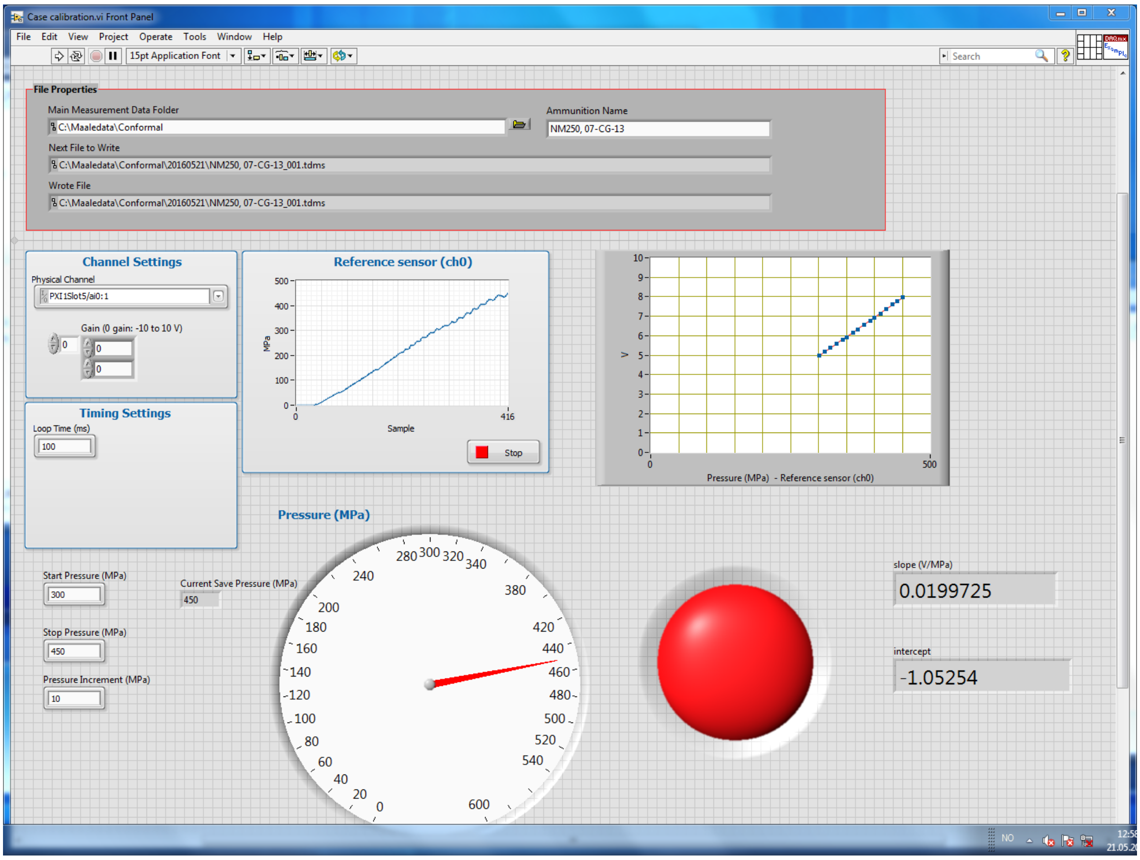

Figure 5.2   Graphic user interface of the conformal sensor calibration software.

when a preset level is reached. Then, values for both sensors are saved at regular pressure intervals. When the preset stop level is reached, the blue signal changes to red and the program stops. During calibration, the current reading of the reference sensor is displayed on a clock-like scale. The user interface of the conformal sensor calibration software is shown in Figure 5.2.

6 User guide – measurement

6.1 Measurement checklist

1. Make a record in the logbook.
2. Power on all electronics so as to reach a stable operating temperature.
3. Check and if needed, set the computer time.
4. Check that the conformal sensor and, if desired the case mouth sensor are mounted and connected to the charge amplifier.
5. Connect the charge amplifier control and outputs to the computer.
6. Check the charge amplifier settings with the ICAM control or ManuWare.
7. Check that the pressure recording LabView program is running and the settings are correct.
8. Load the weapon.
9. Fire the weapon.
10. Check the recording.
11. Repeat as often as needed.

6.2 Measurement in detail

6.2.1 Mounting the PCB model 117Bxx conformal sensor

Mounting the conformal sensor in a barrel is very similar to mounting it in the calibration adapter. Detailed instructions are given in Reference [25] and in Section 5.3.4 of this document.

6.2.2 Mounting the Kistler model 6215 pressure sensor

Instructions for mounting the Kistler model 6215 pressure sensor are given in the EPVAT document [04] and some information is also given in the Kistler model 6215 data sheet [12]. The following is more or less a copy of the instructions given in the EPVAT document Section 12.A.2.2-e "Installation of the KIAG (Kistler) Model6215 Transducer: Installation shall proceed as follows:"

IMPORTANT NOTE: Only a very small amount of Kistler 1063 grease is to be used as indicated below before assembling the transducers with their sealing rings and protective diaphragms. This grease is used to aid sealing and additionally adhesion of the sealing ring(s) and protective diaphragm to assist with intact removal of the transducer assembly from the mounting cavity. The volume within the protective diaphragm MUST NOT be filled with grease as it causes erratic pressure readings.

1. A very small amount of Kistler 1063 grease shall be placed in the vee impression on the face of the KIAG (Kistler) Model 6215 Transducer to make the sealing ring adhere.
2. The sealing ring, model 1100, shall be placed on the face of the Transducer.
3. The Protection Diaphragm, model 6567, shall then be placed over the face of the transducer and snapped evenly into position over the face.
4. A very small amount of Kistler 1063 grease shall be placed on the face of the Protection Diaphragm to make the second sealing ring adhere.

5. A second model 1100 sealing ring shall then be placed in the vee impression on the face of the Protection Diaphragm and the complete assembly inserted into the mounting cavity. A very small amount of Kistler 1063 grease shall be applied to the Transducer thread.
6. The Transducer shall be tightened with a torque wrench to 20 Nm. This shall apply to all installations of the KIAG (Kistler) Model 6215 transducer.
7. The signal line shall be connected to the transducer and securely tightened, finger tight.

We only add this to the list. One should always inspect the mounting hole to assure that it is clean. Epecially, it is possible to lose the seal ring of the previous sensor that was mounted in there. Not removing it would seriously affect the measurement.

7 Conformal calibration of 7.62 x 51 NATO cartridges

In a first attempt to perform a real calibration, we selected the popular 7.62 x 51 mm NATO caliber. The particular cartridge was the Nammo model NM258 (also known as Nammo 7.62x51 mm Ball 11 Long Range) with lot number 07-CG-13. We wanted to get some experience as to what factors do influence the calibration and varied more parameters than one would normally do.

7.1 Equipment and settings

The sensor we chose to calibrate was the PCB model 117B44 with SN 5390 and we used the calibration adapter PCB model 090B44 with date stamp 12/16/14. As the reference sensor and charge amplifier, we chose Kistler model 6213BK with SN 4468215 and Kistler model 5073A411 with SN 1800068, respectively.

The charge amplifier settings are straight forward. For the channel of the Kistler model 6213BK pressure sensor, we set the "Unit" to MPa and specify a range of 600 MPa. For the sensitivity, we choose the widest range.

For the PCB model 117B44 sensor, we do not use the manufacturer's calibration to obtain a pressure values. Rather we set the charge amplifier to provide a voltage signal. Hence, we set the "Unit" to voltage, the sensitivity to 1000 pC/V and the "Mechanical Range" to 10 V. This produces a charge amplifier output of 1 V times the delivered charge in nC. We need to pay attention to the sensitivity setting so that the full scale of 10 V is not exceeded at the maximum pressure of some 500 MPa. In general, the PCB model 117B44 sensor has a sensitivity of around 21 pC/MPa, so at 500 MPa it will deliver about 10.5 nC of charge, which translates to an anticipated 10.5 V output from the charge amplifier. This is slightly above the full scale of 10 V of the ADC. For a more precise calculation, we may use the actual sensitivity of the PCB model 117B44 with SN 5390, which is 19.39 pC/MPa. With the given amplifier gain of 1 nC/V, the factor to translate the voltage at the ADC to a pressure value is then $1/19.39\mathrm{E}-3 = 51.57$ MPa/V. However, one must remember that the pressure seen by the conformal sensor is not the same as the internal pressure of the cartridge casing – this is the reason for the need of a calibration.

7.2 Measurements and results

We started off by running a calibration following the procedure outlined in Chapter 5, and repeated the calibration on the same cartridge casing. Figure 7.1 shows the pressure on the PCB conformal sensor as function of pressure on the Kistler reference sensor. We also have plotted a $y = x$ line.

Figure 7.1 shows that for a new casing, the pressure on the conformal sensor does not rise until the internal pressure reaches about 30 MPa. This part of the graph is reproduced in detail in Figure 7.2.

Hence, for an unused casing, the conformal sensor does not respond until the internal pressure is at a level of 32 MPa. This is in qualitative agreement with our schematic model for this phenomenon, which is described in Appendix B. Here, the pressure to expand the 7.62 x 51 mm casing to make contact with the chamber wall is estimated to be 22 MPa. When the same cartridge is pressurized again, the conformal sensor signal rises immediately when internal pressure is applied. While the disappearance of the hysteresis may be as expected, what is more surprising is that the pressure seen by the conformal sensor on a reused casing does approach and even falls slightly below the values seen on the same casing, when pressurized for the first time. This is shown in Figure 7.3,

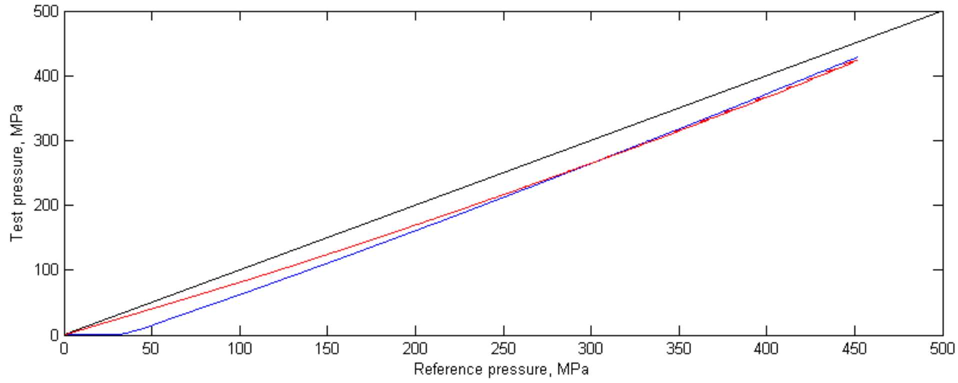

Figure 7.1 *Conformal sensor pressure as function of reference sensor pressure for cartridge lot number 07-CG-13. The blue and red lines correspond to the first and second calibration measurement, respectively. The black line is the y = x diagonal to guide the eye.*

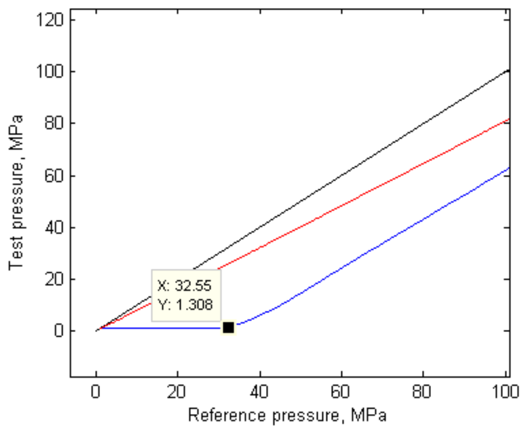

Figure 7.2 *Closeup of Figure 7.1 in the 0-100 MPa range with color scheme as before.*

where the red line is below the blue one. Still, this is a single observation and may not be a repeatable phenomenon. Also, the figure shows that the red line is a bit curved, hence there is some nonlinearity observed in the calibration.

Intrigued by this, we altogether performed nine calibrations, where we used new and old casings and at the same time did some experimentation on the effect of the seating depth of the conformal sensor. The latter was done by changing the shims rings that determine the seating of the PCB model 117B44 sensor. Table 7.1 gives a summary of all the different measurement conditions.

The shims rings are delivered as a set of nine, with differences of 0.02 – 0.03 mm in thickness. By mounting the sensor with these different washers, we found that the 0.33 mm washer gave the closest to a flush mount of the sensor head without letting it protrude into the chamber. To assess the effect of the seating depth of the sensor, we made two measurements with the 0.35 mm washer, i.e. the sensor head is withdrawn from the chamber wall. Each change of shims rings required a remount of the sensor, which is indicated in a separate column in Table 7.1. Figure 7.4 shows all nine measurements in the relevant maximum pressure region of 350-430 MPa and Figure 7.5 shows

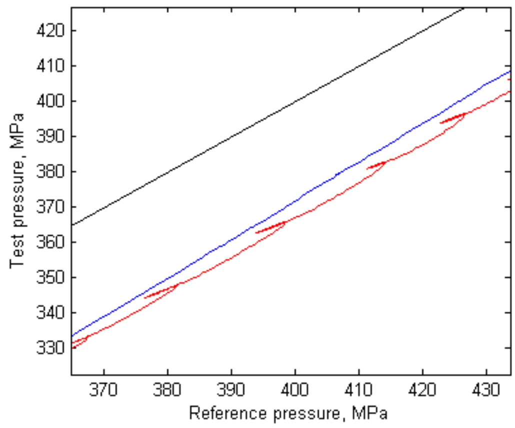

Figure 7.3 Closeup of Figure 7.1 in the 360-440 MPa range with color scheme as before.

Entry	Date	File	Casing	Shims ring	Remount	Color	Symbol
1	2016-06-21	001	used	0.33 mm	no	green	plus
2	2016-06-21	002	new	0.33 mm	no	blue	plus
3	2016-06-23	001	used	0.33 mm	no	green	circle
4	2016-06-23	002	new	0.33 mm	no	blue	circle
5	2016-06-23	003	new	0.33 mm	no	blue	circle
6	2016-06-24	001	used	0.33 mm	no	green	circle
7	2016-06-24	002	new	0.35 mm	yes	red	square
8	2016-06-26	001	new	0.35 mm	no	red	square
9	2016-06-26	002	new	0.33 mm	yes	blue	star

Table 7.1 Summary of calibration measurement conditions on NM258 ammunition. The color and symbol entries refer to Figures 7.4 and 7.5; the entry number is used as reference in the text.

a closeup around 400 MPa for a better separation of the data.

Under the exchange of the washers, we also performed some thickness measurements. To our surprise, the washer that supposedly was 0.33 mm now measured slightly below 0.31 mm. In hindsight, we cannot rule out the possibility that this measure is in error, or that we simply measured the wrong washer by mistake. Nevertheless, this was so alarming that we set up a little experiment to investigate the possibility that there might be a significant flattening of the washers.

It is quite cumbersome to measure the seating depth of the sensor when it is mounted in the calibration chamber or the test barrel. We therefore fabricated a steel bar with mounting holes for the PCB model 117B44 sensor, but with the sensor head side easily accessible and the sensor head protruding a few mm. The device is shown in Figure 7.6.

We selected an unused washer with a nominal height of 0.33 mm and confirmed this by measuring it both with a micrometer and the Mauser CADAX 2 height measurement station. The conformal sensor was then mounted with a torque of 10 Nm and the protruding height of the sensor head was measured with the CADAX 2 to be 2.205 mm. The stated uncertainty of this measurement station is 0.005 mm. This result was constant throughout three repeated measurements. After

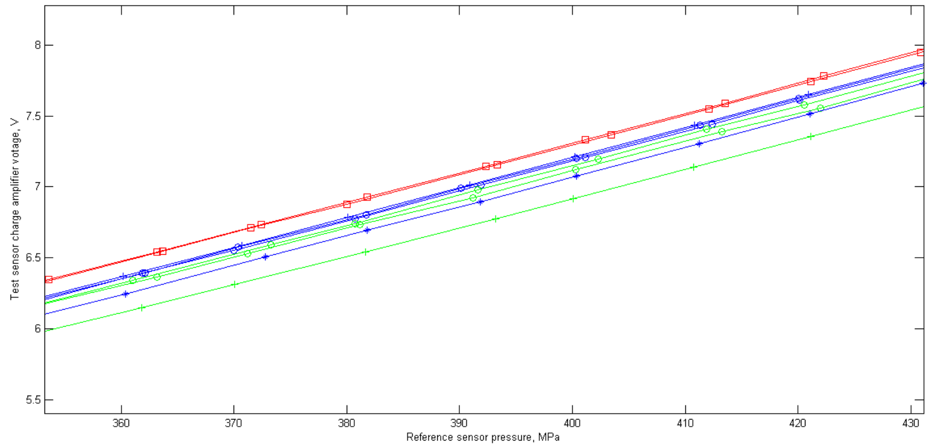

Figure 7.4 Calibration of the PCB model 117B44 conformal sensor on Nammo NM258 ammunition (lot number 07-CG-13) against the Kistler model 6213BK reference pressure sensor. Green lines correspond to used casings, blue and red lines to new ones. Red lines indicate a more recessed mount. Symbols and colors are referenced in Table 7.1.

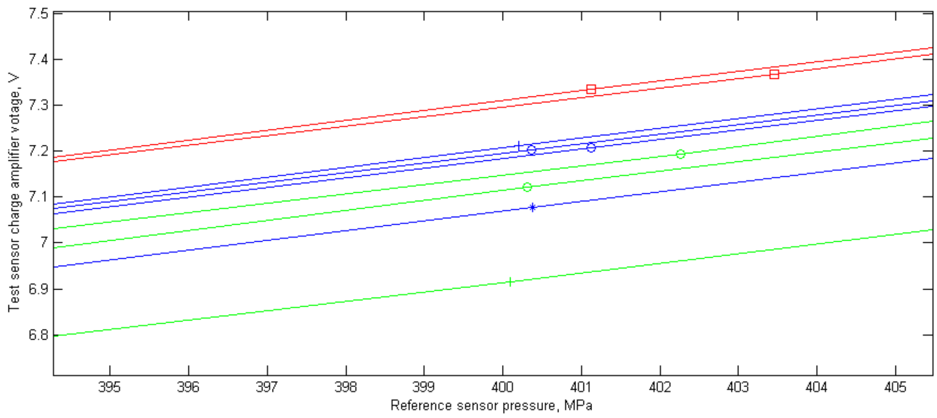

Figure 7.5 Closeup of Figure 7.4 in the 395-405 MPa range with color scheme as before.

disassembly, the washer still measured 0.33 mm, using both the micrometer and the CADAX 2. This procedure was repeated 4 times and through all of the 12 measurements the protruding height of the sensor head was always the same 2.205 mm. After the second disassembly, the washer thickness was measured as 0.325 mm both with the micrometer and the CADAX 2, which is still equal within the stated uncertainty. Using the same micrometer, we also measured both the previously used 'old' washer (used during shooting and calibration) and the 'new' washer used only during these seating depth tests. The old washer measured slightly less than 0.31 mm, while the new one measured slightly above 0.32 mm. To us, it seems that we cannot rule out that the washers may become compressed or deformed when they are used a number of times, but certainly any eventual change in thickness is not observable after four times mounting the sensor.

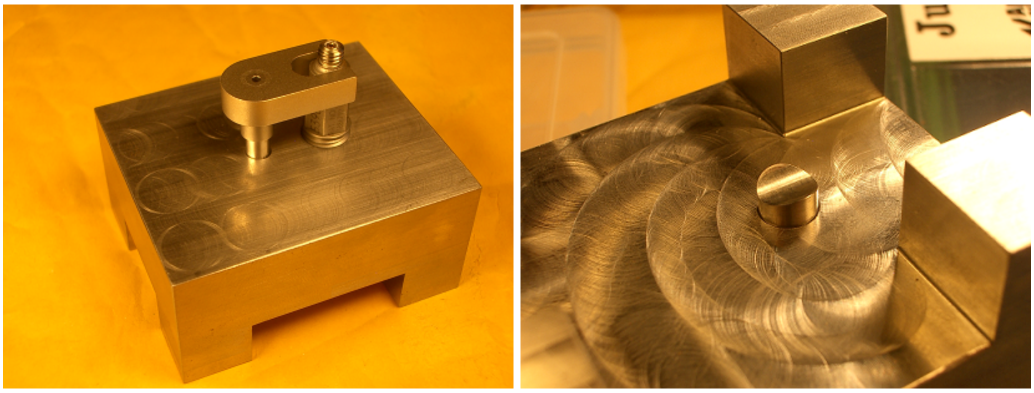

Figure 7.6 Device for measuring sensor seating depth change, top and bottom view.

7.3 Discussion of the 7.62 x 51 mm calibration measurements

The calibration measurements confirm that a new casing should be used only once for calibration. Furthermore, the mounting of the sensor may have a rather large effect on the calibration – although the current data is sparse. This is worrying as we currently do not have any way to precisely measure the sensor seating depth. Even worse, we cannot compare the sensor seating depth in the calibration chamber to the one in the barrel. Possibly, even the washer thickness might not relate simply to the seating depth. For instance, we could not detect any change of seating depth during four mounts of the conformal sensor, while we did measure a slight (but not significant) decrease in thickness of the same 0.33 mm (nominal) washer. We should certainly pay attention to the washers over time – we cannot rule out the possibility that they become deformed by use.

Still, as long as nothing is changed, except for the casing to be calibrated, the calibration seems to produce very consistent results. The three blue lines in Figure 7.4 corresponding to Entries 2, 4 and 5 in Table 7.1 are just 0.3% apart at the reference sensor pressure of 400 MPa. However, when the sensor is removed and remounted, while using the same 0.33 mm washer, we see a value that is 1.7% lower at 400 MPa. When the sensor is removed and remounted, while the 0.33 mm (nominal) washer is replaced by the 0.35 mm washer, we measure a value that is 1.4% higher at 400 MPa. It is at this point unclear, why a more recessed mount should yield a higher value. Maybe the seating depth difference is in fact of little relevance and the 1.4% higher value, just as the 1.7% lower value, may be explained by the fact that the conformal sensor was removed and remoted. Clearly, we have not yet gained understanding of the seating depth and remounting as possible sources of systematic uncertainties in the calibration. However, we may confidently state the presence of a systematic uncertainty and estimate its value as to some 1.5%. Also, based on the observation that all calibration lines are approximately parallel to each other, this systematic uncertainty will affect mostly the offset and only to a very small degree the gain of a linear calibration.

We will now attempt to obtain a calibration for the PCB model 117B44 sensor with SN 5390 applied to Nammo ammunition NM258 with lot number 07-CG-13. To simplify the numerics, we will only use the three very consistent measurements on new cartridges done with the 0.33 mm washer, without remounting the sensor. These are the three blue lines marked with circles and a plus in Figure 7.5. According to Table 7.1, these are File 002 from 2016-06-21 and the two Files 002 and 003 from 2016-06-23. The calibration software stores simultaneously the pressure of the Kistler reference sensor and the voltage of the PCB conformal sensor. Measurements are stored at regular pressure intervals for the reference sensor. For the calibration runs, we used 10 MPa intervals.

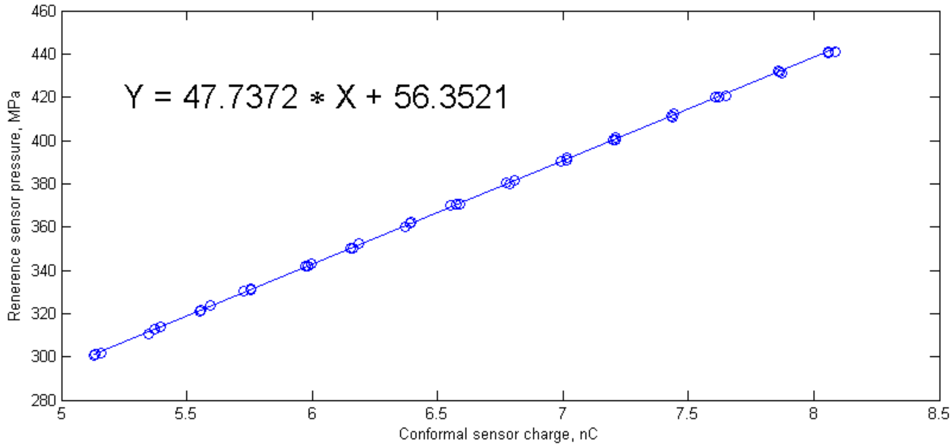

Figure 7.7 Calibration of the PCB model 117B44 sensor with SN 5390. The data are indicated by circles and the line shows the least square fit.

PCB's suggestion of a calibration scheme for conformal measurements are expressions of the form $p_i = C_U U_c + p_c$ or $p_i = C_Q Q_c + p_c$. Here, p_i is the internal pressure of the casing. $C_{U \text{ or } Q}$ is a calibration constant relating the voltage or charge of the conformal sensor to the pressure, in short, the gain. U_c is the charge amplifier output voltage and Q_c is charge delivered by the conformal sensor. Finally, p_c is the pressure to be added to the conformal sensor reading to compensate for the casing effects, or short, the offset. We are mostly concerned with pressures in the 300-450 MPa range, so we will use all measurements within this range in a least square linear regression to obtain the gain C_Q and the offset p_c. The operation may be performed in Matlab or Octave using the code:

```
idx=find(300.0<refp&refp<450.0);
srefp=refp(idx);
scnfQ=cnfQ(idx);
cp=polyfit(scnfQ,srefp,1);
```

Here, the Vectors refp and cnfQ contain all corresponding measurements of the reference pressure and conformal sensor charge, respectively. The Vectors srefp and scnfQ contain only those corresponding measurements for which the reference pressure falls into the selected pressure range. The polyfit(scnfQ,srefp,1) function finds the coefficients of a polynomial P(Q) of degree 1 that provides a least square fit to the data. When we apply this method to the three selected calibration runs, we obtain the linear equation $p = 47.74$ MPa/nC $* Q + 56.4$ MPa, where the charge Q is given in nC and the pressure in MPa. The data points as well as the calibration line are shown in Figure 7.7. No uncertainties of the coefficients are calculated based on the spread of the data points, but we remember the presence of a systematic uncertainty of some 1.5% of 400 MPa, i.e., 6 MPa, which should be applied to the offset.

8 EPVAT versus SAAMI for 7.62 x 51 NATO cartridges

With a completed calibration system and an instrumented barrel, we proceed now to assess whether the conformal sensor does produce results of equal quality as those obtained with a case mouth mounted sensor. This will be done using a caliber that is well known and where both sensor locations capture the maximum pressure. Also, we will have to do as many measurements as needed to obtain statistically significant results.

8.1 Equipment

We used a match grade Sig-Sauer barrel chambered in 7.62 x 51 mm NATO with serial number W50428, that is modified to accept both the conformal as well as the case mouth mounted sensor. Details are given in Section 4.4.1. As for the case mouth mounted sensor, we used the Kistler model 6215 with SN 1812888 and the conformal sensor was the PCB model 117B44 with SN 5390. A borescope was used to inspect the chamber inner wall and to select the thinnest washer that allowed a non-protruding mount of the conformal sensor. The charge amplifier was a Kistler model 5073A411 with SN 1800068. The voltage signal from the charge amplifier is captured by a National Instruments (NI) PXI-4462, four channel, 24-bit, data acquisition card, placed in an NI PXIe-1082 chassis. Further details of the digitizing hardware may be found at NI's homepage [17]. The data acquisition was controlled by a purpose-built LabView program. The shooting was done at the FFI ballistics laboratory, where also a velocity recorder was set up to measure the projectile velocity.

8.2 Measurements

We decided to follow a small subset of the EPVAT procedure. Initially, both the case mouth and the conformal sensor were mounted in the test barrel. We then fired 5 warming shots while recording pressures and velocity. After that, 30 shots were fired and recorded. At this point, we removed the case mouth sensor and plugged the hole. The plug completely fills the mounting hole for the Kistler model 6215 sensor and also the channel into the chamber, without protruding. Then, 30 more shots were fired and velocity and pressure were recorded. Figure 8.1 shows three casings after firing.

Figure 8.1 Used casings with circular impressions of the conformal sensor. Shot numbers are visible.

The extrusions on the casings due to the recessed mount of the conformal sensor are hardly visible at all. The height of the extrusions was measured at some later point by moving a needle across the surface and record the topography along the path. Such measurements were performed with a Mitutoyo Surftest SJ-400 machine. The results indicate an extrusion of less than 5 μm closest to the case mouth and nothing, i.e., absolutely flush casings on the opposite side. On the latter position, the circular impression is probably due to a small gap between the sensor and the chamber wall. At all times, we were systematic with the handling of the ammunition and also allowed for at least 20 seconds between shots. A chambered cartridge was always fired within 20 seconds.

8.3 Results and discussion

For this first test, we did not initially perform any calibration of the conformal sensor with the specific casings. Instead, the manufacturer's calibration was used. These 'raw' results are displayed in Figure 8.2.

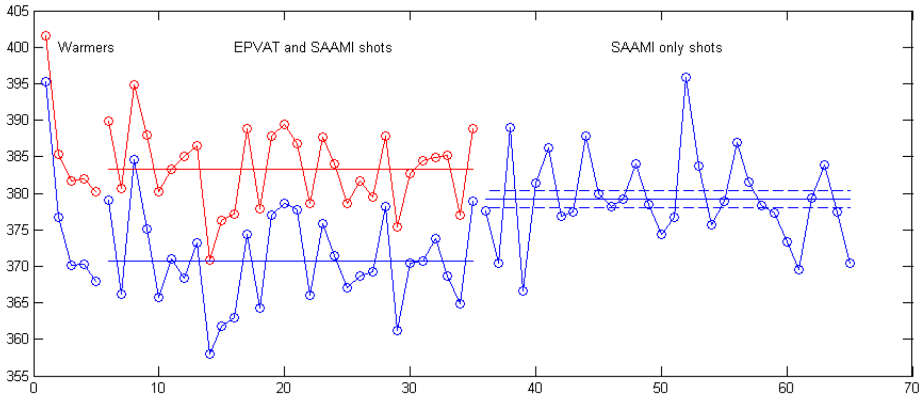

Figure 8.2 Case mouth (red) and uncalibrated conformal pressure measurements (blue).

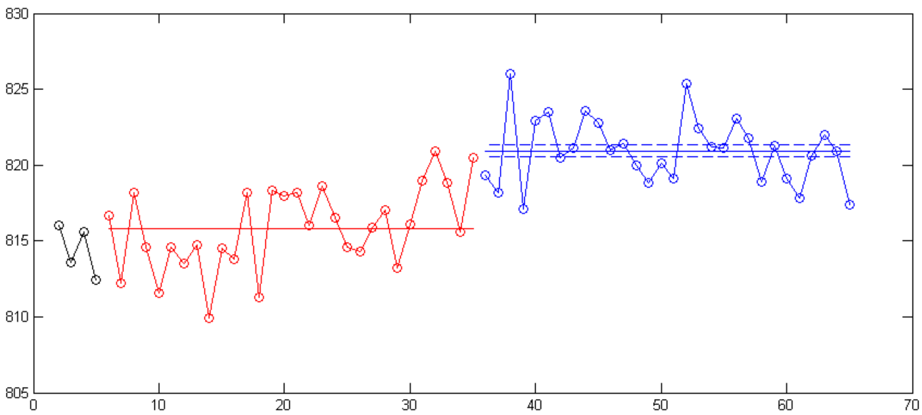

Figure 8.3 Projectile velocities.

In Figure 8.2, the shots within each group are connected by lines. This is a guide for the eye to make it easier to recognize the shot groups. Except perhaps for the warming shots, we do not expect any dependency of the pressure or velocity on the sequence number. The associated velocity measurements are shown in Figure 8.3.

For the change in mean pressure measured by the conformal sensor with and without the case mouth sensor in place, we may ask whether this difference could happen just by chance. The procedure outlined in Section C.5 may show that this is not the case based on a given confidence level. We use a Matlab implementation of the procedure with a significance level of 1% and find that the samples are indeed different to this level. Actually, when we repeat the test with a 0.1% significance level, we still find support for this conclusion. Section C.6 outlines a test to check whether samples drawn from distributions with different mean values may be drawn from distributions with equal variance. Using this test, we find that the observed difference in variance between the two series could indeed happen by chance, assuming the underlying distributions have the same variance.

With statistical certainty, we can therefore state that the pressure measured by the conformal sensor increases, when the case mouth mounted sensor is removed and the hole plugged. We now move on to physics arguments and state our conjecture that this is due to the then reduced volume occupied by the propellant gases. A calculation based on adiabatic expansion is done in Section 3.3 which indicates an increase in internal pressure of 1.5%. The mean values of the conformal pressure with and without the hole plugged show a difference of 8.4 MPa, i.e., of 2.3%.

We now use the calibration discussed in Chapter 7 to compare directly the conformal pressure to the case mouth pressure measurement. In the first step, we have to 'undo' the manufacturer's calibration and calculate raw charge by multiplying the values in Figure 8.2 with the sensitivity of 19.39 pC/MPa given by the manufacturer. Then, we apply the calibration reported in Chapter 7 to the raw charge values to obtain calibrated conformal pressures. Figure 8.4 shows the direct comparison of the calibrated conformal measurements to the case mouth measurements.

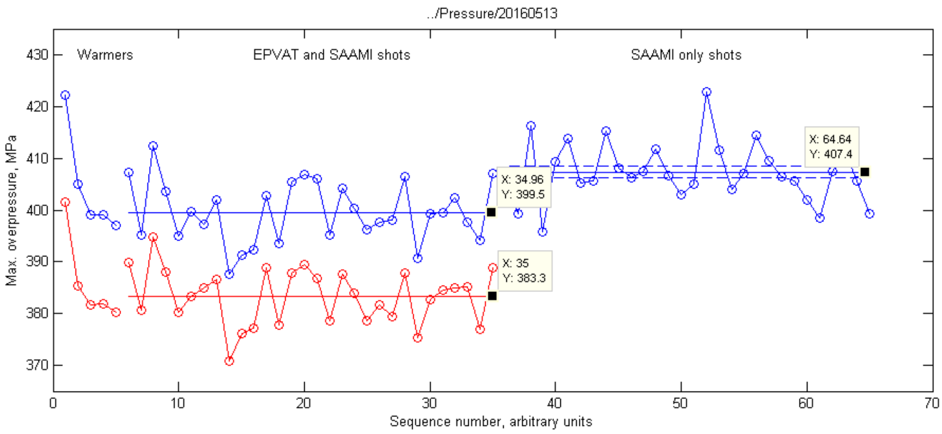

Figure 8.4 Case mouth (red) and calibrated conformal pressure measurements (blue).

The mean pressure value from the conformal sensor is about 16 MPa higher than the one measured with the case mouth mounted sensor, see Figure 8.4. At a reference pressure of 400 MPa, this amounts to 4%. The difference is not due to the added gas volume related to the case-mouth measurement, as this should affect both sensors equally.

Looking at the first half of the shots, i.e. when both sensors were mounted, one observes, shot-by-shot, a fairly constant offset between the measurements of some 16 MPa. This offset is significantly larger than the systematic uncertainty of the offset calibration which was only 6 MPa. This points to a physics effect, probably to a pressure gradient between the two sensors' mounting positions – the cartridge and the barrel.

The very strong correlation of the shot-by-shot fluctuations observed by both sensors around their respective averages reflects physical variations of the shots (e.g. variations of the propellant) and not statistical measurement uncertainties. Clearly, both sensors are perfectly capable of capturing these physical variations.

Comparing the size of fluctuations shot-by-shot reveals residual differences between the sensors which might be due to statistical uncertainties or physical variations of less importance than those of the propellant. For instance, since the conformal sensor also is sensitive to physical variations of the cartridge, one may expect to see somewhat larger fluctuations in total. This is, however, not supported on a sufficient significance level according to the result of the Fisher F-test. More data is needed to answer such questions in more detail.

A Piezoelectric pressure sensors

A.1 The piezoelectric effect in crystals

In very short, a piezoelectric material produces surface charges when it is compressed. Correspondingly, it changes its shape when placed in an electric field. The piezoelectric effect is closely related to the pyroelectric effect that works on temperature gradients. However, it should not be confused with the piezoresistive effect. The piezoelectric effect may exist in single crystals (quartz, tourmaline, gallium phosphate, etc.) or in polycrystalline ceramics like $BaTiO_3$, $SrTiO_3$ and similar. Here, we will only consider single crystal materials, mainly quartz. With the term crystal we mean materials composed of arrays of atoms in a repeating pattern. Much more on crystal structure may be found in e.g. Reference [13]. In a piezoelectric material, the chemical bonds between atoms are such that an amount of charge is transferred from one atom to the other. Straining the crystal deforms the lattice and the distribution of charge is altered.

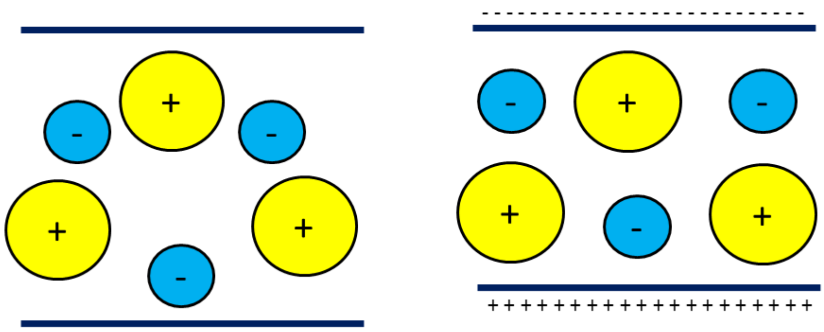

Figure A.1 Relaxed (left) and strained (right) lattice of piezoelectric material composed of silicon (yellow) and oxygen (blue).

Figure A.1 shows parts of a crystal lattice composed of silicon and oxygen. The bonding is a polar covalent bond, where electrons (negative charges) are displaced towards oxygen. For the relaxed crystal, the displacement of charge cancels between the unit cells. In case of a strained crystal, the atoms are displaced such that there will be charge layers on the crystal surfaces. In the case depicted, the charge is on the surfaces that are normal to the strain, but this is not a given. The charge layer on the crystal surface does not consist of free electrons. Quartz is an excellent insulator and no current can flow inside the material. The surface charge layer may be detected by electronic circuitry and is a measure of the compression of the crystal and again the applied pressure. The sensitivity of such transducers is given as amount of charge per applied pressure. The sensors of interest for high pressure, as for the case of a weapon chamber, have sensitivities in the order of 10 pC/MPa to 20 pC/MPa. This produces a charge of 5 nC for a 10 pC/MPa sensor at 500 MPa. 1 C is equivalent to the charge of $6.242 \cdot 10^{18}$ electrons, hence 5 nC corresponds to about $31 \cdot 10^{9}$ electrons.

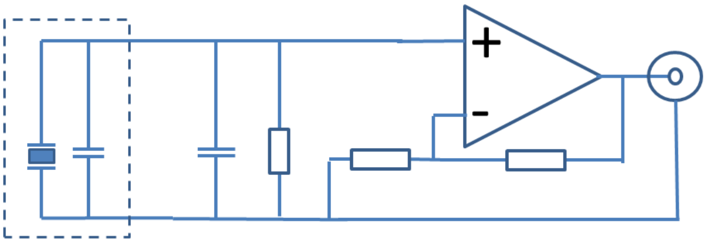

Figure A.2   Schematics of a piezoelectric sensor connected to a high impedance amplifier.

A.2 Amplifiers for piezoelectric sensors

The piezoelectric effect produces a charged layer on the surface of a piezoelectric material. The charge carriers on the surface layer are not free to move e.g. as an electric current, but may be detected when the surface is metalized and connected to circuitry for measuring charge. Two different types of amplifiers may be considered for detecting the surface charge. A high impedance amplifier as shown in Figure A.2 could be used to directly measure the electrostatic potential across the piezoelectric crystal. With this circuit, the charge that equalizes the charge layers on the surfaces of the piezoelectric crystal is delivered by the cable capacitance. This charge will present a voltage to the non-inverting input of the operational amplifier and the amplifier will at all times equalize this voltage on the other input by means of the resistive feedback. The gain may be adjusted by picking specific resistors for the voltage divider. Another option is to use a very low impedance current integrating amplifier as shown in Figure A.3. With this circuit, the voltage on the inverting input will be forced to zero by charging the feedback capacitor. There will be no voltage on the cable and there will be no charging of the cable capacitance. The feedback resistor determines the time constant of the amplifier and may be omitted when a very long time constant is needed, as for quasi static calibration of sensors.

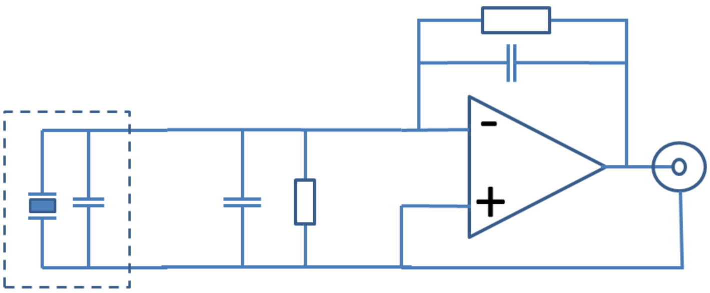

Figure A.3   Schematics of a piezoelectric sensor connected to a very low impedance, current integrating amplifier

For the high impedance amplifier, the cable capacitance will influence the measurements by equalizing parts of the piezoelectric surface charges. I.e. calibration of the sensor alone will not be possible, rather the sensor-cable combination must be calibrated as one unit. For the low impedance, current integrating amplifier, the voltage on the cable is close to zero and there is no effect of the cable capacitance. By the above reasoning, the current integrating amplifier is the preferred amplifier to use with piezoelectric sensors. We must still add that there is a multitude of piezoelectric sensors that have built-in amplifiers.

B Cartridge expansion due to internal pressure

A conformal sensor measures the pressure on the outer casing of the cartridge. Thus, the internal pressure will not be transferred to the sensor until the cartridge casing has made contact with the chamber wall. I.e. the internal pressure needed to expand the cartridge to this point is the pressure to be added to the pressure reading of the conformal sensor – it corresponds to the offset of the calibration. We may calculate this internal pressure from a knowledge of the elastic modulus of brass, the outside dimensions of the cartridge, the inside dimension of the chamber and the thickness of the cartridge wall. These values may be taken from either the SAAMI tables or from proper measurements. If measured, the measures should by taken at the position (along the cartridge) where the conformal pressure sensor is located.

We will need to relate the pressure inside the cartridge to the stress along the circumference (loop stress) of the cartridge. Then, through the elastic modulus (Young's modulus) of brass, this is related to the increase of the circumference, which again gives the increase of the diameter of the cartridge.

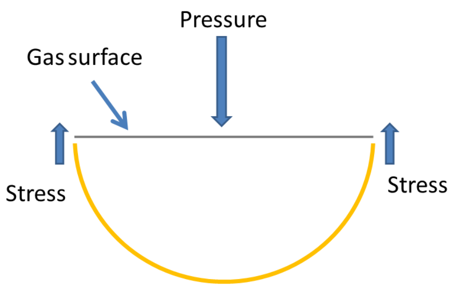

Figure B.1 Force balance in a pressurized tube, end view.

Looking at the cross-section of the cartridge, shown in Figure B.1, the forces on the gas surface balance out the force on the cartridge wall, i.e.

$$p_i D_c l_c = 2\, t_w l_c \sigma, \tag{B.1}$$

where p_i is the internal overpressure in the cartridge, D_c is the diameter of the cartridge at the position of the conformal pressure sensor, l_c is the length of the cartridge, t_w is the thickness of the cartridge wall and σ is the tangential stress in the cartridge wall. The definitions of stress and strain and the relation between them are explained below. Equation (B.1) models the cartridge as a thin walled, infinite tube. When we rearrange Equation (B.1) to solve for the stress of the cartridge or tube wall, we obtain

$$\sigma = \frac{p_i D_c}{2\, t_w}. \tag{B.2}$$

At this moment, we are not really interested in the stress of the tube wall, rather, the degree of expansion of the cartridge diameter is of importance. For this purpose, we need the relation between stress and strain, which is given by Young's modulus, the modulus of elasticity, namely[1]

[1] A more correct calculation shows that for the specific geometry, with an infinite tube, where no expansion in the

$E^* = \sigma/\epsilon$. Here, the stress σ is the force per area in N/m^2 and the strain is the relative expansion (or compression) $\Delta l/l$ in m/m. This results in a material-specific modulus of elasticity given in N/m^2. Although it has the same physical unit as pressure, the elastic modulus cannot be interpreted as a pressure.

With this in mind, we note that the circumference of the cartridge will increase from l_{loop} to $l_{\text{loop}} + l_{\text{loop}}\sigma/E^*$, when the stress of the catridge wall is σ. To produce a change of circumference of Δl_{loop}, the diameter has to change by $\Delta D = \Delta l_{\text{loop}}/\pi$. With this and Equation (B.2), we may relate the change in diameter of the cartridge to the applied internal pressure by

$$\Delta D = \frac{p_i D_c^2}{2\,E^*\,t_w}. \tag{B.3}$$

Solving for the internal pressure needed to produce a given increase in diameter, we obtain

$$p_i = \Delta D \frac{2\,E^*\,t_w}{D_c^2}. \tag{B.4}$$

As an example, we may calculate the internal pressure needed for a .308 Winchester cartridge to expand to the chamber dimensions. The position of the conformal sensor, as specified by the ANSI/SAAMI Z299.4-1992 document [33], is 35 mm from the boltface. At this position, the cartridge has an outer diameter of 11.5 mm and the wall thickness is 0.5 mm. The latter value has been obtained by cross sectioning a Lapua .308 Winchester cartridge. This value will vary between manufacturers. Based on chamber dimensions published by SAAMI, the clearance between an unfired cartridge and the chamber is 0.028 mm at the position of the conformal sensor. This is based on the maximum cartridge and minimum chamber drawings for the .308 Winchester. The actual difference should therefore never be less than 0.028 mm, but could be larger. The elastic modulus E of brass is reported as varying in the range of 100 GPa to 110 GPa. We select a value of 105 GPa. Remember that any of the discussed values carry an uncertainty; the most uncertain values are the cartridge wall thickness and the cartridge to chamber clearance. Also, using the unmodified Young's modulus, i.e., the implicit assumption that the cartridge is free to move at the ends, is a questionable one, but it produces the least internal pressure for a given increase in diameter. Anyway, when we insert these values in Equation (B.4), we obtain a pressure of 22 MPa or 3.2 kpsi. This explains about half the offset observed in the calibration procedure which is described in Chapter 7.

With a pressure of 22 MPa inside the casing, the stress in the cartridge wall is calculated to be 253 MPa. The tensile strength of brass is 200 MPa or more, while the ultimate tensile strength is 550 MPa. These values are taken from Wikipedia [45]. It is likely that the stress induced in the cartridge may exceed the tensile strength, and some plastic deformation and/or work hardening may occur. When the cartridge wall makes contact with the chamber, no further expansion occurs. Further work hardening and/or deformation may still occur due to the squeezing of the cartridge against the chamber.

At this point, we may discuss possible sources of systematic error of the calibration offset. The first one is, of course, differences in mounting depth of the conformal sensor. This may be adjusted by selecting the thinnest spacer ring which does not make the sensor head protrude into the chamber, but it is not clear whether the same mounting depth may be obtained consistently. The remaining gap should probably be added to the diameter expansion in Equation (B.4). The next point is the possibility of a slightly different inner diameter of the calibration adapter and the actual barrel used

axial direction is possible, a slightly increased modulus $E^* = \frac{E}{(1+\mu)\,(1-\mu)}$, modified by the Poisson number μ, should be applied.

for firing. This would produce different values of diameter expansion to be used in Equation (B.4). A third point concerns different cartridge dimensions for calibration and firing. If one, by chance, picks an untypical cartridge for calibration with, e.g., a strongly deviating diameter, it might upset the calibration.

As a counterpoint, we would like to mention that with a stress of 253 MPa in the cartridge shell, the region of plasticity may be reached quite comfortably, and all the here discussed sources of systematic errors may be wiped out long before the maximum cartridge pressure is achieved. In the plasticity region, the differential elastic modulus $\delta\sigma/\delta\epsilon$ is smaller than in the elastic region, i.e. the same increase in stress (pressure) results in a larger increase in diameter.

Based on the above reasoning and the results shown in the main part of this work, we may conclude that conformal pressure measurements at this point still leave open several questions which may be investigated further.

C Use of statistics

Different methods for measuring chamber pressure may produce different results. This could be due to different placements of the sensors, changes of the measured volume, differences due to measuring either static or dynamic pressure, different characteristics of the sensor, e.g. different responses to a transient and many other factors. Such differences may be called systematic effects (if they can be corrected for in the data analysis) or, systematic errors or uncertainties (if the physical source for the differences is unclear and thus, the differences may not be corrected for in the data analysis). Also, when just one method is used repeatedly, the results from shot to shot will differ. This may be due to variations in powder content, variations in casing dimensions, specifically wall thickness, variations in the handling of the cartridges, wear and tear of the test barrel or other, unknown mechanisms. Even thermal noise in the sensor and electronics may produce different results, although variations due to noise are expected to be small compared to the other mentioned effects. Anyway, as long as we consider the measurements from a series of shots as a sample drawn from one lot, such differences may be called statistical effects which may be investigated with the methods of statistics.

Measurements done with pressure sensors and data acquisition electronics will produce a time series of pressures, hopefully catching the whole pressure history from ignition to after the exit of the bullet from the barrel. From this time series we extract one single value, the maximum value of the pressure curve, which we refer to as the maximum pressure. We will refer to this maximum pressure as one single measurement, while a sample is a number of single measurements from the same production lot of ammunition and which has been loaded with the same loading machine without any issues. Table C.1 shows such a sample of 10 single measurements.

Evaluating pressure measurements demands a sound use of statistical methods, as is obvious from the EPVAT and SAAMI standards. A small subset of statistical methods that may be useful for assessing ballistic data is described below. We have obtained much of the information from Wikipedia. Further information may be found in the online handbook of statistical methods [18] by the National Institute for Science and Technology. For a thorough course in statistics, you may like to visit Rice University's online course [31].

The maximum pressures, as measured by firing a number of rounds of ammunition, span a range of values. However, they are expected to center around a well defined mean and are also expected to follow a normal distribution. The latter has not been proven by us, but is stated in Reference [32], Section I: *It is an experimental fact that the pressures are normally distributed.* Wikipedia [42] contains more on the normal distribution.

C.1 Mean and standard deviation of a sample

Table C.1 shows the results of a sample of 10 single measurements using the method described in Section 2.3, i.e. the measurements are taken with a recessed piezoelectric sensor ahead of the case mouth. The mean maximum pressure for a sample of N single measurements p_n is given by

$$\overline{p} = \frac{1}{N} \sum_{n=1}^{N} p_n, \tag{C.1}$$

Shot #	V_0 (m/s)	Max. pressure (MPa)
1	881	378
2	884	386
3	888	389
4	883	379
5	881	376
6	891	390
7	892	391
8	893	396
9	881	376
10	882	377

Table C.1 Velocity and maximum pressure for a sample of 10 shots.

and the corrected standard deviation [43] is

$$s = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(p_n - \overline{p})^2}. \tag{C.2}$$

The use of $N-1$ instead of N in Equation (C.2) is the Bessel correction, named after Friedrich Bessel. This corrects the bias in the estimate of the population variance s^2. It also partially corrects the bias in the estimate of the population standard deviation.

For the sample shown in Table C.1, the mean maximum pressure is 383.8 MPa and the corrected standard deviation, using Equation C.2, is 7.42 MPa. The table also gives the projectile velocity measured at a distance of 5 m from the weapon. The mean and standard deviation for the velocity measurements are 885.6 m/s and 4.90 m/s, respectively.

C.2 Standard deviation of the mean

The red graph in Figure C.1 shows the normal distribution with a mean of 383.8 MPa and a standard deviation of 7.42 MPa, i.e. the values taken from Table C.1. Positions of 1, 2 and 3 standard deviations on both sides of the mean have been marked by vertical red bars. For a normal distribution, 68% of the single measurements fall within $\pm\sigma$ of the mean, 95.5% within $\pm 2\sigma$ and 99.7% within $\pm 3\sigma$. This is the 68-95-99.7 rule. Since the normal distribution is symmetric, if one only cares about one tail of the distribution, one may divide the complement to 100% by two. For instance, 84% of all single measurements fall below the mean plus σ, 97.5% fall below the mean plus 2σ and so on.

Figure C.1 also shows normal distributions with the same mean as before, but with standard deviations divided by $\sqrt{10} \approx 3.2$ and $\sqrt{30} \approx 5.5$. They show the distribution of the sample mean around the true mean (of the red distribution) for sample sizes of 10 and 30, respectively. The EPVAT procedure prescribes 30 single measurements to obtain a large enough sample. The distribution of the sample mean around the true mean may be interpreted as follows. If we produce many samples of the same sample size N (all of which drawn from the same lot), the sample means will in general all be different. However, the sample means themselves will form a distribution centered around the true mean (which is the same as before), with a standard deviation reduced by a factor of $\sqrt{N}$

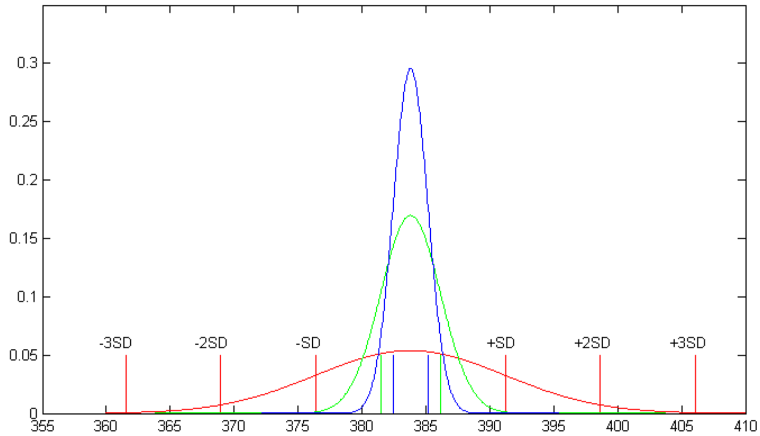

Figure C.1 Probability density of normal distributions with mean 383.8 MPa and standard deviations 7.42 MPa (red), 2.35 MPa (green) and 1.35 MPa (blue).

compared to the standard deviation of a single sample. A proof for this is given in Reference [43]. The reduced standard deviation may thus be interpreted as the uncertainty of the estimated mean value.

In Figure C.1, the one σ uncertainties of the mean value are marked by vertical bars of corresponding color. We see that a mean of 30 single measurements will most likely be within 2 – 3 MPa of the true mean, assuming the standard deviation of the sample of 7.42 MPa is a correct estimate. Clearly, the estimate of the uncertainty of the mean relies on a good estimate of the true standard deviation. Remember that the only way to obtain the real distribution of a lot of ammunition is to fire every single round of the lot.

C.3 Special functions and statistical distributions

Statistical distributions take the form of probability density functions (PDF) whose integrals are their corresponding cumulative distribution functions (CDF). The PDF of a continuous random variable is the function that describes the relative likelihood for this random variable to take on a given value. The probability for the variable to fall within a given range is the integral of the PDF within this range. When $f(t)$ is the PDF and $F(x)$ is the CDF, the latter is written as

$$F(x) = \int_{-\infty}^{x} f(t)\,\mathrm{d}t. \tag{C.3}$$

The probability of t to be in the range of t_1 to t_2 will then be $F(t_2) - F(t_1)$.

As a reference, we will present the explicit expressions for several PDFs and CDFs. These expressions are complicated and provide little insight by themselves. A clearer view is often obtained by a graphical presentation. The explicit expressions are important as they are needed to perform statistical tests, as will be shown later, but in these cases, the numerics is built into the tools used for analysis, e.g. Matlab, Octave, Excel or others.

The Gamma function and the Beta function are not considered as PDFs, but they are special functions that are often used in the explicit expressions of certain PDFs. We therefore give brief comments on these functions below.

C.3.1 Beta and Gamma function

The Gamma function (Γ) extends the factorial function to real and complex numbers. Also, the argument is shifted down by 1 so that the Gamma function for positive integers equals $\Gamma(n) = (n-1)!$ Extending the argument to complex numbers with positive real parts, the definition is

$$\Gamma(x) = \int_0^\infty t^{x-1}\, e^{-t}\, \mathrm{d}t. \tag{C.4}$$

The Beta function was studied by Euler and Legendre and was given its name by Jacques Binet. The symbol B is actually a Greek capital β. The definition of the Beta function is

$$B(x, y) = \int_0^1 t^{x-1}\, (1-t)^{y-1}\, \mathrm{d}t. \tag{C.5}$$

C.3.2 Normal distribution

The PDF of the normal distribution is given by

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \tag{C.6}$$

C.3.3 Standard deviation distribution

Let us assume a normal distributed property x. Drawing a sample of measurements of this property, one may calculate the biased standard deviation

$$s = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_n - \overline{x})^2}, \tag{C.7}$$

where $\overline{x}$ is the sample mean, and $\sigma^2 = \frac{1}{N-1}\sum_{n=1}^{N}(x_n - \overline{x})^2$ is the unbiased sample variance. According to Wolfram Mathworld [46] and [09], the biased standard deviation may be considered as a statistically distributed property with the standard deviation distribution as its PDF

$$f_N(s) = \frac{2s^{N-2}}{\Gamma\left(\frac{N-1}{2}\right)} \left(\frac{N}{2\sigma^2}\right)^{\frac{N-1}{2}} e^{-\frac{Ns^2}{2\sigma^2}}. \tag{C.8}$$

This expression is far too complicated to give any insight. Not only is it complicated by itself, but it also contains the Gamma function [47]. Plotting the distribution may provide a clearer view. Figure C.2, that has been taken from Wolfram Mathworld, shows the standard deviation distribution function for $\sigma^2 = 1$ and different values of sample size N.

To relate this distribution to our pressure measurements, we may also conduct some numerical experimentation. We simply use the Matlab Statistical Tooolbox [14] and process a large number of random observations drawn from the normal distribution. Again, we select a mean value of 383.8 MPa with a corrected population standard deviation of 7.42 MPa. Figure C.3 shows generated distributions of the biased sample standard deviation s based on samples of size 2, 5, 10, 30 and 100.

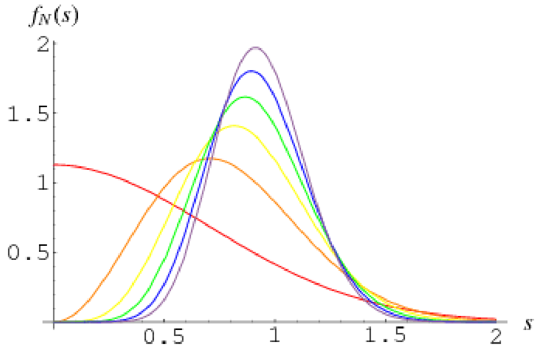

Figure C.2 *Standard deviation distribution for $N = 2$ (red), 4 (orange), 6 (yellow), 8 (green), 10 (blue) and 12 (violet). The figure is taken from Wolfram Mathworld.*

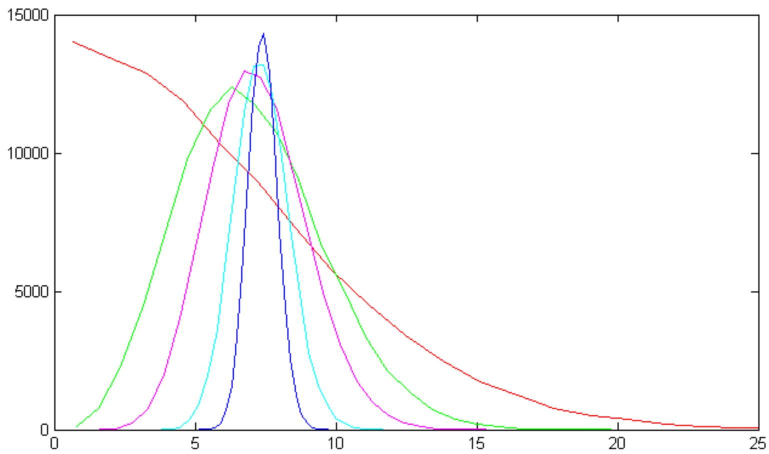

Figure C.3 *Biased sample standard deviation distribution from an underlying normal distribution. Sample sizes are $N = 2$ (red), 5 (green), 10 (mangenta), 30 (cyan) and 100 (blue).*

We see that a standard deviation calculated from a sample of two measurements is just about meaningless. Using 5 or 10 observations seems to result in a wide distribution that also has the maximum on the low side of the true σ, which is probably since it is a distribution of the biased standard deviation and not the corrected or unbiased one obtained by dividing by $N - 1$ instead of N. It seems to us, that the EPVAT procedure with 30 measurements may be a good choice. The SAAMI uses only 10 measurements, but does not ask us to calculate the standard deviation from the measurements, rather the standard stipulates a Coefficient of Variation of 4% of the Maximum Average Pressure values to be used as the standard deviation.

C.3.4 χ^2 distribution

Let us assume a normal distributed property x with mean $\mu = 0$ and standard deviation $\sigma = 1$. Then, x^2 is χ^2 distributed (with one degree of freedom). This distribution is of some significance since it describes the distribution of partial decay widths in quantum mechanics (assuming normal distributed transition matrix elements). This is particularly recognized in the field of nuclear physics, where this distribution is also known as the Porter-Thomas distribution. A sum of k such randomly distributed variables is χ^2 distributed with k degrees of freedom. As a sum of squares cannot be negative, the probability density function is only defined for positive values. The χ^2 PDF is given by the expression

$$f(x \mid k) = \frac{x^{\frac{k}{2}-1} e^{-\frac{x}{2}}}{2^{\frac{k}{2}} \Gamma\left(\frac{k}{2}\right)}. \tag{C.9}$$

The standard deviation distribution is a modified χ^2 distribution.

C.3.5 Student *t* distribution

As discussed above, we may calculate the probability distribution of the sample mean in the case where the true mean and standard deviation are known. What we really want is to relate the sample mean to the true mean in the case where the sample is small and the true standard deviation is unknown. This problem was solved by William Sealy Gosset and published under the pseudonym Student [37]. The Student t distribution is discussed in Wikipedia [44] where we can read: "If we take a sample of N observations from a normal distribution, then the t distribution with $\nu = N - 1$ degrees of freedom can be defined as the distribution of the location of the sample mean relative to the true mean, divided by the sample standard deviation, after multiplying by the standardizing term $\sqrt{N}$." The PDF of the Student t distribution is

$$f(t \mid \nu) = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\nu\pi}\,\Gamma\left(\frac{\nu}{2}\right)} \left(1 + \frac{t^2}{\nu}\right)^{-\frac{\nu+1}{2}}. \tag{C.10}$$

Here, Γ is again the above mentioned Gamma function [41]. A brief explanation of the Student t distribution is also given in the Numerical Recipes [19].

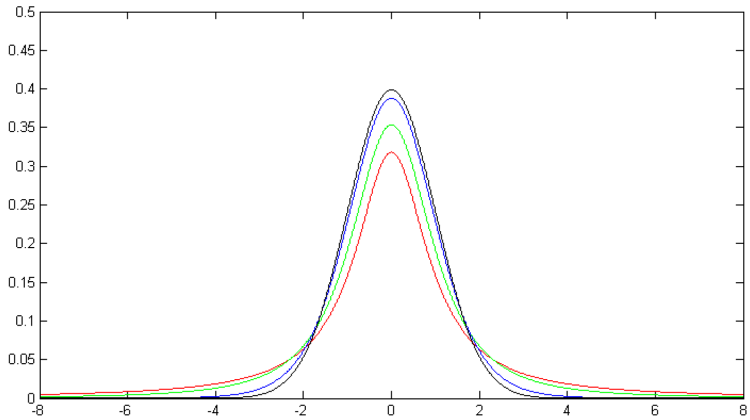

Figure C.4 Student t distribution with 1 (red), 2 (green) and 9 (blue) degrees of freedom and compared to the normal distribution (black).

Figure C.4 shows the Student t distribution for several different numbers of degrees of freedom together with the normal distribution. When the sample size increases, the t distribution converges to the normal distribution, and already at a sample size of 10, the two distributions seem pretty close. The t distribution is used for the t test, with which one may determine, whether two observed distributions have mean values that are *significantly* different from each other.

C.3.6 F distribution

The F distribution, also known as Snedecor's F distribution or the Fisher-Snedecor distribution (after Ronald Fisher and George W. Snedecor) is another continuous PDF. The F distribution has two parameters, d_1 and d_2, which may be interpreted as degrees of freedom. The PDF is given by

$$f(x \mid d_1, d_2) = \frac{1}{x\,B\left(\frac{d_1}{2}, \frac{d_2}{2}\right)} \sqrt{\frac{(d_1 x)^{d_1}\, d_2^{d_2}}{(d_1 x + d_2)^{d_1+d_2}}}, \tag{C.11}$$

where B is the above mentioned Beta function.

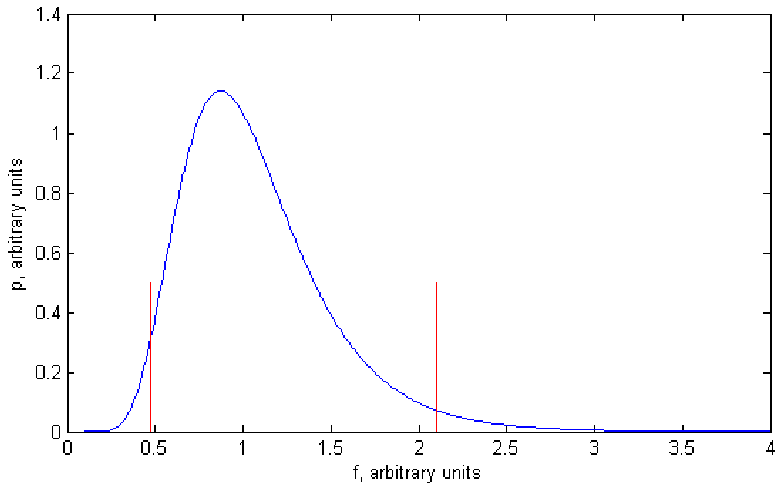

Figure C.5 F-distribution for $d_1 = 29$ and $d_2 = 29$ degrees of freedom. The two critical values marked by the red lines are explained in the text.

An example graph of the F distribution is shown in Figure C.5. The distribution has been calculated for sample sizes of 30 observations each, i.e. $d_1 = d_2 = 29$ degrees of freedom. The F distribution is not symmetric. The F distribution is used for the F test, with which one may determine, whether two observed distributions have variances that are *significantly* different from each other.

C.4 χ^2 test

The χ^2 test may be used to calculate the probability that a sample is drawn from a particular distribution. Typically, observations are binned and the squared difference of observations O_i with the expected number of observations E_i is calculated for each bin. In such a case, since Poisson counting statistics apply for each bin, each squared difference is divided by its variance, which is the number of expected observations. The results for all bins are added up

$$\chi^2 = \sum_{i=1}^{N}(O_i - E_i)^2/E_i. \tag{C.12}$$

The calculated χ^2 is now, not surprisingly, χ^2 distributed with the number of degrees of freedom ν equal the number of bins N minus the number of free parameters of the assumed distribution n minus one, i.e. $\nu = N - n - 1$.

Alternatively, if observations O_i with their proper error estimates ΔO_i as function of some variable x are available, one may calculate the probability whether the observations follow a particular functional form $f(x)$. Again, one may calculate the number

$$\chi^2 = \sum_{i=1}^{N} (O_i - f(x_i))^2 \,/\, (\Delta O_i)^2 , \tag{C.13}$$

which is χ^2 distributed with $\nu = N - n - 1$ degrees of freedom and all recurring symbols have the same meaning as before. Typically, good agreement is achieved when the number χ^2/ν is close to unity.

C.4.1 Matlab implementation

Matlab implements this test as the function

```
Matlab: h=chi2gof(X);
```

that returns the test decision h. It returns 0 if the null hypothesis, that the data in X come from a normal distribution cannot be rejected. It returns 1 when the null hypothesis is rejected at the 5% significance level. In other words, this Matlab implementation is restricted to the first case, it may only test for the normal distribution, and it is restricted to one single significance level.

C.5 Student *t* test

A common situation when doing measurements is to evaluate whether a change in experimental conditions has any influence on the measured results. One would perform a number of measurements, change one single condition, and then repeat the measurements. One may now ask whether the first set of measurements, i.e., the first sample is drawn from the same distribution as the second set of measurements, i.e., the second sample. In particular, one may want to know whether the inevitable difference of the two resulting sample means is significant (pointing to a change of the true mean, i.e., a real effect due to the changed experimental conditions) or whether it may be due to a statistical fluctuation. An example would be the measurements reported in Chapter 8. There, we present results of measurements with the conformal pressure sensor method. The measurements are done both with a case mouth pressure sensor mounted and with the case mouth sensor removed and the hole plugged. What we expect is that the difference in volume will produce measurable differences in pressure. This seems to be the case, but we must still consider the possibility that such a change in mean value could happen just by chance. The Student t test may be used to determine the significance level.

C.5.1 Details of t test

The sample mean μ and the sample standard deviation σ of a normal distributed property can be shown to be independent random variables. This result is not trivial, since the sample mean is needed to calculate the sample standard deviation. The Student t distribution arises as the distribution of the quotient of the sample mean and the sample standard deviation. This points to how the Student t distribution may be used to see whether two sample means are significantly different. Specifically, for this test, we need to relate the difference of the sample means to the standard deviation of the mean. The latter is calculated from the "pooled variance" or "combined variance" of the two samples of observations x_i and y_i. In practice one calculates

$$s_p^2 = \frac{\sum_{i=1}^{N_x}(x_i - \overline{x})^2 + \sum_{i=1}^{N_y}(y_i - \overline{y})^2}{N_x + N_y - 2}, \tag{C.14}$$

from which the standard deviation of the mean may be calculated by

$$E_{xy} = \sqrt{s_p^2 \left(\frac{1}{N_x} + \frac{1}{N_y} \right)}. \tag{C.15}$$

Now, we relate the difference of the sample means to the standard deviation of the mean, and obtain with

$$t = \frac{\overline{x} - \overline{y}}{E_{xy}} \tag{C.16}$$

a quantity which follows a Student t distribution with $N_x + N_y - 2$ degrees of freedom. The absolute value of t will increase, when the difference between the means increases. It will also increase when the standard deviation of the mean decreases. The latter occurs, when the standard deviation gets smaller and also when the number of observations increases. The null hypothesis may be rejected when $|t|$ is too large. The Student t test is a procedure for deciding whether an observed t value is significant in relation to a given significance level. The name "alpha" is used for the numerical value of this significance level. An alpha of 0.05 (5%) seems to be somewhat of a default used in both Matlab and Octave, as well as in examples given in the Engineering Statistics Handbook available at the National Institute of Standards and Techonology (NIST) homepage [18].

Figure C.6 shows a plot of the Student t distribution with 58 degrees of freedom (two different samples, each with 30 independent single measurements). This is the situation described in Chapter 8. The blue vertical bars are placed at the $\pm t$ values calculated from the two samples of maximum pressures obtained with the conformal pressure sensor method, i.e. $t = -5.1837$. Now, the probability that the t value will deviate that much from zero is the integral of the Student t distribution from $-\infty$ to this t plus the integral above the upper blue bar to $+\infty$. In this example, the integral computes to 2.8777E-06. If this probability is less than the "alpha", we reject the null hypothesis, since the chance that the observed difference of the sample means may be explained by a statistical fluctuation is less than the significance level. In fewer words, we may say that the two sample means are significantly different.

In this example, we reject the null hypothesis and the mean values are considered significantly different. The red vertical bars in Figure C.6 indicate the critical t values, where the cumulative probability density is 0.025 for the leftmost bar and 1-0.025 for the rightmost. This obviously indicates an alpha (significance level) of 0.05 or 5%. The position of these critical values may be obtained by evaluating the inverse cumulative Student t distribution at alpha/2 and (1-alpha)/2. The

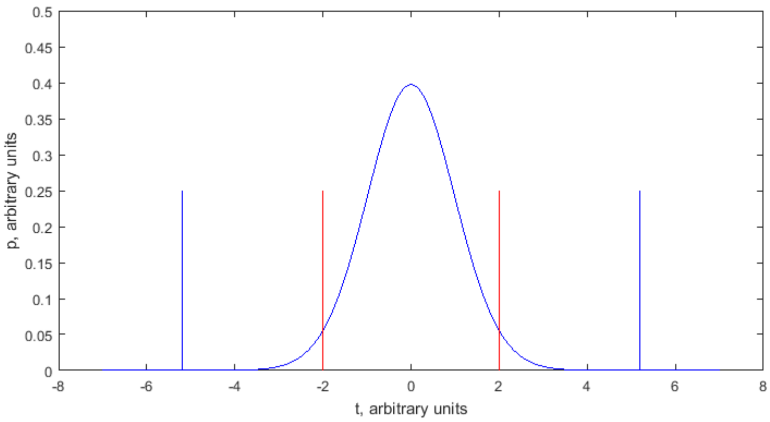

Figure C.6 Example of the Student t test, see text for details.

areas of the probability distribution outside the critical values are equal to alpha – here 0.05. Any t value outside these critical values indicate that there is less than a 0.05 probability that the observed difference of the means could happen by chance.

C.5.2 Octave/Matlab implementation

We may avoid doing the mathematics of the Student t test each time it is needed, since Mathworks [14] and the developers of Octave [20] have done this for us. In these computational programs, the test for significantly different means is simply

```
Matlab: h=ttest2(X,Y,alpha);
Octave: h=ttest2(X,Y,"alpha",alpha);
```

where X and Y are the two samples in vector form, and alpha is the significance level. The alpha is the requested significance level given as a fraction. I.e. for a 5% significance level, alpha should be entered as 0.05. The result, h, is 0 if the null hypothesis may not be rejected and the difference of the sample means may be explained just by chance. When the return value is 1, there is less than "alpha" probability that the observed difference may be explained by a chance fluctuation, and the two sample means are said to be significantly different. Both samples are assumed to be drawn from a normal distributed property with unknown, but equal variance. The actual probability for the observed difference of sample means as well as the actual t value and the critical t value for the given significance level may also be obtained from the Matlab/Octave function by requesting more return values.

C.6 Fisher F test

Sometimes, in statistics, it is of interest to find out whether sample variances are significantly different. The Fisher F test may be used to determine whether the inevitable difference of two sample variances may be explained by a chance fluctuation, or whether it is significant. Interestingly, the sample means are of no interest for this test, in particular, the sample means may be significantly different. The reason for this is that for a normal distributed property, the sample mean and sample standard deviation are independent random variables. However, this also means that the Fisher F

test will only yield useful results if the investigated property is normal distributed. In fact, the test is known to be quite sensitive to violations of this assumption, which makes it rarely used. The null hypothesis of the Fisher F test is that two sample variances are drawn from the same distribution.

C.6.1 Details of F test

The F distribution may be formulated as the distribution of the quotient of two sample variances. This points to how the F test may be employed. One calculates the quantity

$$F = \frac{S_X^2}{S_Y^2}, \tag{C.17}$$

where S_x^2 and S_y^2 are the two sample variances (of a normal distributed property). The sample mean values may be significantly different. The quantity F follows the F distribution with $N_x - 1$ and $N_y - 1$ degrees of freedom. A value of $F = 1$ means equal sample variances. Differences of sample variances will produce F values different from one. The cumulative F distribution will tell whether a value different from $F = 1$ may be explained by a chance fluctuation. The red bars in Figure C.5 show the upper and lower limits of F for a significance level of 5%. If the calculated F value falls outside of this range, the null hypothesis may be rejected on a 5% significance level.

C.6.2 Octave/Matlab implementation

Again, this test has been implemented both in Matlab as well as in Octave as the Function vartest2. The test for significantly different variances is simply

```
Matlab: h=vartest2(X,Y,alpha);
Octave: h=vartest2(X,Y,"alpha",alpha);
```

As before, X and Y represent the two samples in vector form, and alpha is the significance level. The significance level is given as a fraction, i.e. for a 5% significance level, alpha should be entered as 0.05. When the test returns 0 the observed difference in sample variances may be explained by a chance fluctuation and the null hypothesis may not be rejected. When a 1 is returned, the observed difference of sample variances is unlikely to happen by chance, i.e., with a probability of less than alpha, and the null hypothesis may be rejected on the given significance level. The actual probability for the observed difference of sample variances as well as the actual F value and the critical F values for the given significance level may be obtained by requesting more return values from the Octave/Matlab function.

C.7 Test for pairwise different mean

Such a test may be used when the measured data have much of their variance related to effects that correlate in the two samples. As an example, one may cite the pressure measurements reported in Chapter 8 and shown in Figure 8.2.

C.8 Required sample size

Back in Chapter 8, we performed two independent series of measurements with the conformal method. We expected the two samples to have different mean values and indeed, this is what we observed. Using the Student t test, the observed difference may even be called significant – with a good margin. However, if the means had been closer, or the variance had been larger, we may not have been able to conclude that the means were different. We also deduced that the two sample variances cannot be called significantly different. The point is, that a verdict of significant difference will be dependent on a sufficiently large sample size. If a significant difference is observed, further testing is usually unnecessary, since more data may strengthen the conclusion – heighten the significance level – but not reverse it. On the other hand, not being able to reject the null hypothesis may incite one to perform more measurements, but there comes no natural point for when to stop and accept the null hypothesis. This has always been a problem with the statistical approach and it will not be solved by us, either.

D Parts and materials

Both the build and the maintenance of the conformal measurement system takes a lot of different parts, and locating and ordering parts takes a lot of time. In an attempt to streamline the acquisition process, when parts and consumables need to be replaced, we will describe the different sources in some detail.

D.1 PCB components for calibration and measurement

PCB Inc. seems to be the sole supplier of equipment for conformal measurements and for calibrating the conformal sensors. FFI initially acquired sensors and calibration adapters for six different calibers. The order was placed to PCB Piezotronics Europe GmbH. Delivery was in early 2015. At that time, our point of contact was Piotr Gasiorczyk (mail: pgasiorczyk@pcb.com). He was the application engineer from PCB US who aided us in the decision of what parts to order. The sales quote came from PCB EU and in the end, the offer was sent from Elisabeth Duenschede at PCB Europe. Since the calibration adapters themselves were obtained from PCB Europe [26], we believe that this will be the most natural place for ordering spare parts and consumables, and that our order contact should be Mrs. Duenschede [03].

For each caliber, we need the sensor itself, as well as the calibration adapter. The calibration adapter consists of the calibration chamber and the chamber adapter. The chamber adapter mounts to the high pressure port. The port has the same threading and seal as the PCB sensors 118A, 108A and 119A. The seal is the PCB model 065A06. A few of these are supplied with each calibration adapter. The other end of the chamber adapter enters into the cartridge casing, and an O-ring holds the pressurized oil inside the cartridge. There must be no damage to this O-ring, and according to the PCB manuals, it should be inspected and replaced whenever the chamber is mounted to the chamber adapter. Our impression is that this O-ring is always damaged when the chamber is pulled off the chamber adapter. This actually takes some force. The O-rings are of different dimensions for each caliber, as they must fit tightly inside the case mouth. It seems that the O-rings do not have PCB part numbers, but are referred to by the manufacturer's (Parker [22]) size index. You may find this information in the outline drawing in the Installation and Operating Manual for the actual calibration adapter. You may also find the dimensions in the Parker O-ring Handbook and obtain similar O-rings elsewhere. The O-ring material is "BUNA", which we believe is nitrile rubber, but we do not know the hardness. Table D.1 lists the O-ring to use with some popular calibers. A few lines have been left open for filling in new calibers and calibration adapters. With our initial purchase in early 2015, the O-rings were delivered in bags of 15 rings.

The conformal sensor method relies on the sensor being mounted so as to appear to be a part of the chamber wall. The correct mounting depth of the sensor is determined by a spacer ring placed on the sealing surface of the sensor. These spacers are delivered in sets of nine spacers of various thickness. The spacers need not form a gas-tight seal, as the burning powder gasses are contained within the casing. For most calibers, the sensor is a quarter inch in diameter, and the spacer set is the PCB model 065A19. For the 4.6 x 30 mm caliber HK, the PCB model 117B69 sensor is 0.194 inch and the spacer set is the PCB model 065A27. The information may also be found in Table D.1.

Caliber	Sensor	Adapter	O-ring	Spacer set
4.6 x 30 mm HK	117B69	090B275	#2-004	065A27
.223 Rem	117B30	090B30	#2-005	065A19
.308 Win	117B44	090B44	#2-008	065A19
9 mm Luger	117B25	090B201	#2-009	065A19
.300 AAC Blackout	117B204	090M153	#2-007	065A19
.338 Lupa mag	117B229	090B274	#2-009	065A19

Table D.1 O-ring and spacer part numbers for some PCB sensors.

D.2 Parts for build and maintenance

The high pressure pump and associated equipment were built at the PTV according to drawings by Sven Ivar Holm. PVT fabricated the high pressure pump and the mounting arrangement. The conformal calibration adapter was obtained from PCB. Several other parts were obtained from various sources.

1. The valves for the oil supply tank and sensors are both HiP model 100-11XF4 valves. This is a 100 000 psi capacity needle valve. After removing the valve on the adapter side, it was kept as a spare part.
2. The central manometer is a HiP model 6PG100, 0–100 000 psi, 316, panel mounted manometer with a 6 inch dial.
3. There are several adapters, fittings and tubes. All were obtained from HiP, and all are rated to 100 000 psi pressure capacity.
4. The hydraulic oil for the high pressure pump is Shell Tellus model S46 oil.
5. The reference sensor is a Kistler model 6213BK sensor. This is a 1 GPa capacity pressure sensor. The "K" version is a calibration version with a linearity of $\pm \leq 0.3\%$. Late 2016, a recalibration of this sensor was performed by Norwegian Scanditest [36]. Our person of contact was Jostein Kyte.
6. Several hydraulic connection blocks are fabricated by the PTV.
7. The plunger that actually forces the oil out of the cylinder is a hardened steel rod. We obtained it from "Form og Stanseteknikk" [05].

D.3 Parts for measurements

1. The first barrel to be instrumented was the Sig-Sauer match grade 7.62 x 51 mm NATO caliber with serial number W50428.
2. The case-mouth mounted sensor is a Kistler model 6215 pressure sensor.
3. The conformal sensor is a PCB model 117B44 pressure sensor.

E Conversion between units

According to the système international (SI), the unit of pressure is the Pascal (Pa), which is equal to one Newton per square meter N/m^2. US based organizations frequently use the pound per square inch (psi). The conversion between psi and Pascal is 1 psi = 6894.75728 Pa and 1 Pa = 0.000145037738007 psi. SAAMI uses psi for the published pressure limits, but the tabulated values are divided by 100. I.e. the actual unit they use is 100 psi. So when the tabulated value for the MAP of .308 Winchester is given as 620, the pressure is 62 000 psi or 62 kpsi. To convert values found in the SAAMI tables to MPa, one should multiply the tabulated values by 0.6895.

The US based PCB Inc. and the High Pressure Equipment Company HiP will often give the torque for tightening pressure sensors and fittings in foot pound (ft. lbs.) Elsewhere it may be written as lb.ft., while the SI unit is Nm. Again, 1 lb.ft. = 1.35581794833 Nm, while 1 Nm = 0.737562149277 lb.ft.

Table E.1 lists some relevant values in different units.

non-SI unit	SI unit
1 inch	0.0254 m
5/16 inch	7.9375 mm
7/16 inch	11.1125 mm
1 pound (force)	4.4482216 N
1 psi	6.895 kPa
5000 psi	34.5 MPa
10000 psi	69.0 MPa
40000 psi	276 MPa
620 (psi/100)	427 MPa
650 (psi/100)	448 MPa
1 bar	100 000 Pa
1000 bar	100 MPa
1 foot	0.3048 m
1 ft. lbs.	1.356 Nm
5 ft. lbs.	6.8 Nm
10 ft. lbs.	13.6 Nm
20 ft. lbs.	27 Nm
60 ft. lbs.	81 Nm

Table E.1 Conversion of non-SI units to SI units.

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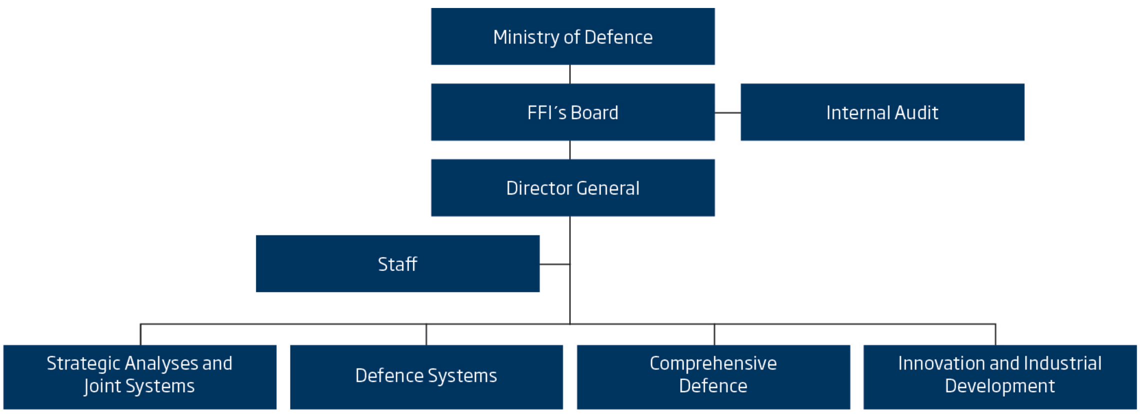

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