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INSTITUTE OF AEROSPACE ENGINEERING

LETECKÝ ÚSTAV

MINIATURE DEVICE FOR FLUIDS PRESSURE IN-SITU MEASURING

NÁVRH MINIATURNÍHO ZAŘÍZENÍ PRO MĚŘENÍ VNITŘNÍHO TLAKU MÉDIA

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis Assignment

Institute:	Institute of Aerospace Engineering
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Miniature device for fluids pressure in–situ measuring

Brief Description:

Pressurized units and systems are specially controlled for use in space. The risk of explosion or contamination of other units must be minimized. Any incident can cause a failure, loss of the mission or serious threat to human life. Pressure of the liquid inside the capsule can change depending on the external environment, e.g. temperature. How to effectively measure the pressure in a very small space where pressure gauges cannot be installed?

Bachelor's Thesis goals:

– Overview of micro–pressure sensors for aerospace applications.
– Preliminary design of installation in a very restricted area, evaluation of variants.
– Structural design, assembly and test procedure.

Recommended bibliography:

RUPITSCH, Stefan Johann. Measurement of Physical Quantities and Process Measurement Technology. In: Piezoelectric Sensors and Actuators. Germany: Springer Berlin / Heidelberg, 2018, p. 407-509. ISBN 9783662575321. ISSN 2364-3293.

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Abstract

This thesis researches the possibilities of high pressure measurements in extremely small spaces (around 8 mm in diameter). It proposes several different approaches to measuring pressure inside a paraffin capsule. This capsule is a part of an actuator inside a satellite, meaning the whole assembly consisting of the sensor, the capsule and the casing has to be designed to withstand the harsh conditions of outer space. This includes sealing against vacuum and resistance against temperature changes. This thesis creates an overview of possible solutions and can be of benefit to anyone with similar problems and space limitations.

Keywords

pressure measurement, aerospace, miniature device, high pressure

Rozšířený abstrakt

Tato práce navrhuje různé způsoby pro měření tlaku v extrémně malých prostorech. Konkrétně je řešeno, jakým způsobem se dá zjistit tlak roztaveného vosku v miniaturní kapsli (o celkové velikosti cca D = 30 mm). Takto drobné rozměry jsou nutné, protože celá kapsle je uložena v malém satelitu, kde je nezbytné správně využít všechen dostupný prostor. Další velmi důležitý požadavek na senzory pro tento projekt je rozsah měřených tlaků. Tlaky naměřené v kapsli mohou dosahovat až okolo 16 MPa (160 bar), což znamená značnou námahu jak pro kapsli, tak pro samotný senzor. První část této práce se věnuje rešerši dostupných tlakových senzorů na trhu. Existuje velké množství přístrojů pro různé specifické aplikace. Největší pozornost je věnována senzorům, které jsou používány v raketách či sondách, protože takovéto přístroje musí zvládnout podobné podmínky jako jsou požadované i v tomto projektu. Pro takovéto senzory je například důležité, aby byly hermeticky uzavřené a elektronika tak byla chráněna proti vakuu. Také je nutné, aby byly schopné vydržet poměrně velké teplotní výkyvy (v případě tohoto zadání -60 až 70 °C).

Pro konkrétní představu, tlakové senzory v raketách jsou často používány například pro monitorování tlaku paliva ve spalovacích komorách či dynamického tlaku v hydraulických systémech lodi. Tato práce se inspiruje zejména tlakovými senzory uvnitř hydrauliky. Tyto přístroje musí nejenom vydržet extrémně vysoké tlaky v řádech megapascalů, ale také se nesmí poškodit při kontaktu s různými tekutinami. Všechny tyto vlastnosti musí senzory v této práci splňovat také, jinak by nebyly pro řešení problému použitelné.

Důvodem, proč nelze jako finální návrh jednoduše použít některý z dostupných senzorů používaných v hydraulice je ten, že tyto snímače jsou moc velké. Existují sice čidla, která výrobci označují jako ”miniaturní”, ale v tomto případě jde stále o přístroje o velikosti v řádech centimetrů. Pro velkou většinu jiných použití by byla tato velikost dostatečná, pro specifický design této práce však nikoli. Protože použitelný senzor musí mít velikost pouhých několik milimetrů, velká pozornost je v této práci dána také možné miniaturizaci.

Aby bylo možné tento problém s velikostí vyřešit, tato práce se obrací na tzv. MEMS systémy, v překladu mikro-elektro-mechanické systémy. Jejich výhodou je, že k fungování nepotřebují žádné velké fyzické části či čidla, což je obvykle problém barometrů či manometrů. MEMS mohou být tak malé, protože měří změny tlaku pomocí různých elektronických součástek. Může se jednat o elektrický odpor rezistorů na miniaturní membráně nebo kapacitu kondenzátoru, ale vždy se jedná o vlastnost skladného elektronického prvku. Nejkompaktnější způsob využití MEMS je použít pouze jejich hlavní snímací prvek - malou kostku s rozměry okolo 2 × 2 × 2 mm. Tato část využívá Wheatstoneův můstek v konstrukci, která anodicky spojuje sklo s chemicky leptanou křemíkovou membránou a vytváří tak velmi kompaktní snímač tlaku.

Při použití těchto elementů bylo nutné dát pozor, jestli jsou odolné proti působení tekutin. Jelikož jsou tyto kostky vyráběny bez jakékoli vnější ochrany, většinou jsou používány pro měření tlaku vzduchu či inertních plynů. Ve finálních konceptech pro možná řešení jsou takovéto elementy zahrnuty, zejména kvůli své velikosti. Pokud by nebylo možné je použít (např. kvůli nedostatečné odolnosti vůči okolnímu prostředí), tato práce zahrnuje také dva alternativní návrhy využívající větší, konvenční senzory. Aby bylo možné tyto větší senzory využít, jsou v této práci navrhnuty speciální díly, díky kterým jsou tyto snímače kompatibilní a připojitelné k malé kapsli.

V závěru této práce jsou všechna možná řešení ohodnocena a je vybráno takové, které nejlépe splňuje všechny zadané podmínky. V tomto případě jde o řešení, které zahrnuje MEMS senzor který je integrovaný do víčka, které drží tekutý vosk vevnitř kapsle. Pokud by tato verze z jakéhokoli důvodu nebyla proveditelná, je stále možné implementovat kterékoli jiné z navrhovaných řešení. Ta stále splňují zadané podmínky vytyčené v této práci, i když jsou poněkud méně vhodná či hůře realizovatelná.

Tato práce nejen vytváří přehled těchto možných řešení, ale může být i přínosem pro kohokoli s podobnými prostorovými omezeními a nároky.

Klíčová slova

měření tlaku, miniaturní zařízení, vysoký tlak, letecký průmysl

Bibliography

HOLEČKOVÁ, Kateřina. *Miniature device for fluids pressure in-situ measuring.* Brno, 2026. bakalářská práce. Vysoké učení technické v Brně, Faculty of Mechanical Engineering. Vedoucí práce Jakub Mašek.

Declaration of Authenticity

I declare that this bachelor thesis is the result of my own original research and that all sources used and referenced have been duly acknowledged.

Kateřina Holečková

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I would like to thank my supervisor Ing. Jakub Mašek Ph.D. for his mentoring and guidance during my work on this thesis. I would also like to thank my family for their support during my studies.

Kateřina Holečková

Contents

Introduction

Pressure measurement is one of many branches of current technology that gets overlooked quite easily. However, that does not mean it is not useful. Even something seemingly trivial as high blood pressure would be quite hard to spot without appropriate instruments. Or for a more technical example - without accurate pressure indicators, no aircraft would be able to calculate its altitude. For that matter, it would not even get anywhere without the correct pressure in its engines. All of these and many more systems rely on various devices that can indicate pressure in a variety of conditions. And clearly, those devices themselves are widely different in both design and complexity, starting with a mechanical manometer and ending with a silicon etched MEMS sensor.

This work will be mainly interested in one field specifically - uses of high pressure measurement in aerospace. The applications range from relatively tame environments such as an inside of an international space station, to monitoring the flow of the fuel in an SLS rocket engines. The specifications and requirements for such pressure sensors obviously vary greatly. This thesis will take inspiration from several such measuring instruments which have similar qualities as the ones neccesary for the sensors in this project.

To be more concrete, the goal of this work is to find a sensor for a capsule that is inside of a satellite. In this case, the focus will be on measuring very high pressures (several MPa) in very tight places (few millimeters wide), where there is no room for conventional pressure gauges. Specifically, a direct pressure measurement of liquid paraffin closed off in a small capsule.

To choose the best possible option, this thesis researches the many different ways that pressure can be measured, with special interest in high pressure applications. From general types of sensors, the focus is then narrowed to concrete instruments from several different producers which fulfill all the parameters given for the specific discussed problem.

Moreover, this research provides the reader with several different ways to incorporate those sensors into the body of the capsule and compares the feasibility of those options. The goal is to clearly lay out all the options and possibilities regarding high pressure measurement in confined spaces. This thesis aims to make a simple and well-arranged overview that can be benefitted from by anyone with similar problems and limitations in potential future uses.

2 Theoretical background

2.1 Pressure

2.1.1 General equations

The general definition of pressure is a force divided by the area perpendicular to the force over which the force is applied, as seen in the following equation:

$$p = \frac{F}{S} \tag{2.1}$$

This formula, however, is applicable only if the force applied to the surface is distributed evenly. Such constant pressure is most easily applied by fluids, either liquid or gas. It is often the case in many fields, but sometimes, it is needed to account for an uneven distribution of force. Then, the previous equation needs to be changed to its differential form [1]:

$$p = \frac{dF}{dS} \tag{2.2}$$

This way one can determine pressure on one infinitesimally small point of the surface. More commonly used version of this equation is this:

$$dF_n = pdS \tag{2.3}$$

Where F_n is the normal (perpendicular) component of the force. The equation also indicates that for any surface S in contact with the fluid, the total force exerted by the fluid on that surface is the surface integral over S of the right side of the equation [2].

2.1.2 Pressure in fluids

In this instance, both liquids and gases are considered fluids. The measured pressures in liquids are :

- static pressure
- dynamic pressure
- total pressure

Static pressure is only measured in a stationary fluid. If the fluid is flowing, dynamic pressure has to be taken into account as well. In such instances, the summary of the static and dynamic pressure equals to the total pressure. Incidentally, if the medium is at rest, its total pressure equals to the static one [3].

Both in liquids and gases, static pressure is caused by their own weight. It is also isotropic in any specific point of the substance and acts perpendicular to surfaces it is in contact with. In a uniform fluid, static pressure only varies with vertical distance from the surface (in liquids). In such case, following equation applies [4]:

$$p_1 - p_2 = -\int_{h_1}^{h_2} g\rho \, \mathrm{d}z \tag{2.4}$$

Where p_1 is the pressure at the higher point of the liquid, p_2 the pressure at the lower point, ρ is the function of the density of the substance, g is the gravitational acceleration and h_1,h_2 are the respective vertical distances from the surface for pressures p_1 and p_2. z is the vertical distance from the surface / reference plane.

Dynamic pressure is caused by the kinetic energy per unit volume of a fluid flow. The value can be calculated using this formula [5]:

$$q = \frac{1}{2}\rho u^2 \tag{2.5}$$

Here, q stands for dynamic pressure, ρ is the density and u is the fluid velocity. This formula is in fact derived from Bernoulli's equation, which is applicable to an incompressible flow [6]:

$$\frac{1}{2}\rho u^2 + h\rho g + p = const. \tag{2.6}$$

Besides the already mentioned variables, h is the distance from the ground (the formula being adjusted to a homogenous gravitational field) and p stands for the internal pressure of the fluid. This equation simply shows that the overall energy of a perfect fluid cannot be lost or gained - it is constant.

2.1.3 Pressures measured

Even after the pressure is already determined, there are still several pressure levels, which can be used as a zero-reference both during measuring and specific calculations. From this fact, the following terms are derived :

- absolute pressure
- gauge pressure
- differential pressure

Absolute pressure is referenced against perfect vacuum, which means that the reference is a constant. And assuming that the pressure of vacuum is 0 Pa, absolute pressure can never be negative. Vacuum as a reference point is frequently used in applications where an unchanging point of reference is needed, such as aviation inspection, air conditioning, meteorology and vacuum technology.

The zero-reference for gauge pressure is the ambient atmospheric pressure. This means that to get the value of gauge pressure one must subtract the air pressure from the absolute one. If the gauge pressure is zero, it means that the pressure measured is the same as the current air pressure [7].

Differential pressure, as the name states, is a difference between the pressures of two environments. It is usually used to determine how much of a pressure difference has to be handled at the interface of those two environments. If for example there was an atmospheric pressure (∼100 kPa) on one end of the tube and over-pressurized air (150 kPa) on the other, the differential pressure will be 150 000 - 100 000 = 50 000 Pa.

2.2 Pressure units

The basic SI unit of pressure is pascal - Pa, which equals to one newton per square meter. However, there are many different systems using other units, usually because they were proven to be more convenient. This work will also include several instances of using these specific units, which is why this chapter includes a brief list of the most common ones, including conversion to pascals [8], [9].

Symbol	Unit	In Pascals	Practical use
psi	pounds per square inch	6 894.76	pneumatic pressure
bar	bar	100 000	atmospheric pressure
atm	standard atmosphere	101 325	meteorology
mmHg	millimiters of mercury	133.33	medicine
Torr	Torr	133.322	micropressure

Table 1: Pressure units

2.3 Pressure measurement terminology

Pressure can be measured using several different techniques. From liquid column in a manometer to electricity in piezoresistive crystal (discussed in chapter 3 - see 7). This section focuses on whether the pressure is measured with respect to either a constant or a varying reference (also see ”Pressures measured” - 2.1.3).

2.3.1 Absolute pressure sensors

An absolute pressure sensor measures pressure in reference to the ideal vacuum. These instruments are used where a constant reference is needed - not affected by fluctuating atmospheric pressure. When vacuum is used as the baseline, all measurements must deliver a value larger than zero.

This can be further used if Boyle’s Law is applied. It states that the pressure of a gas is inversely proportional to its volume (at a constant temperature [10]). This way, if the absolute pressure is used as an input, the changes in such pressure also indicate the changes in the volume of the gas.

Absolute vacuum as a reference is very hard to achieve, which in practice means that such sensors usually have to make do with an approximate vacuum, usually around 5 microbar (0.0005 psi) [7].

2.3.2 Gauge pressure sensors

A gauge sensor measures pressure with reference to the atmospheric pressure (101 325 Pa). The output is also called relative pressure. Gauge sensors are very common and the applications include air compressors, oil pressure sensing, pressure valves and medical instruments. They should be used whenever the process of measuring is influenced by a change in atmospheric pressure. For example to measure liquid level in a vented tank. Gauge sensors usually contain a single pressure port on the process side and ambient (atmospheric) pressure is applied through to the back of the sensing element via a vent [10].

2.3.3 Sealed gauge pressure sensors

A sealed gauge sensor also measures pressure with reference to atmospheric pressure. Unlike regular gauge sensors, sealed pressure refers to ”atmospheric pressure” trapped within the back of the diaphragm in the sensor. This simply means, that the back of the diaphragm is pressurized to the same level as the standard atmosphere, but with no vent path for pressure to flow in or out, the reference pressure is constant and unaffected by pressure changes in the real atmosphere.

Sealed gauge pressure can assume both positive and negative values. For positive values, it is called overpressure, for negative underpressure. This sensor is often used in conditions with a high pressure range and a consistent temperature. It can be useful in applications where atmospheric pressure change affects the sensor only minimally. It is also suitable for applications where it is not possible for the sensor to provide a vent path [10],[11].

2.3.4 Differential pressure sensors

A differential pressure sensor measures pressure with reference to a variable pressure. Differential pressure is regarded as the pressure difference between two points. For that reason, these sensors must include two separate pressure ports in order to identify the difference between the two separate areas. Only if those two values differ from each other, a differential pressure will be indicated. The sensors usually measure very low-pressure range with very high accuracy (up to 0.1 kPa). Some of its uses include medical applications, HVAC systems or braking systems in cars [7].

3 Pressure sensors

It is critical to choose a correct pressure sensor for every specific application. In this chapter, several of the basic pressure measurement methods and instruments are introduced. This section serves more as a general overview than a detailed insight into this matter.

3.1 Instruments

There is an incredible number of different pressure sensors used in specific industries, each specifically developed for its unique application. To list all of them would be an exercise in futility so the following chapter lists only the most common ones in order to give the reader some general idea about the matter. The list starts with simple mechanisms and proceeds to the more complex ones.

3.1.1 Manometer

This instrument usually consists of a U-shaped glass tube filled with liquid (often mercury). One end of the tube is kept open (only pressure exerted is the atmospheric one), while the other end is connected to the pressure source via a gas tight seal. If this additional pressure is greater than the atmospheric, it will result in downward force acting on this side of the liquid. This leads to a difference between the column heights of the liquid. (see fig.1). The bigger the height difference, the greater the difference between the measured pressures. In this case, atmospheric pressure is used as a reference, which makes manometer a type of differential pressure sensor [12].

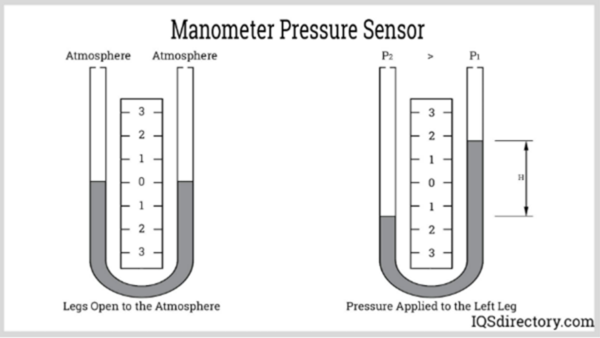


Figure 1: U-tube manometer [13]

3.1.2 Bourdon tube

Bourdon tubes are the most common mechanical pressure-measuring instruments. The main element is a c-shaped bent tube, which works as an elastic spring, as seen on the diagram below. One end of the tube is closed, the other serves as a connection to the pressurized air supply. As the tube gets pressurized, it is forced to change its shape - it straightens ever so slightly, which is shown in the following figure (fig. 2) . The closed end of the tube also has a pointer. When the device straightens, the pointer is moved and shows the pressure on a scale. Bourdon tubes which are c-shaped can measure up to 60 bars. For higher pressures one can use helical or spiral-type tubes [12],[14].

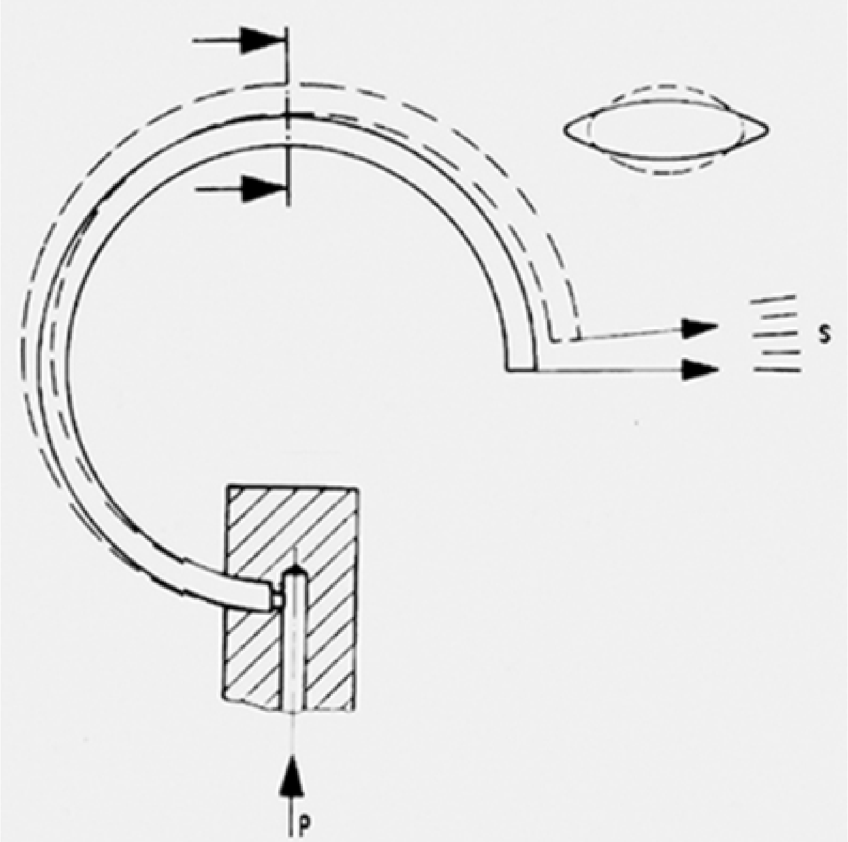


Figure 2: Bourdon tube with applied pressure [14]

3.1.3 McLeod gauge

McLeod gauge is used to measure very low pressures, in the range of 10^{-2} to 10^{-6} Torr, usually in vacuum systems. The purpose of the gauge is to raise the pressure of the substance enough to be measured by conventional means, and from that than calculating the value of the original low pressure. In the tubing of the gauge, there is trapped a known volume of gas of unknown pressure. The gas is then isothermally compressed by a mercury column. At this point, the pressure grows and can be measured by conventional methods (manometer). A simplified diagram of this apparatus is shown below (fig. 3). To calculate the original pressure from the current heightened pressure, Boyle's law is used [15]:

$$p_1V_1 = p_2V_2 \tag{3.1}$$

Where p_1 is the unknown original pressure, p_2 the hightend pressure and V_1,V_2 are the (known) volumes of the gas before and after compression. With all these provided values one can easily calculate the original low pressure p_1 [16], [17].

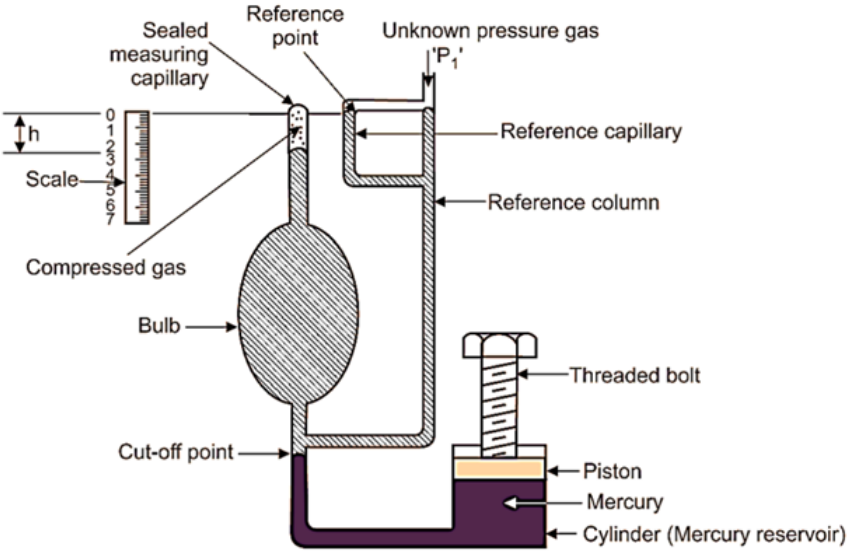


Figure 3: Simple diagram of McLeod gauge [16]

3.1.4 Aneroid barometer

The barometer uses a small metal box made from an alloy of beryllium and copper. The box is quite flexible but its collapse is prevented by a strong spring. This box is called an aneroid capsule. The changes in pressure deform this capsule. The contraction is amplified through a chain of levers and then displayed on the face of the barometer. Aneroid barometers can also be used in aircraft as altimeters, because air pressure linearly decreases with the increase of altitude of the plane [18],[19].

3.2 MEMS sensors

These sensors are made up of both electronic and mechanical components on a silicon chip. The mechanical parts handle physical feedback, while electronic ones process the data from the sensors. The specifics of their design depend on the type of the sensor, the most common ones being piezoresistive, piezoelectric and capacitive. In all of these, a flexible layer is created which acts as a diaphragm that deflects under pressure. The difference is in methods that are used to measure the displacement [20].

In general, because of their small size, MEMS sensors can be very low power. In some cases, they can be powered by a small battery that lasts for several years. Some can even operate without a battery, either using energy harvested from the environment or provided by the external device that reads the sensor data [21].

3.2.1 Piezoresistive strain gauge sensors

The pressure is measured as the change in electrical resistance of resistors that are fabricated directly on to the diaphragm. The strain caused by the pressure on the diaphragm causes the change of resistance. The resistors are connected in a Wheatstone bridge network, which allows for very accurate measurement of changes in resistance. To maximize the output signal for a given pressure, the resistors can be arranged in a way, that half of them are stretched and half of them are compressed [22],[20].

The advantages of piezoresistive sensors are:

- very simple readout circuits - enable high-resolution measurement [23], [24]
- output is linear with pressure [25]
- response time is typically below 1 ms [23]
- wide range of pressure measurements from 21 kPa to 150 MPa [23]
- highly resistant to shock, vibration, and dynamic pressure changes [24]

However, there are also some disadvantages:

- sensor output is temperature dependent [26]
- the accuracy can be reduced by junction leakage current [27]

3.2.2 Piezoelectric pressure sensors

Piezoelectric sensors work thanks to the so-called piezoelectric effect. This is the ability of certain materials to generate an electric charge when mechanical stress or pressure is applied to them. Those materials are usually quartz or lead zirconate titanate (PZT) [28]. The material is typically configured in a diaphragm. When the pressure changes, the diaphragm deforms, causing mechanical stress on the piezoelectric material. The stress causes the atoms within the material to shift positions slightly, creating a charge imbalance. This results in the generation of a small electrical voltage. The voltage is lead to an amplifier and then to an external measurement equipment [22], [29].

Some of the advantages are:

- robust and durable [30]
- suitable for dynamic pressure measurement [30]
- insensitive to electromagnetic interference [31]

The disadvantages are:

- normally not suitable for measuring static pressure [32]
- high temperature sensitivity [32]

3.2.3 Capacitive pressures sensors

To create such sensor, conducting layers are deposited on the diaphragm and the bottom of a cavity to create a capacitor. Deformation of the diaphragm changes the space between the conductors which means that it also changes the capacitance. This sensor can be used with electronic components on the chip to create an oscillator (usually based on an RC circuit), which generates the output signal, usually high frequency. This can be detected with a suitable external antenna. [21]

The advantages are:

- most accurate of the MEMS
- capacitators can operate in vacuum [21]

- very low power consumption [21]
- tolerant to temporary over-pressure conditions [21]
- low hysteresis [21]
- low sensitivity to temperature change [21]

The disadvantages are:

- non-linear output [24]
- very meticulous circuit design, therefore also quite expensive [24]

3.3 General comparison of the measuring instruments

The following table compares several previously mentioned sensors in terms of accuracy, size, pressure ranges etc. Special focus is on the different MEMS variations, because their swift response time and relatively small size make them the most likely candidates to be used for the purposes of this thesis.

Please note that the pressure ranges and other specifications listed are the widest available on the market and very few of the sensors from the specific group are actually able to achieve them. The sizes on the other hand are meant to describe the majority of the sensors in given category. This is to give the reader an approximate idea of the scale, not precise measurements of concrete products. There are several instances where some companies specialize in miniaturizations of such sensors and therefore produce some outliers from the sizes that the table provides. If such instances are used further in the thesis, the instruments and producers are specifically named to avoid any potential confusion.

Table 2: Comparison of Pressure Sensors

Sensor Type	**Functional in vacuum**	**Approximate size**	**Accuracy**	**Response Time**	**Cost**	**Pressure Range**	**Temp. Range**
digital manometers	YES, hermetically sealed [33]	100 × 60 mm	±0.1 % to ±0.5 % [34]	50–500 ms [35]	anywhere between 20$ and 700$	0–100 MPa [36]	-40°–80°C [36]
diaphragm pressure gauges	YES, hermetically sealed [37]	100 mm diameter [38]	±0.6 % to 4 % [39]	10 ms [40]	190–800$ [38], [41]	0–4 MPa [37]	-40°–150 °C [42]
capacitive pressure sensors	YES, hermetically sealed [23]	18 × 18 mm[43]	±0,1 % to ±0,5 % [44]	0,1–1 ms [44]	40$–300$ [44]	0–70 MPa [23]	-40°–200 °C [44]
piezoresistive sensors	YES, hermetically sealed [23]	12 × 40 mm [45]	±1 % [7]	1–10 ms [7]	not mentioned	0.7 kPa–70 MPa [46]	-40°–150 °C [45]
piezoelectric sensors	YES, hermetically sealed [23]	37 × 5 mm [47]	±1 % [26]	10–100 μs [48]	not mentioned	0–70 MPa [23]	-80°–350 °C [47]
strain gauge sensors	YES, hermetically sealed [49]	65 × 20mm [49]	±0,5 % [49]	1–10 ms [50]	not mentioned	0–20 MPa [50]	-30°–200 °C [51]
MEMS integrated in a sensing die	YES, hermetically sealed [52]	2 × 2 mm [52]	±0.25% [53]	5 ms [54]	not mentioned	0.1–103 MPa [52]	-40°–150 °C [52]

4 Aerospace application

The primary focus of this work is the uses of pressure measurement in space. That is why this chapter will be focused on the application of pressure sensors in the aerospace industry. These are numerous, because in such harsh environment any unexpected overpressure or loss of pressure must be immediately dealt with. The vacuum and rough conditions of space put very high demands on all included machinery, whether it is an unmanned satellite or a space shuttle [55].

Any failure in the systems (not only the pressurized ones) could pose a great threat to the mission, which is why there are such high demands on the precision of all the measurements and their analysis. That is why all aircraft manufacturers are heavily restricted by quality standards and certifications. These guidelines are put in place for several reasons, such as safety of the craft and passengers, reliability and regulatory compliance. The standards are aimed at many different aspects of aviation, including quality of fuel, communication systems or materials of the components [56],[57]. The organizations responsible for developing these guidelines - ISO, ASTM, NASA created them to ensure quality and uniformity within the industry. To give a few examples, there are:

1. AS9100D

   Implements Quality Management Systems, which deals with companies' policies, processes, and records and ensures the quality of the products and services. [58]

2. ARINC 429

   Deals with transportation of digital data between avionic systems in aircraft. [59]

3. MIL-STD protocols

   Specifies how materials, components and systems are developed and tested. Aircraft with this qualification are also fit for use by U.S. military. [60]

4. ASA-100

   Focuses on the manufacturer, emphasizes impartiality, competence, and reliability. [61]

Several of these guidelines also apply to the electronic systems, including pressure transducers and transmitters. When they pass all the tests, the sensors have many different aerospace applications, including but not limited to:

- pressure transducers in combustion chambers of rockets
- monitoring cabin pressure
- pressure monitoring of spacesuits
- monitoring of aircraft during flight

4.1 ISS

To present an example, throughout the modules of ISS (International Space Station) a network of differential pressure sensors is installed to look out for even the most minuscule leaks. To match the conditions on Earth, the ISS is pressurized to 14,7 psi - one atmosphere. The outer side of the hull, exposed to the outer space, is subjected to basically zero ambient pressure. Because of this the sensors have a big differential to monitor, and a very small tolerance for any errors.

For that reason, high-precision MEMS differential pressure sensors optimized for low pressures were chosen. Thanks to the fact that they can discern a pressure difference as low as 25 Pa, the sensors can detect any minor leaks before they become catastrophic. If a breach is detected, the sensor network can help identify the origin using relative pressure readings in neighboring regions of the space station. Areas exhibiting pressure drops pinpoint zones of leakage. Fast response time of the sensors allows astronauts to react quicky and isolate the leak. [62]

The most crucial restrictions in this application are the extreme pressure ranges and a great emphasis on the high precision and fast response times. These same factors will be monitored when it comes to choosing the right sensor for the purpose of this project (although with quite less strict requirements).

4.2 Combustion chamber of rocket engines

Another extreme environment a sensor can be subjected to is the inside of a rocket engine. There are several different components of the engine which require constant monitoring. For instance, during the ignition, the dynamic pressure inside the combustion chamber must be continuously observed. Such sensors are on the lookout for any combustion instability caused by pressure fluctuations or acoustic resonances. Those instabilities can cause a reduction of engine performance and structural vibration at best, and a breakdown of the thermal insulating boundary (a catastrophic failure) at worst.

It is very difficult to model a three-dimensional flow inside the engine even with modern computing power. To have the most accurate readings, engineers choose to use dynamic quartz piezoelectric pressure sensors. Those are rugged, hermetically sealed and structured with acceleration-compensated quartz sensing elements. They detect rapid pressure transients, pulsations, turbulence, noise, and spikes. Thanks to those properties, the sensors can monitor dynamic pressure while still being subjected to high static background pressure caused by the combustion [63].

4.3 Hydraulic systems

Another key feature of a spacecraft is its hydraulic system. It can control massive parts of the rocket with incredible precision and without any significant response delay. Inside these systems, the fluids create very high pressure, both static and dynamic. That of course has to be monitored to ensure no part of the system gets overloaded or bursts.

Hydraulics are often used to control thrust in rocket engines via fuel and oxidizer valves. During the takeoff, the launch pad structures (clamps, arms, etc.) are also being retracted using sophisticated hydraulic system. Besides rockets, hydraulics are also used during spacecraft docking or solar panel and antenna deployment [64]. All these features are highly dependent on the hydraulic systems working properly and precisely. These systems are also very complex, including numerous actuators, pumps, valves and control surfaces.

To be able to properly test and measure the properties of such structures, the sensors within have to be sturdy enough to withstand harsh conditions such as high vibration and shock levels, while still having a relatively wide pressure range. Those sensors also have to meet very high stability and accuracy requirements to be used inside those systems [65].

The conditions for a wide pressure range and compatibility with fluid mediums correspond with the conditions of the problem discussed in this thesis. Some of the sensors could be a potential solution for the problem presented, however, most of them are too large to be suitable.

4.4 Liquid propellant fuel tanks

Last but not least, some rockets use liquid propellant systems, with the components being liquid hydrogen and oxygen. In order to keep the hydrogen in a liquid form, it must be stored in temperatures almost reaching absolute zero (around 20 K) [66]. If the sensors are to measure the pressure of liquid hydrogen, they need to be able to withstand those extremely low temperatures. The rocket engine is fed by cryogenic turbo pumps, which pump the fuel from the tank and pressurize it.

Cryogenic pressure sensors are ideal for evaluation of frequency oscillations of fuel and oxidizer turbo pumps, which could cause cyclic variations in thrust, and could damage payloads or the rocket. Such sensors were first used to successfully measure uneven fuel flow that caused the “pogo” effect - a vibratory motion occurring in multistage rockets caused by unstable combustion, which were a huge problem for example in the early Apollo missions [63].

5 State-of-the-art

This thesis focuses on pressure measurement in very small spaces. That on itself does not sound too problematic - companies advertise many different types of miniature sensors that seem like a perfect solution. Unfortunately, more often than not, these microsensors are still too big for the problem at hand. The instruments are several centimeters long but this thesis looks for a solution that can fit into a space of only few millimeters. This chapter focuses on the few already existing sensors that could be possibly used in this thesis. It also highlights which traits this thesis will focus on when searching for an adequate sensor.

5.1 Preexisting sensors

It would be convenient to use a modern medical sensor, which measures pressure inside the human body - the size would be perfect. This work, however, discusses a specific problem that requires measurements of very high pressures - several megapascals. This eliminates the possible use of any medical sensors, because they are built to sense human blood pressure - magnitudes smaller than this application needs. This thesis aims to find a viable solution which is both small enough and sturdy enough for the high pressures.

This leads to a logical assumption - if the medical sensors are useless, it is probably better to take inspiration from pressure sensors with a regular technical application. And the field that offers itself the most is obvious - sensors in aerospace are often subjected to similar conditions as the ones defined in this work.

The previous chapter mentioned several different uses of sensors in spacecrafts. For example in fuel tanks or combustion chambers. One specific application has very similar requirements for the sensors to those defined in this project. In hydraulic systems, the sensing instruments have to survive both very high pressure and are being exposed to various liquids. That much is basically the same as what this thesis requires.

The only major difference is the size of the instruments. Even though some hydraulic systems need ”small” sensors, it usually means several centimeters. To incorporate even the smallest of those devices would mean to go out of the boundaries of the original assignment. The space around the measured capsule would have to be significantly altered to accommodate such sensor. The possibility of integrating such a device into this project should be considered only if every other solution fails.

Having a much smaller sensor is way more convenient, which is why it is important to mention the so-called sensing dies.

5.2 Sensing dies

When it comes to miniaturization, the MEMS are the clear winners. Their advantage is that they do not need any huge physical apertures to function, which is usually the problem with barometers, manometers, etc. MEMS can be so small because they usually measure the changes of physical properties using different electronic components. It can be an electrical resistance of resistors in a diaphragm, or a capacitance of a capacitor, but it is always a property of a small electronic element.

Since there is not much more to a sensor than the sensing part and several wires, there is no need for the device to be much bigger. To find the smallest ones, one has to focus on so-called sensing dies. Those are the core parts of the sensor - the ones providing the actual measurement. When the manufacturers are not space restricted, they put these sensing elements into different sorts of housing - either to protect from outer damage, or to make them compatible with other devices. Because of that, the size of the whole sensor is usually determined by its outer casing, not by the size of the actual sensing element.

One can save quite a lot of space by using just the sensing die itself (the whole cube usually around 2 × 2 × 2 mm). However, there are also disadvantages. Without the casing, the sensing die is exposed to all the external influences. Because of that, most of them are usually only built to measure air pressure or inert gases. Very few are insulated in such way to operate and measure in liquids. This problem can be fixed with a type of special small casing, but any sort of cover makes the whole sensor bigger again. If the sensing die is to retain its small proportions, one has to choose from the very few that are insulated and can measure in liquid as they are.

5.3 Useful characteristics

It does not matter whether one looks for specialized sensing dies or an adequate bigger (”regular”) sensor. There are always several specific requirements to look out for. Then even if the specific sensor provided by the manufacturer is not fully suitable, one can often draw inspiration from its inner workings and mechanics so that it could be used in designing the final solution.

One of those important specifications to search for is the sensor’s pressure range. Every instrument discussed in previous chapters was built with a concrete application in mind, and its pressure range reflected that. That varies from high vacuum sensors that can detect the equivalent of 0.13 Pa of pressure to instruments inside hydraulic systems which detect and survive 20 to 70 MPa.

As this work is primarily focused on high pressure measurement it can be convenient to take inspiration from the inner design of hydraulic sensors that were mentioned before. These are built to be very durable, resist high pressure spikes and vibrations. The electronics inside are carefully sealed from the outside environment to prevent any damage. The most common are strain gauge sensors, then there are capacitance and piezoelectric ones. While strain gauge transducers are very durable and accurate, there is not much room for miniaturization, which makes them unfit to apply to the problem of this work.

If one wants to compromise between high pressure range and small size, it is better to focus on the other methods of measuring pressure. Both the capacitive and piezoelectric sensors do not require too much space. This can be used as a starting point, because even though they are not as small as the MEMS, they have several other advantages. They are oftentimes equipped with an effective method of protection against harsh conditions (liquids) as well as being resistant against high pressures. Protection against liquids is another important characteristic one has to take into account when looking for a suitable measuring instrument. That is because the sensor in this thesis is supposed to measure pressure of a hot liquid - paraffin.

Last important feature to search for is temperature resistance. It does not have to be hundreds of degrees, but still needs to be effective enough to protect the sensing parts from the liquid paraffin (around 70 °C).

The goal of this work is to find a compromise between all those characteristics. In general, there are very few instances of ”ultra-miniature” pressure sensors on the market. To find a solution, this work focuses on various ways of installing the existing small sensors (MEMS) into the specified assembly without violating other given requirements for pressure ranges etc. It also proposes several other solutions using bigger, more conventional instruments in a way that still saves as much space as possible.

6 Problem overview

In previous chapters, the main goal was to give the reader a brief intro into the topic of pressure measurement. From now on, this work will be focused on finding a concrete pressure sensor suitable for a specific application, space restrictions and environment, which is also the objective of this thesis.

Here are the specifications for in-situ measurement:

Pressure:	static, up to 16 MPa (160 bar)
Medium:	paraffin in liquid form or water
Capsule shell:	stainless steel 316L / aluminium 7075
Volume available:	max. dimensions 3 × 3 × 2 mm
Measurement accuracy:	0.1 MPa
Temperatures:	15–70 °C (operational) -60–70 °C (non-operational)
Data acquisition system:	ESAM Traveller CF Analog and digital inputs

These are required because the sensor is designed for in-situ measurement of pressure inside of a satellite. To be more specific, there is an actuator based on the paraffin expansion, which creates an internal pressure in small, closed capsule. The effect on internal pressure was measured indirectly, by deformation of the metal capsule and correlation with FEM model and is expected to be up to 16 MPa. Nevertheless, such approach is burdened with significant error. Therefore, in-situ measurement of the paraffin pressure is required for calibration tasks. However, due to the installation, the sensor cannot be placed outside the paraffin capsule. The cross section below shows two potential places in the capsule, where the sensor could be placed (see fig. 4).

For a better understanding, the following picture is the cross section of the 1st sensor location and also a visualization of the volume the paraffin will occupy (see fig. 5). Every placement has its own limitations regarding either the size of the sensor or possibilities for installation and for each, different sensor is required.

Aside from some standard requirements, there are some specifications that could make finding a fitting sensor quite challenging. The two most prominent ones are the dimensions and the pressure range. The following chapters will bring some insight into this problematic as well as present few possible solutions.

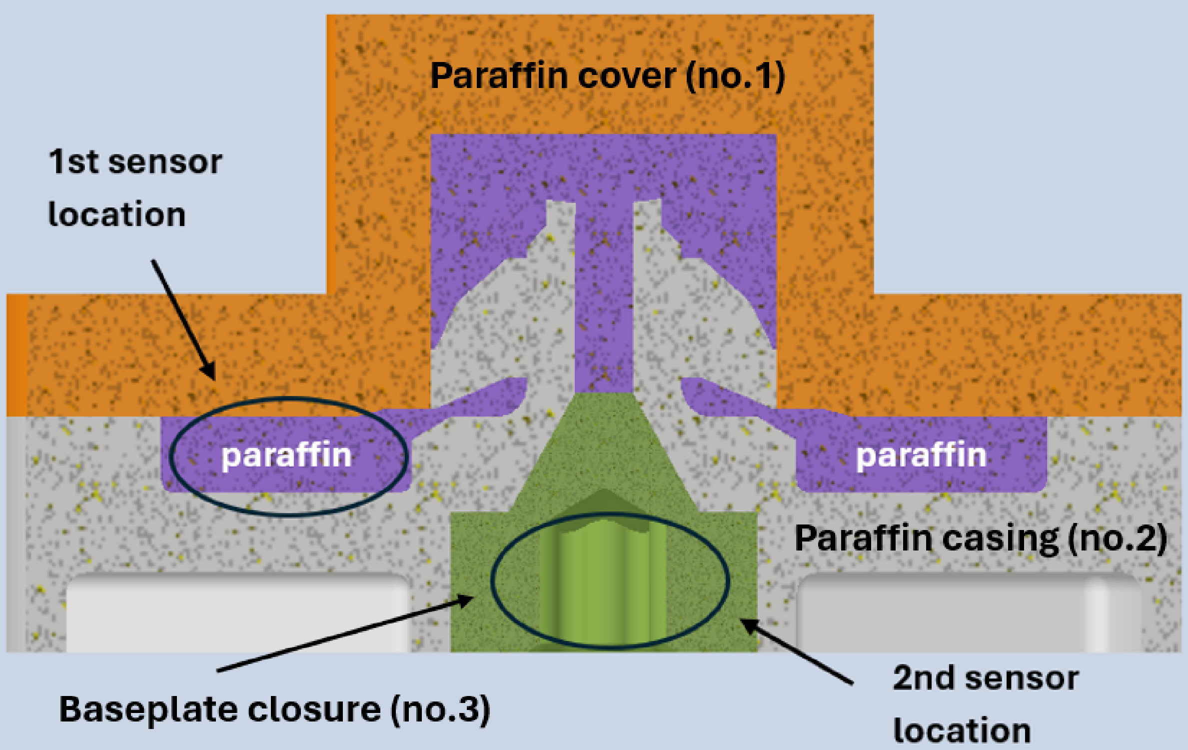


Figure 4: Possible placement of the pressure sensor

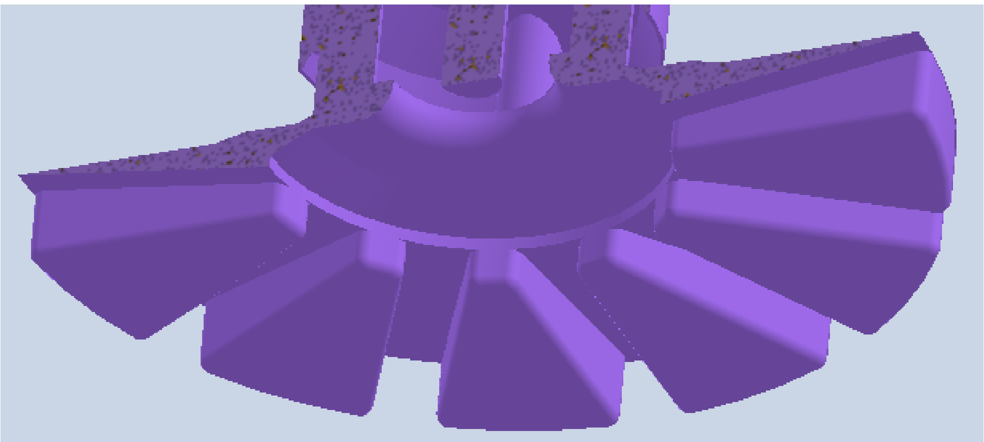


Figure 5: Available volume in the 1st location

7 Suitable sensor

This chapter includes several different ways to integrate various sensors into the assembly. To make it as straightforward as possible, every part of the assemblies is numbered and named. The numbers of the parts are consistent throughout all the drawings to avoid confusion. If a cap is numbered 3 in the first drawing, it will be number 3 in all other drawings as well. Below is a list of all the mentioned parts.

Table 3: List of mentioned segments

Number	**Name**
1	paraffin cover
2	paraffin casing
3	baseplate closure - cap
4	extension
5	insulation - O-ring
6	body of the sensor
7	customized MEMS holder
8	sealing ring on a sensor
9	tightening nut on a sensor
10	sensing part of sensor

7.1 1st sensor location

7.1.1 Sensor

Only accounting for the dimensions this placement allows, most of the regular sensor types such as manometers are eliminated - none of them are smaller than 10 mm in diameter. One of the few options to choose from are the aforementioned MEMS sensors, which are usually smaller, but still not quite as small as necessary. Another complication is the required operational pressure - up to 16 MPa. MEMS sensors commonly have a range in hundreds of kPa. Sensing MEMS for such high pressures are very rare, or they are already integrated in a much bigger casing, which renders them useless for this project.

The issue with the size can be fixed by using so-called pressure elements (dies) - they operate on the same principle as MEMS and utilize a piezoresistive Wheatstone bridge in a design that anodically bonds glass to a chemically etched silicon diaphragm. The setup is fitted into a cube with the rough size of $2 \times 2 \times 2$ mm.

To connect this device with an external receiver, four wires are usually required. This fact is important later, because the wires will have to lead out of the setup through a series of holes. And as everything else, the sizes of these holes are severely limited, thus also limiting space for the cables.

As an example of a such an instrument, the picture below (fig. 6) shows the sensing die from the K Series manufactured by Merit Sensor.

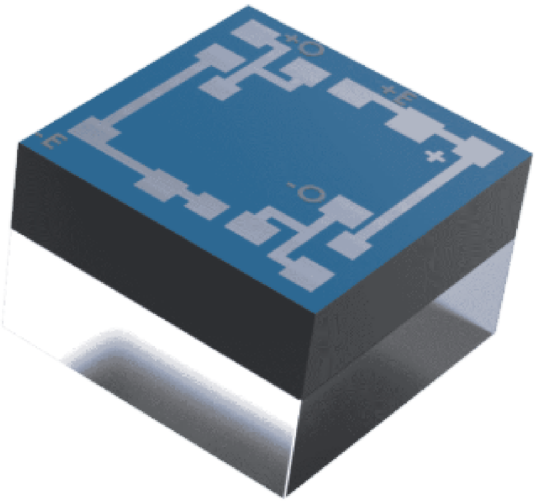


Figure 6: Sensing die Series K [67]

The most discerning features of this die are the operating pressure (6 895 to 68 948 kPa) and dimensions (1.4 × 1.4 mm), which makes it a perfect candidate to fit our specifications. The operating temperature is -40 to 150 °C. A small drawback could be the fact that the sensor is manufactured to measure media such as clean, dry air or non-corrosive gases. For our application, however, the element needs to measure the pressure of either paraffin or water [67]. The contact with liquid could quite well damage the sensor irreparably, because it was not built to measure neither corrosive substances, nor any other liquids which could cause the electronics to short circuit. This could be possibly prevented by an anti-corrosive coating of the sensor.

To find a sensor perfectly suitable for this thesis, one must outline the most restrictive criteria - in this case the maximum pressure measured and the resistance to harsh media. As it turns out, most of the sensors which fill one of the criteria do not meet the other and vice versa. This compiled table shows several different sensing dies from various manufacturers. It presents the critical criteria and concludes, whether the sensor meets all of them or not (see tab. 4).

As seen in the table, a producer called NovaSensor offers different piezoresistive sensor dies that are built specifically to withstand measuring pressure and temperature of harsh media. The NovaSensor PT899 is compatible not only with clean dry air and non-corrosive gases, but also liquids, and other fluids compatible with silicon and borosilicate glass. The most notable facts about P899:

Table 4: Sensing dies comparison table

Name	**Company**	**Temp. range [°C]**	**Size [mm]**	**Compatible with liquids**	**Max. Pressure [MPa]**	**Applicable**
Series K [67]	Merit Sensor	-40–150	1.4 × 1.4	NO	68	NO
IPD 40 [68]	Insenso	-40–150	2 × 2	NO	60	NO
C43 [69]	TDK	-40–150	1.6 × 1.6	NO	70	NO
C44 [70]	TDK	-40–150	1.6 × 1.6	YES	6	NO
PT899 [71]	Novasensor	-40–150	1.8 × 1.8	YES	103	YES
P1907 [72]	Novasensor	-40–150	1.9 × 1.9	YES	6	NO
PT898 [71]	Novasensor	-40–150	1.8 × 1.8	YES	103	YES

- 1.7–103 MPa pressure range
- silicone piezoresistive sensor
- operating temperature range -40–150 °C
- dimensions of 1.86 mm × 1.86 mm × 2.0 mm
- is used for applications in aerospace
- wire bonding possible either on only one side or along perimeter of the die [71]

The table also mentions another NovaSensor die - PT898, which meets all the outlined conditions as well. The reason that it will not be referenced further is that it is virtually the same as PT899. The differences are in some performance specifications that are not that important at this point. Using NovaSensor solves the issue of harsh conditions, it also has a sufficient pressure range and is small enough to fit into the designated space.

7.1.2 Sensor integration

Concerning the problematics of integrating the die into the complete structure, there could be some difficulties bringing out the electrical wires from the die (inside the paraffin capsule) and making them accessible from the outside. This is crucial because the information from the sensor needs a wire connecting the sensing die to the outside of the assembly. Without the information datalink, this solution becomes completely unusable.

The most important questions regarding the wire connections are: Which way will the wires be lead - how many additional passages will have to be created? How is the passage going to be insulated - what solution is both compact enough and sturdy enough to withstand the pressure of 16 MPa of paraffin?

As for the passage options, there are realistically two solutions. The following picture shows both of them (fig. 7). Either of those require some drilling into the original body to create the passages. The yellow option might seem quite suitable at first, but it has one significant problem. Before the final assembly, some length of the wire would be connecting the central paraffin passage and the baseplate closure (no. 3). While assembling the closure and the casing (no. 2), the wire would have no place to go and would be preventing the parts from fitting properly together. The red option does not have to deal with the same problem and is therefore much more appealing.

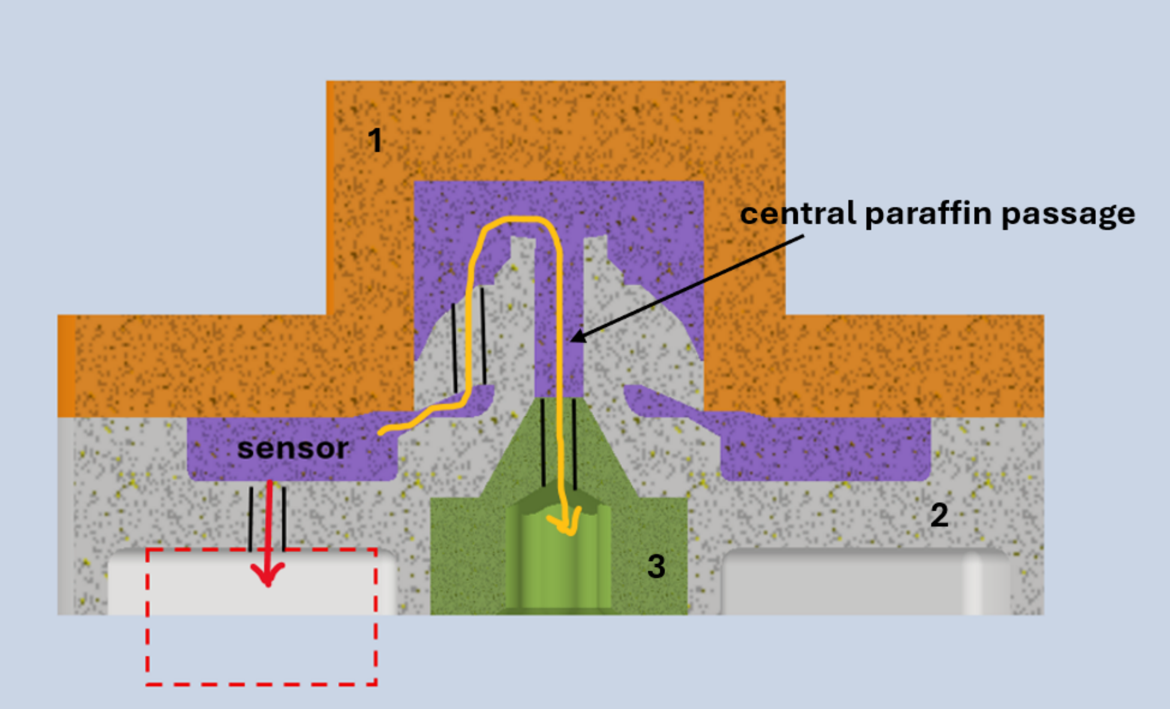


Figure 7: Possible wire passages

One also has to address the problem of insulation. If the wires are simply led through the holes, even if fitted in with interference, it is not enough to prevent the pressurized paraffin from leaking through. For this kind of pressure difference, a hermetic feed-through in the passage seems to be the best solution. Also, not any kind of feed-through can be used because the overall small sizes of the parts are again quite limiting.

7.1.3 Feed-through

To find (or create) the thinnest feed-through, one has to acknowledge several facts. First being that most of the factory made feed-throughs are unnecessarily wide or have metal flanges that take up a lot of space. That is why it is more practical to take the wires through the hole and pour them over with epoxy, creating a hermetically sealed epoxy feed-through. Such process has several rules that need to be followed. The most important one is wire spacing. That is used to prevent the so-called crosstalk. This takes place when the electromagnetic field from one wire interferes with another nearby wire, causing unwanted noise or signal distortion. The general rule of thumb for wire spacing is the ”3W rule” that says that the spacing between two adjacent wires should be at least three times the width of the wire [73]. Assuming that the wire is around 1 mm wide (including the rubber insulation) and for the connection of the die, 4 wires are needed (as mentioned previously), the conclusion is that the feedthrough will be between 4 and 5 mm in diameter. That is, if the wires are positioned in a square configuration. Compared to the dimensions of the sensing die, the feed-through is relatively big, but still possible to integrate into the assembly, which is the main goal.

7.1.4 Connector

Last thing to mention is the connector. When the wires are led outside, there should be a connector to link them to the rest of the electronic system. As there are just 4 wires, only a 4 pin connector is needed. The smallest connectors on the market have a spacing between the pins of 1 mm. To put the size into perspective, the red rectangle in the picture (fig. 7) represents one of the smallest available connectors - roughly the size of 4 × 6 mm [74]. For comparison, regular connectors are usually the size around 40 × 20 mm. Because even the smallest connector would be sticking out of the assembly, for this option it would be easier to simply solder the outgoing wires to the feedthrough.

7.2 2nd sensor location

As mentioned previously, there is a possibility to drill a narrow gap in the marked space (fig. 8) to connect the paraffin reservoir with the premade hole marked as a 2nd location (circa 3 mm in diameter). This option makes the sensor more accessible than in the 1st location.

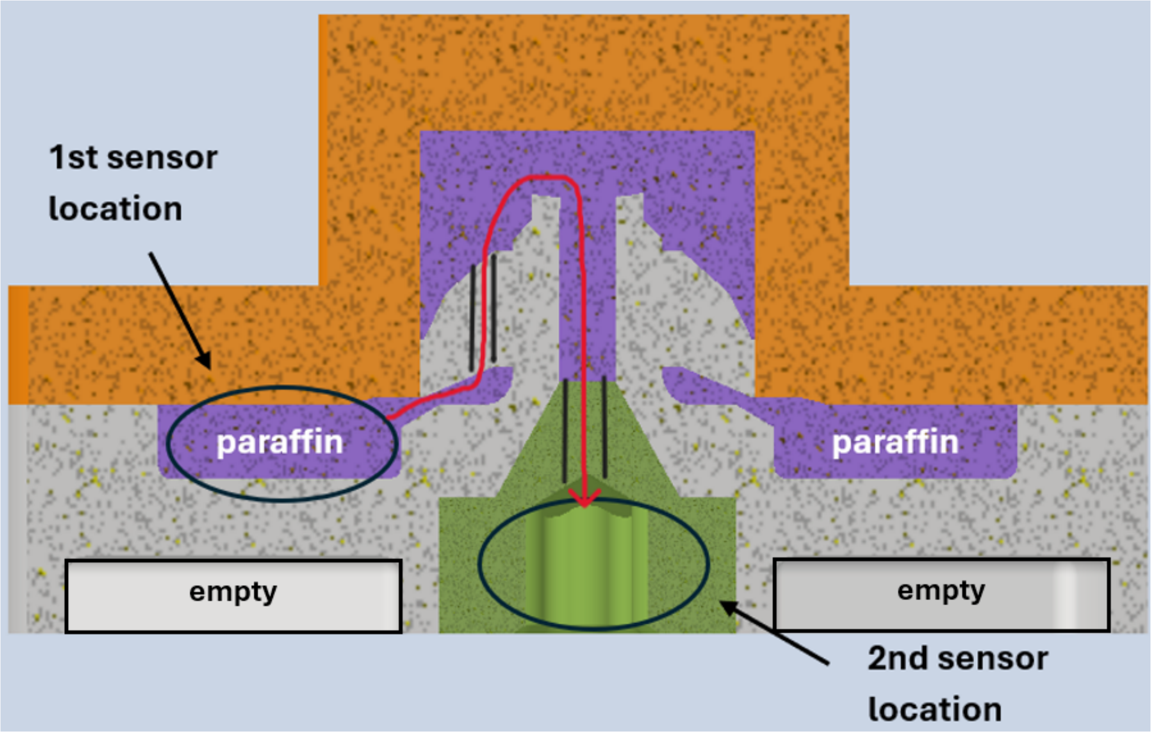


Figure 8: Passage for paraffin flow

The area could be utilized in two different ways - either by putting in one of the sensing dies from the previous section (sensor integrated in the cap), or it could be simply used as a passage for paraffin to flow through and reach a partially external sensor.

7.3 Sensor integrated in the cap

One way to utilize the space in the hole of the cap (no.3) is by putting a much smaller sensor inside, which fits there as a whole. The aforementioned sensing dies make great possible candidates. Of course, they must fit inside perfectly and be very well insulated to prevent any pressure leakage.

In order for the sensor to be secured inside, a customized part - holder (labeled 7 in the concept drawing fig. 9) has to be created. A simple visualization is provided below (see fig. 10). This can hold the tiny sensor die and also have a hole in the middle for wire connection of said sensor. The main concerns in this design are the insulation and wire access.

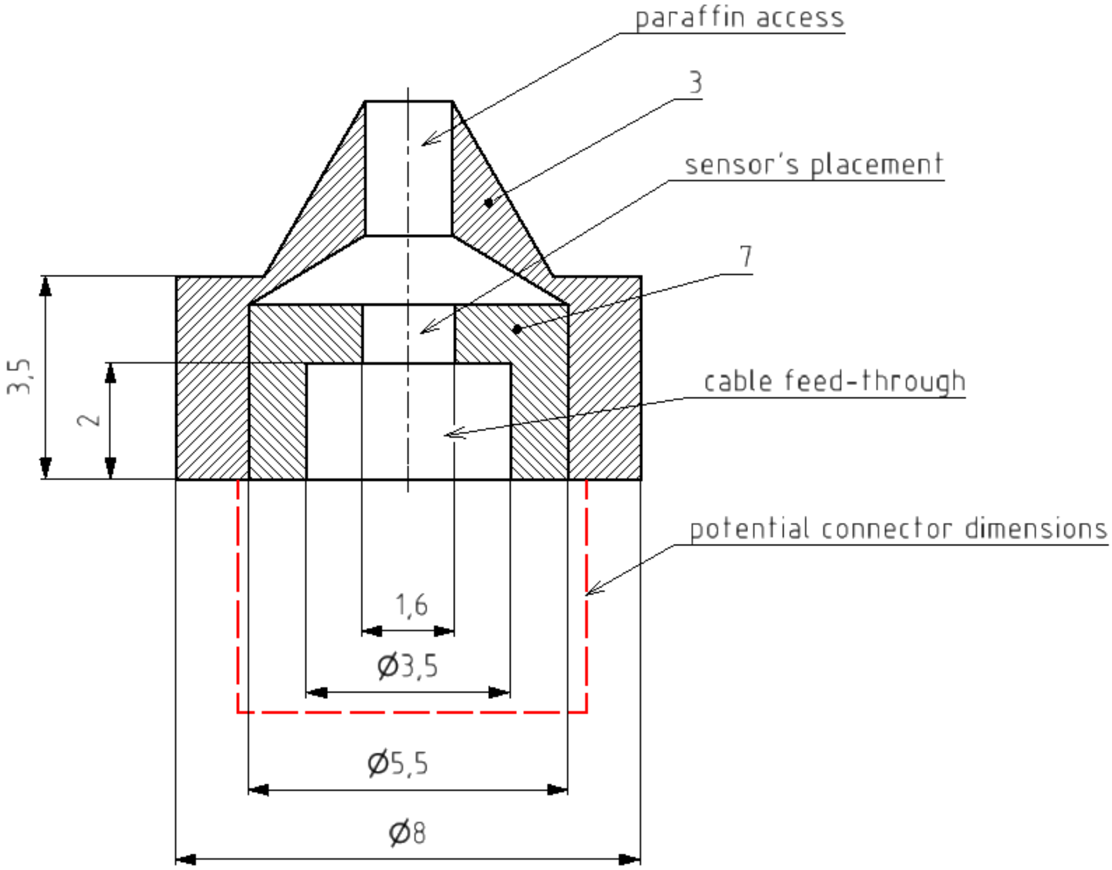


Figure 9: The holder (7) fitted inside the cap (3)

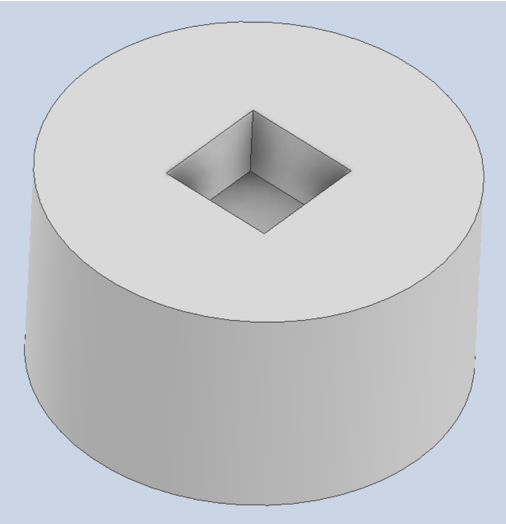


Figure 10: Customized holder for the sensor

7.3.1 Insulation

For this solution to be viable, three crucial spots have to be insulated:

1. the interface between the cap (no.3) and the holder (no.7)

2. the hole in the holder (no.7) which serves as a place for a cable feed-through
3. the interface between the cap (no.3) and the rest of the assembly (specifically the paraffin casing - no.2)

To address the interface first: one of the options is to make a thread on the outside of the holder, screw it into the cap and insulate the assembly with an O-ring placed on the inside. Unfortunately, due to the limited space, even a very small O-ring does not have enough place to fit in properly. Not to mention the very high pressure of 16 MPa exerted on the material.

Second considered option is to set the holder into the cap with an overlap. To roughly calculate how much pressure can an interference of 16 µm (heavy press fit) hold, one can use these equations:

It is necessary to first calculate the contact pressure p_s along the surfaces that touch each other. This can be done by the following equation, where E stands for Young's modulus of steel (210 GPa), δ is the radial interference (16 μm) and ν Poisson's ratio of the material (0.3) [75].

$$\begin{aligned} p_s &= E \cdot \delta \cdot (1-\nu) \cdot (1+\nu) \\ p_s &= 3057 MPa \end{aligned} \tag{7.1}$$

From this pressure, one can calculate the axial force necessary to dislodge the holder (7) from the cap (3) (see fig. 9). Here, d stands for the nominal diameter of the holder (5.5 mm), l is the engagement length between the holder and the cap and μ is the coefficient of friction (0.15 for steel) [75].

$$\begin{aligned} F_a &= \pi \cdot \mu \cdot p_s \cdot d \cdot l \\ F_a &= 23N \end{aligned} \tag{7.2}$$

To calculate the final pressure this force exerts on the holder, one must divide the force by the surface of the holder, on which the force is exerted.

$$\begin{aligned} p_a &= \frac{F}{S} \\ p_a &= \frac{4F}{\pi d^2} \\ p_a &= 1MPa \end{aligned} \tag{7.3}$$

As seen here, the pressure necessary to dislodge the holder is around 1 MPa. The paraffin will be exerting a pressure up to 16 MPa. This means that a fit with an interference is not strong enough.

Third possibility is to simply permanently weld the holder into the cap. The welding has to happen after the sensing die and the wires were placed into the holder. After the welding, the sensor is not accessible anymore without damaging the cap. But unlike the previous suggestions, the weld is able to survive the pressure, which makes it the best option.

The insulation of the wire access is a different matter entirely. The cables cannot be welded in or fitted with overlap. Very similar problem was already discussed in this chapter regarding the 1st sensor location (see chapter 7). To briefly summarize - the solution was to use an epoxy feedthrough which can connect the sensor and the outside of the assembly (see fig. 9).

The last thing to keep in mind is insulation between the surface of the cap and the rest of the assembly. This has already been solved while designing the original assembly. Between the cap and the paraffin capsule, there is a small O-ring. The slope of the cap also works as a secondary mechanical insulation.

7.3.2 Connector

It is also to connect the external wires with the feedthrough via a connector. An approximate size can be seen below (fig. 9). The connector is a possibility, but not a necessity. As is shown in the picture, even the smallest connector is quite hefty when compared to the cap. The decision on whether or not to use depends entirely on the available space outside of the cap. For this moment however, it is easier to solder the outside cables directly to the feedthrough.

After everything is put together, this alternative presents a much more compact solution than with a sensor partially on the outside. The integration of the sensor into the assembly is also easier than in the 1st placement.

7.4 Partially external sensor

Another possibility could be drilling a thread inside the preexisting hole of the closure (no.3) and simply screwing in a fitting sensor. However, most sensors are not equipped with a thread smaller than M4 and even if they were, the threads are often placed behind the actual sensor / sensing membrane. This means that conventional sensors require both wider and deeper hole in the cap which is unfortunately not doable.

7.4.1 Sensor integration

A different option calls for a special custom-made extension (fig. 11, 12), which could act as a hold for the sensor. For example, there is a sensor with an M4 thread (fig. 13) that could be screwed into the extension while still having enough place for the sensing part. As seen in the schematics (see fig. 13), tightening the nut (no.9) applies force on the sealing ring (no.8) of the sensor, making a perfect insulation. The connection between the extension and the original body is sealed with an O-ring (no.5).

This option is also viable for sensors with somewhat bigger threads, because the extension is not as space restricted as the cap and a bigger thread can be possibly drilled in. As seen in the technical drawing, the sizes marked A,B and the thread C can be reasonably interchangeable.

One setback can be that a lot of the threaded ports are manufactured with British Standard Pipe Parallel (BSPP) or National Pipe Thread (NPT) and not with the metric thread. The diameter of these threads is measured in inches and the smallest one used on sensors is G 1/8, meaning the major diameter is around 9.728 mm. That size just about fits into the extension and anything else with BSPP is practically unusable (G 1/4 is approx. 13 mm hole which is at the limit of doability).

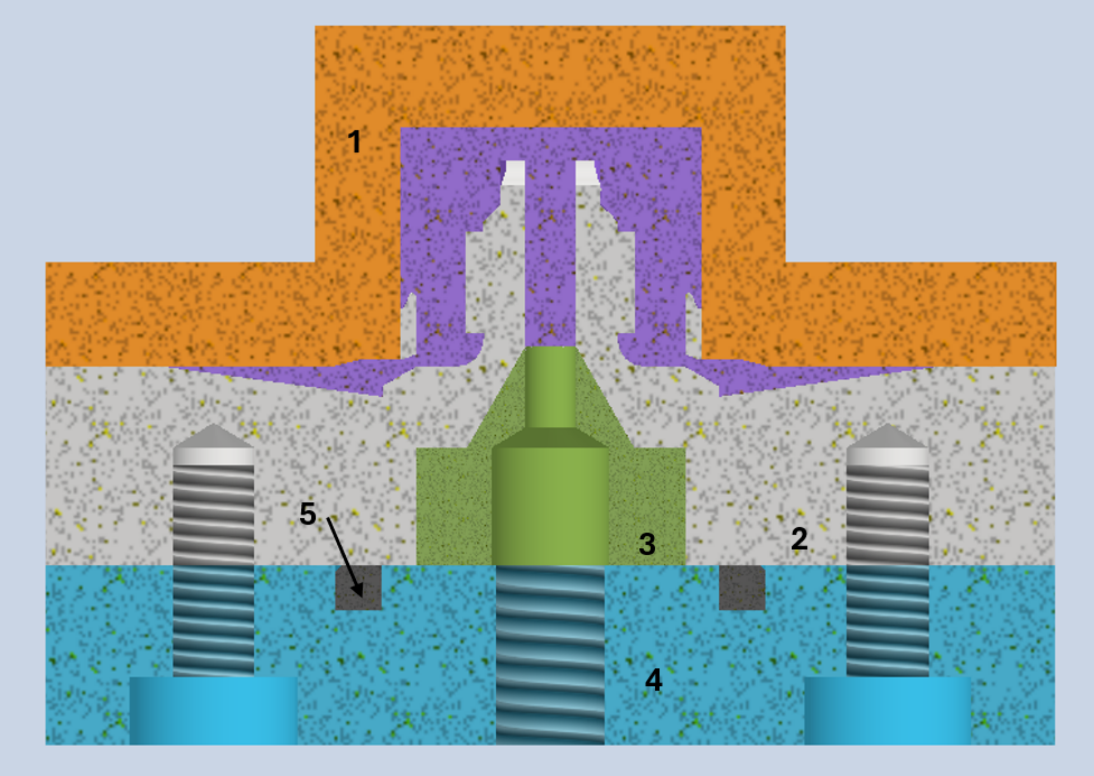


Figure 11: Possible extension

The following table shows basic information about sensors suitable for this option along with their specific sizes A, B and C (see tab. 5). If the sensor is not marked with letter ”B”, it means that the geometry of the sensor does not require an enlarged hole in the cap (3).The column ”E (extra length)” refers to the part of the sensor that is not hidden inside the extension and therefore requires extra space on the outside of the device. For illustration, this dimension is marked in the drawing of the XPM4 sensor (see fig. 13).

Unlike previous tables, this one does not include a ”compatible with liquids” column because all of the sensors are for liquid pressure measurement and built to withstand harsh conditions.

To highlight one of the examples, the XPM4 sensor has an advantage of a very small extra length protruding from the extension, which is very desirable for this project, where every millimeter matters. It does not reach the pressure ranges of other sensors, but the maximum of 20 MPa is quite sufficient for this application, making it one of the ideal candidates [76].

In general, however, this solution is not prioritized because it takes up quite some space outside of the assembly, which is not desirable. Still, it can be used as a backup possibility if there are any complications with implementing the MEMS integrated sensors.

When implementing this version, one has to mainly focus on choosing the right sensor that is compatible with the extension. Another characteristic to look out for is how much of the sensor is protruding out from the extension. The size of the extension is already given and it is best to ”hide” as much of the sensing instrument inside the extension as possible. That way the extra volume is reduced to a minimum. With that one also reduces the possibility of the sensor getting in the way of any other instruments outside of the assembly.

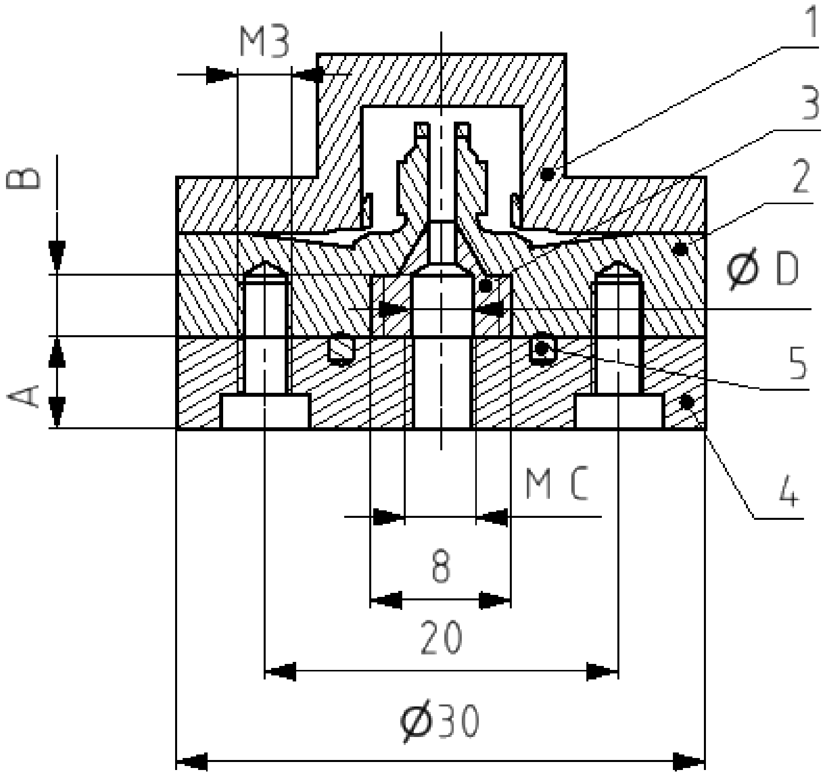


Figure 12: Possible extension drawing

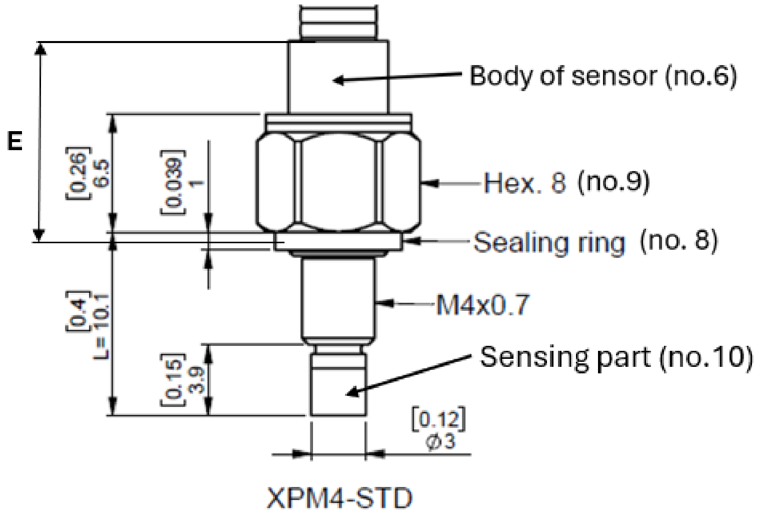


Figure 13: XPM4 sensor (edited)[76]

Table 5: Suitable sensors

Name	**Company**	**A [mm]**	**B [mm]**	**C (thread)**	**E (extra length) [mm]**	**Max. Pressure [MPa]**
21Y [77]	Hydro Press	12	-	G1/4	41	60
XPM4 [76]	TE Connectivity	9.1	3.9	M4	10	20
4080B [78]	Kistler	9	-	M6	32.3	25
XPM6 [79]	TE Connectivity	15	5	M6	12	100
EPRB-2 [80]	TE Connectivity	8.2	-	M5	20.4	70
EB100 [81]	TE Connectivity	6.6	-	M4	25	35
PT9550 [82]	Hydro Press	12	-	G1/4	53	40
AP028 [83]	Autosen	12	-	G1/4	47	25
NPI-15 [84]	NovaSensor	12.7	-	G1/8	23	35

7.5 3rd sensor location

This location is not marked in the schematics (fig. 4) in chapter six because it technically does not meet the original conditions of the problem.

It was stated that the sensor cannot be placed entirely outside of the paraffine capsule. It would be best to meet this condition, but if no other options are viable, it is not completely out of question to put the sensor completely outside and only connect it with the assembly via a tube.

7.5.1 Integration

In such case, there has to be a tube securely connected to the premade hole inside the cap (no.3 in the assembly - fig. 7). The tube must transmit the pressure of the paraffin outside from the device and to an external pressure sensor. This way, the dimension limitations can be practically eliminated because one can place the sensor further away from the assembly and avoid the space restrictions in the immediate vicinity of the assembly. There is enough space a bit further away from the capsule to fit in any of the previously mentioned sensors, or even some slightly bigger. Such types of sensors are way more common, more easily obtainable and of course cheaper.

The advantage this gives over the ”partially external sensor” is that this way, one can choose where to put the bulky volume of the measuring device. The only limitation is how far one is willing to lead the pressurized tube. This is unlike in the previous possibility, where the sensor is screwed into the extension and its excessive volume cannot be moved to any more convenient place.

As an example of a viable external sensor there is a pressure transducer from Swagelok company. It can withstand up to 60 MPa and more importantly has a tube adapter. Unlike most other sensors which end with a thread, this has a thinner non-threaded end with an 1/4 in hollow diameter. This can be fitted straight into the connection tube (see diagram below - fig. 14).

Importantly, this sensor's length is around 90 mm in total, which makes it completely unusable in any previous marked locations and its use outside the paraffin capsule is highly dependent on the available space near the capsule [85].

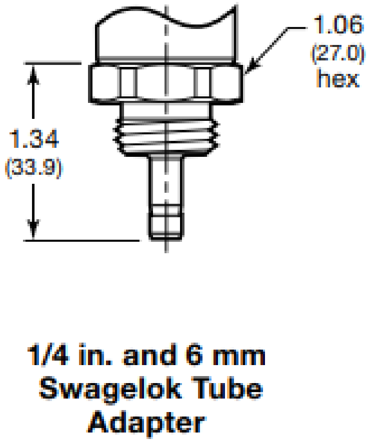


Figure 14: Tube adapter [85]

Even if some sensors do not have the same tube adapter as Swagelok, many tubes can be bought with special ending adapters. This means that the tube ends with a metal threaded part, to which a common sensor with a threaded end can be fitted.

7.5.2 Insulation

The problematic part of this solution is the pressure transmission. One needs to ensure that the tube does not burst under the pressure of 16 MPa.

One can assume that the tube is made with an inside diameter of about 6 mm to fit into the cap in the assembly the same (or similar) way as the sensors in 2nd option. In such a tube, the outside walls can be only 1 mm thick to fit perfectly into the hole in the cap (no. 3 in fig. 4). Of course, the connection also needs to be perfectly insulated on both ends. The end connected to the sensor is relatively well insulated thanks to the tube adapter.

There is also a question of how the tube is going to be connected to the paraffin capsule (specifically to the cap). The tube has to be held in place firmly as to not be forced out of the hole by the sheer pressure of paraffin or simply gravity. The simplest way to solve this is to have the tube fitted with a metal thread, and then it is possible to screw it inside the cap (similarly to the sensors in option 2).

7.5.3 Accuracy

The question of measurement accuracy also has be addressed. Compared to the previous placement choices, this option has a whole length of the tube to gather slight inaccuracies and in this regard is in definite disadvantage. There is a real possibility that this external sensor turns out to be less accurate than the one directly in the paraffin capsule because of that.

Another factor to look out for is the total volume of paraffin measured. One of the requirements of this project is that the volume is exactly 1.5 cm^3. The original space for the liquid is already too big which is solved by putting in some extra padding to make the space smaller. The addition of a tube means that some of the 1.5 cm^3 would be filling out the tube instead of just the designated area. This results in the need for more stuffing, and moreover, the need for stuffing of the *exact same volume* as is the internal volume of the tube. This makes it more complicated to carry out this solution, but it does not make it impossible. And because of its other advantages, this solution is still worthy of consideration.

8 Testing

To ensure that the whole setup (assembly + sensor) runs properly, it has to be thoroughly tested first. The testing has several steps, in which the conditions will be slowly getting more and more accurate and similar to the real environment. More importantly, the sensor must be tested twice:

1. on its own
2. when it is mounted inside the assembly - complete setup

To get the idea across, every step is also provided with a practical example featuring a specific sensor.

8.1 Isolated sensor

8.1.1 Visual inspection

The simplest check-up method. This way, one can inspect the housing to make sure that there is no outer damage / scratches that could cause the outside environment (paraffin) to affect the internal components and electronics. Another important part to focus on is the interface. For a stable connection and quality signal, it has to be intact [86]. Below (fig. 15), one can see an example of a damaged pressure sensor - specifically the diaphragm. Such things should be obviously avoided, because even if the device still works, the measurements it takes will not by accurate by any margin.

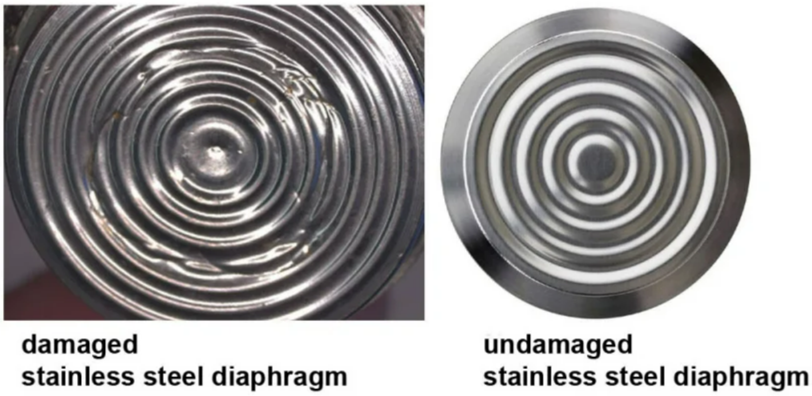


Figure 15: Outer damage [87]

8.1.2 Pressure testing

It is important to check that both the power supply and all the connections work properly. One has to power the sensor and connect its output to a multimeter. If it detects changes in voltage, the power is running through. To check if the sensor is measuring accurately, use a standard pressure source to apply force to the sensor. After several different pressures are measured they are recorded along with the output voltage and plotted in a pressure-voltage curve. From the curve one can check the sensors linearity and repeatability. Linearity describes how closely the voltage output follows a straight-line relationship with the input-measured pressure. Repeatability shows how different are the sensor outputs after applying the same force several times. Good repeatability means that the sensors output is always the same (or realistically, with minimal differences) [86]. Below (fig. 16), there is an example of a linear versus non-linear output. (There are never perfectly linear results.)

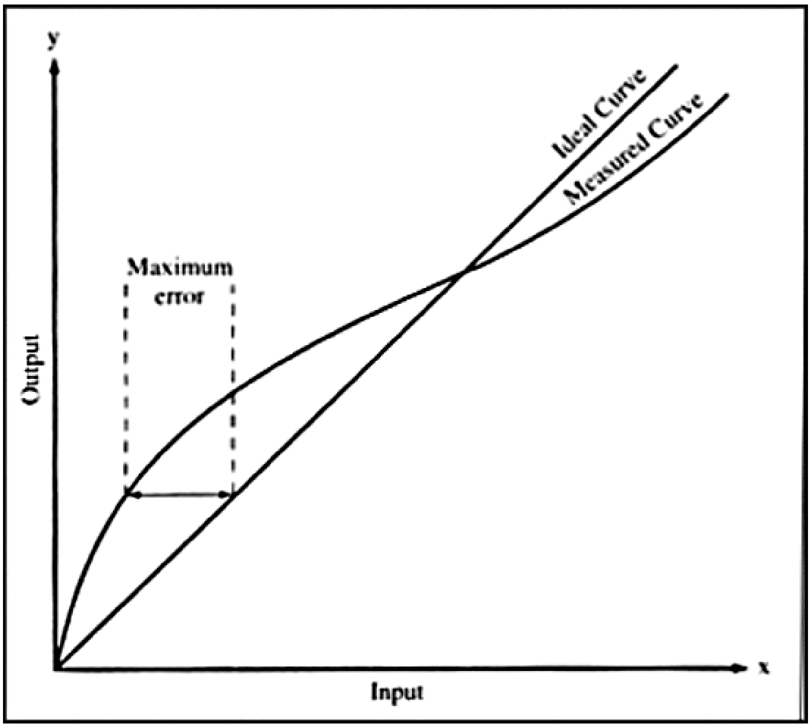


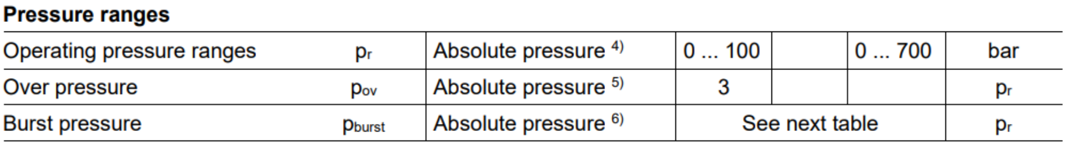
Figure 16: Linearity [88]

8.1.3 Zero-point detection

The sensor is already checked for its output when an external force is applied. It also has to be inspected for its output when there is no acting force. To do this, one simply puts the sensor in a no-pressure state. A multimeter can be used to measure the zero output. Despite its name, the voltage will not be zero, but around several millivolts. If this output exceeds the limits provided by the manufacturer, the sensor probably needs to be calibrated [86]. If calibration does not help, it is best to replace the sensor.

8.1.4 Full-scale test

If the sensor reacts correctly during standard pressure testing, another step is to test it under maximum pressure specified by the manufacturer. The output value is then compared with the full-scale value in the provided technical specifications. This is done to ensure that an overload is not occurring under such pressure. It is important to differentiate between three different types of ”maximum pressure”.



Pressure ranges

Operating pressure ranges	p_r	Absolute pressure [4)]	0 ... 100		0 ... 700	bar
Over pressure	p_{ov}	Absolute pressure [5)]	3			p_r
Burst pressure	p_{burst}	Absolute pressure [6)]	See next table			p_r

Figure 17: Pressure ranges [69]

As seen in the example datasheet (from a previously mentioned C43 pressure sensing die), there is:

1. operating pressure range
2. over pressure
3. burst pressure

When the sensor is in its operating pressure range, it is supposed to provide accurate and reliable data within the specified tolerance. The device is designed to work within those limits without any problems or restrictions. In this instance, the limit is either 100 bar or 700 bar depending on the sensor type.

The over pressure signifies a limit which the sensor can still withstand without permanent damage or permanent shift in its calibration (zero-point offset). If the operating pressure is exceeded, but it stays below the over pressure, the sensor will survive, but it might not provide accurate readings. In the example from the table (fig. 17), the over pressure is three times the maximum of the operating range.

Finally, the burst pressure is the limit of the material. At this point, the surface will probably crack or the housing will rupture. Once this threshold is exceeded, the sensor becomes unusable. While it is not clear from the table, another page of the sensor datasheet states that the burst pressure is 1000 bar, meaning ten times the regular operating range.

8.2 Sensor in assembly

When the sensor is tested on its own, it is also necessary to check if it works properly when built into the assembly. One also must not forget to run the test in an accurate environment - including the right fluid (paraffin) and temperatures.

To start off, first check that the sensor is functional, when the applied force is administered by fluid. In this case, water is the easiest go-to. If the equipment does not get damaged, water is exchanged with paraffin. This is done because even though paraffin and water are both fluids; there are several characteristics in which they differ. This way, it is ensured that the sensor works not only in any fluid, but in the liquid it will be exposed to in reality.

Further steps vary with the specific placement. The following sections briefly describe, how are the sensors tested within the various assemblies.

8.2.1 Sensor in main body

In the first placement (MEMS sensor in the main body), the only way to test it is to fully integrate the sensing die, connect it with the feedthrough and connector and then start measuring. Again, the experiments can be first conducted with water, then with paraffin. A second reference sensor can be placed on the top of the structure with access to the paraffin (a simple hole in the top of the capsule should be sufficient). This way, the results from both the instruments can be compared and crosschecked.

8.2.2 MEMS integrated in the cap

When talking about the second placement, the first focus will be on the MEMS integrated into the cap. Here, the testing can be done in two steps. First step is to place the sensor into the cap and again connect it via a feedthrough. At this point, one can test the pressure without fully integrating the sensor into the assembly. This way, not only the sensor is tested, but the connections in the feedthrough as well. With the second step, the cap has to be put inside the main body with sufficient insulation, which is provided with an O-ring and also by the conical shape of the cap. Now the test can run and simulate the real surroundings of the sensor.

8.2.3 Partially external sensor

This version is the one needing an extension for the sensor to be screwed in. First step of the testing is to connect only the extension and the sensor and check if there are no leaks through the threaded hole even under 16 MPa of pressure. Second part, as before, is to test the full assembly. As the instrument is already screwed into the extension, now this part can be connected to the original assembly (using screws and an O-ring to make the connection leak-proof).

8.2.4 Sensor connected via a tube

If this option is selected, the testing again takes place in two phases. First is with the sensor connected to one end of the tube, while the other end is pumped with pressurized water / paraffin. This checks the connection between the tube and the sensing part of the detector, as well as the strength of the tube itself. Second phase is to connect the end of the tube to the hole in the cap (no.3 in fig. 4) and test the whole assembly for the highest expected pressure.

8.3 Possible complications

As was mentioned at the beginning of this section, it is vital to make all the necessary experiments and check-ups in an environment that is as close as possible to the real conditions the instruments will be in. It was said before that the tests should be concluded twice - first time with water, second time with paraffin. These fluids are obviously very different in many aspects, such as density, viscosity, etc., but that is not the reason for the dual testing. When measuring with water, the pressure can be inflicted by any convenient means (e.g. external force applied to the water).

On the other hand, while dealing with paraffin, it would be logical to simulate the same cause for the pressure increase as there will be in the real experiment. And that is heat applied to the lower side of the casing. Due to the higher temperatures, the paraffin expands and causes very high pressures. This also tests whether the sensor can withstand the high temperatures emanating from its surroundings. The simplest way to simulate this is to let the whole capsule stand on a heated surface (see fig. 18).

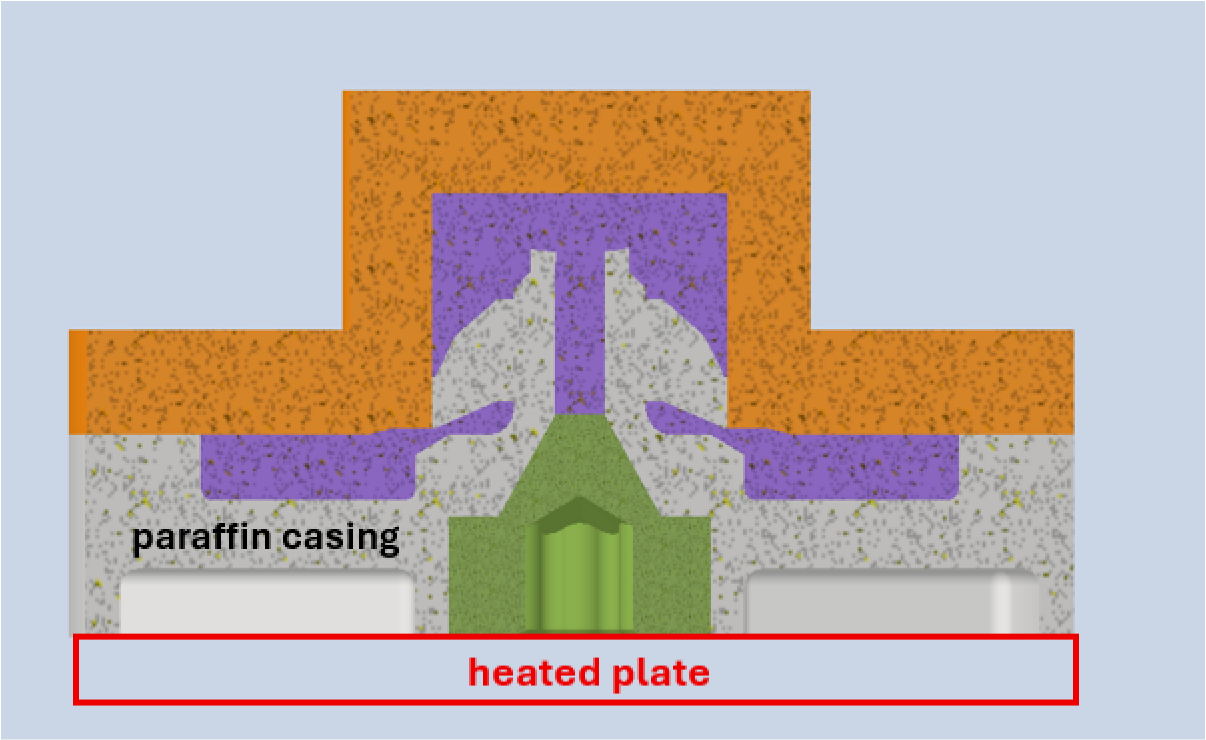


Figure 18: Placement of a heated plate

This method only works if there is nothing attached to the underside of the paraffin casing. Even with the MEMS option, where the sensor is hidden inside, there are still several wires running from the bottom of the assembly.

These protrusions cannot be avoided, because in the final design, the wire connection needs to go through the lower part of the casing. Removing the cables for the duration of the test does not work, because the wires carry the information from the sensor. Without the data, the experiment is pointless.

Similarly to that, any other sensor placement has the device either partially sticking out of the assembly, or at least a tube leading from the underside. Because of that, it is necessary to accommodate the shape of the heating plate around the wires / protrusions on the underside of the capsule.

This is where complications could arrive. Even if the heating plate is shaped appropriately, it could warm up the wires / parts of sensors, which were not designed to withstand the heat. At this point of the measurement, it is necessary to check the temperature resistance of the wires, so that they do not melt. Same would go for the tube, but it already had to be checked for the temperature resistance, because it has to survive the heat of the paraffin flowing through it.

Lastly, if the sensor is partially external, one needs to make sure that both the electronics inside and the cover of the sensor can withstand the temperatures.

9 Discussion

9.1 Sensor placement evaluation

It is a complex task to decide which of the presented solutions is the most suitable. Each one of them has its advantages and disadvantages that are often on different levels of importance. To make them at least somewhat comparable, this chapter evaluates the solutions using seven specific criteria.

For clarity, the last page of this section contains a table (see fig. 13) which shows all possible versions for sensor placement. Those are then rated from 0 to 5 considering seven different criteria they were supposed to fulfill. In this scale, 0 means the criterion is not met at all, while 5 is an excellent rating. All of the points are summed up together (each one having specific weight from 0.1 to 1) and a final score is produced. The higher the outcome, the better that specific solution is in fulfilling all the requirements.

To be more precise, for every requirement, an evaluative scale is provided, including the information about the weight (importance) of each criterion.

1. One of the main restrictions of this project was the lack of space. The main goal of every solution was to find an adequate sensor which also takes up a minimum of room. That is why this condition has the highest weight – 1. ”Amount of extra space” means the increase of volume of the whole assembly after the sensor is properly set up and installed. This also counts in any extra needed extensions that are not part of the original build.

Score	Amount of extra space, weight = 1
0	extra volume bigger than original build
1	extra volume slightly smaller than original build
2	half the casing
3	extra volume bigger than cap
4	extra volume smaller than cap
5	no extra volume

Table 6: Scoring criteria for extra space

2. Though this criterion might not seem as obvious, it is still very important. It evaluates whether one has more options to choose from when looking for a specific sensor. Each sensor placement requires different types of instruments with different specifications. And sometimes it is very hard to find a manufacturer with a product that meets all the general requirements (such as pressure range, ability to function in liquids etc.) and the requirements for the specific sensor placement as well (size, limited amount of cable outputs, ...).

   In the previous chapters, there are several examples of real sensors that can be practically used in specific assemblies. However, when choosing those examples, only the general criteria (mentioned above) were considered. It is very much possible that during the practical assembly / testing, more necessary requirements for the sensor will have to be taken into account.

For this reason, it is always practical to have more sensors to choose from. There are few instances where only one company makes instruments which are compatible with a certain sensor placement. This restricted number of available choices is reflected in the following criterion with an adequate weight.

Score	**More options on market, weight = 0.8**
0	no options
1	one company makes the product, offers few options
2	one company makes the product, offers several different options
3	few companies make the product
4	several companies make this product
5	easily obtainable from several producers

Table 7: Scoring criteria for market options

3. One needs to be very careful about the sensor if it is not fully integrated into the assembly, because that means it will be subjected to the vacuum of space. If the sensor is inside the pressurized capsule, it is protected from the outside forces. However, if it is external, it must be able to survive the vacuum of space. Otherwise, this could be a problem for the delicate electronics inside the sensor. This requirement is not as crucial as the previous ones, because it is relatively easy to find hermetically sealed sensors. This is why it has a slightly lower weight of 0.5.

Score	**Exposed sensor, weight = 0.5**
1	yes
3	partially
5	no

Table 8: Scoring criteria for exposed sensor

4. None of the possible solutions for sensor placement would be functional without a slight modification of the original design. Sometimes it is only a single hole for a cable feedthrough, sometimes it needs alteration for a whole special extension to fit in.

   More adjustments mean more extra work and more room for error. On the other hand, this criterion does not crucially affect whether the solution is viable or not. For this reason, it has only a weight of 0.4.

The following criteria are more preferences than huge feasibility impact factors. Nevertheless, one can still use them to differentiate the sensor placement options if the rest of the requirements are all met.

Score	Alterations to original build, weight = 0.4
0	design changed completely
1	major changes in the cap and body
2	major changes in the body
3	minor changes in the body
4	minor changes in the cap
5	no changes

Table 9: Scoring criteria for alterations

5. In some of the options, it is necessary for the connection cables to lead through the paraffin reservoir / be in contact with the liquid. This is not optimal, because one needs to ensure that all the wires are properly insulated and there is no chance of a short circuit. Even though it is entirely possible to make such insulation, there is still a certain amount of risk and it complicates the whole build. For this reason, this criterion is involved, even if only as an additional one.

Score	Wires going through paraffin, weight = 0.3
1	yes
5	no

Table 10: Scoring criteria for wiring

6. More extra parts mean more extra work, even though all of the proposed custom pieces are relatively simple to create. Again, this is more of a minor inconvenience rather than a dealbreaker when deciding about the best solution.

Score	Custom made parts, weight = 0.3
0	more than five parts
1	five parts
2	three or four parts
3	two parts
4	one part
5	none

Table 11: Scoring criteria for custom made parts

7. This criterion has to do with the testing of the sensor and the assembly. If the sensor needs to be tested and rechecked several times, it is important to know whether it is easily accessible after fitting into the assembly. Some of the solutions require the sensor to be sealed inside the paraffin capsule, which means it cannot be taken out without dismantling the whole assembly.

That obviously complicates the whole process of testing. This evaluation indicates whether one can easily reach the sensor from the outside and reuse it for another testing. This criterion is somewhat similar to the ”Exposed sensor” one, but this time having the device on the outside is considered an advantage. These two criteria will not cancel each other out, because both have a different importance (weight).

Score	**Accessible sensor, weight = 0.3**
1	no
3	partially
5	yes

Table 12: Scoring criteria for accessibility

To give an idea how the final score was determined, provided below is an example of how the first row (location - inside paraffin capsule) was calculated. In the equation, x_n stands for the different weights of the criteria and a_n stands for the number of ”points” the location was evaluated for. N is the value of its final score.

$$N = \sum_{n=1}^{6} a_n x_n \tag{9.1}$$

For the first row, the equation looks accordingly:

$$\begin{aligned} N &= 5 \cdot 1 + 2 \cdot 0.8 + 1 \cdot 0.3 + 1 \cdot 0.3 + 3 \cdot 0.4 + 4 \cdot 0.3 + 5 \cdot 0.5 \\ N &= 12.1 \end{aligned} \tag{9.2}$$

Each row is calculated the exact same way. The higher the number N, the better the specific row (placement option) is in meeting all the conditions.

Table 13: Sensor Location Decision Matrix

Sensor location	**Uses up extra space**	**More options on market**	**Wires going through paraffin**	**Accessible sensor**	**Alterations to original build**	**Requires custom parts**	**Exposed sensor**	**Score**
Weight	**1**	**0.8**	**0.3**	**0.3**	**0.4**	**0.3**	**0.5**	**-**
Inside the paraffin capsule	5	2	1	1	3	4	5	12.1
Partially external	2	4	5	5	2	4	3	12.2
Integrated in the cap	5	2	1	3	4	3	5	12.8
Completely external – connected via tube	3	4	5	5	2	4	1	10.7

9.2 Optimal solution

In the table, one can notice several interesting things. For one, the two solutions using MEMS (inside paraffin capsule or integrated in the cap) have very similar ratings in most of the columns. Virtually the only distinction is in whether the sensor is simply accessible or not. This might make it seem that these placements are very similar or even equivalent. But even though both use the same type of sensor, the setups are completely different and *not interchangeable.* The implementation of each project is also entirely different and requires different custom parts.

It is also important to notice that the differences in final scores are not really significant. It would be enough to manipulate the weights of the criteria and a different solution would come out on top. This does not necessarily mean that the scoring system is wrong, it is more the fact that all the solutions usually have one specific setback while being quite average in the rest of the columns.

Even though the setbacks differ, there is a similar number of them for each solution, which means that the scores slightly even themselves out.

9.2.1 Advantages and disadvantages

The differences between the solutions might not be so evident from the scoring table. To highlight the specific advantages and disadvantages, there are quick summaries for each sensor placement:

MEMS inside paraffin capsule

+ uses up virtually no extra space
+ the only custom-made part is the feedthrough
+ sensor protected from the vacuum outside
– very few sensors on market to choose from
– risk of cables short circuiting in paraffin
– sensor hardly accessible

Partially external sensor

+ only the sensing part of sensor is exposed to the hot paraffin
+ several different sensors to choose from
+ very simple to attach / detach the sensor
– uses up quite a lot of extra space
– requires a custom-made extension
– body of sensor exposed to vacuum

MEMS integrated into the cap

- \+ sensor easily accessible
- \+ body of sensor protected from the vacuum
- − very few sensors on market to choose from
- − complicated to attach the sensor into the cap properly

Sensor connected via tube

- \+ only the sensing part of sensor is exposed to the hot paraffin
- \+ several different sensors to choose from
- − requires extra space
- − connecting tube could cause complications
- − body of sensor exposed to vacuum

9.2.2 Scores comparison

From what the scoring table (tab. 13) shows, the best solution is to integrate an MEMS sensor into the cap of the assembly (with the sum of 12.8 points). This option does not use virtually any extra space, has an accessible sensor and requires only one special custom part. Overall, it is an adequate solution to the given problem. However, the fact that it has the highest score does not make it the perfect solution. It still has some disadvantages and it only offers very few sensors to choose from.

A very close second came the version with a partially external bigger sensor with a custom made extension (12.2 points). It is very practical assuming that the necessary sensor is far more common than a miniature MEMS sensing die. Because of that, it can be considered a backup if the first solution is not suitable for the project.

The third highest score was 12.1 points for the MEMS sensor inside the paraffin capsule. One can notice that the difference between the second and third position is only 0.1 point. This makes the versions basically equivalent in suitability. The key difference between the solutions lies in how much space they occupy. Using that, one can determine which variation is more desirable using this difference. If there is at least some extra space around the assembly, it is better to choose a bigger sensor connected to the extension. Not only it is much easier to obtain a variety of such measuring instruments, but the sensor is also comfortably detachable and can be changed easily if anything does not work. If, however, there is not enough space around the setup, one has to apply the solution with the MEMS directly in the paraffin capsule.

The last option - the sensor connected via a tube - was awarded only 10.8 points. This makes it the worst solution by far. One should consider implementing this only if all the other solutions fail. One could also argue that if the evaluation criteria were set up with different degrees of importance, another solution could have a better score. This is a valid argument, but the comparison table was compiled in such a way that the weight of each specific criterion corresponds with how crucial it is. The weights of all the requirements were decided with this specific project in mind. The final scores correspond with how the solution is overall desirable for *this concrete assignment*. For this reason, it is logical to still choose the option with the highest score.

In this case, it means that the best way to measure the pressure of the paraffin is to put a small MEMS sensor inside the cap of the assembly and connect it with the outside via an epoxy feedthrough.

And if there is a problem during the assembly or testing and this version turns out to be too impractical, the other solutions can be used. This is made possible because integrating the MEMS into the cap does not require any major changes to the body of the assembly and the paraffin capsule is therefore still usable for any other solution.

Conclusion

This thesis researched the different possibilities of pressure measurement in confined spaces. Specifically, a way of measuring very high pressure of paraffin inside a very small capsule in a satellite.

There were two main ways to approach the problem. First one included using minuscule MEMS pressure sensors integrated on a sensing die. It was determined that there were two possible placements of these measuring dies - directly inside the paraffin capsule or inside the cap that secures the paraffin. This allowed for the sensor to be completely "hidden" in the assembly and to be protected from the vacuum of space. Furthermore, it was advantageous because it does not take up any extra volume outside of the structure. The final evaluation also concludes that placing the MEMS sensor into the cap is overall the most acceptable solution regarding all the given criteria.

The second possibility focused on comparatively bigger sensors. They are much easier to obtain and there is a much wider variety of available products on the market. The main issue with this variant was figuring out a way to attach the sensor to the assembly. Again, the thesis proposed two different configurations in which these bigger instruments can be used. One version included the possibility of a custom-made extension the sensor can be screwed into. Another way to attach the sensor was to use a small tube filled with paraffin that connected the assembly and the measuring instrument. Although this solution might seem hefty, it still met the given criteria adequately and is considered as a backup if the MEMS does not work for any reason.

Each possibility for the sensor placement had its advantages and disadvantages but they were all feasible and met the basic requirements. This work highlighted the most important traits of each solution and concluded that the best option based on the data is to integrate an MEMS sensing die inside the cap of the assembly. This way, all the strict requirements concerning space limitations and pressure range are met.

Even if this thesis was mainly focused on solving a problem of one specific satellite, it also provided important research into miniature pressure transducers with special focus on high pressure measurement. This can be used by anyone who has to make pressure measurements in any kind of confined space. It is up to any future reader to decide which solution to use based on their specific requirements and preferences.

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List of Acronyms and Abbreviations

Abbreviation	**Meaning**
ASTM	American Society for Testing and Materials
ARINC	Aeronautical Radio, Incorporated
ASA	Aviation Suppliers Association
BSPP	British Standard Pipe Parallel
CF	CompactFlash
ESAM	External Security Administration Manager
FEM	Finite Element Method
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Organization for Standardization
ISS	International Space Station
MEMS	Micro-Electro-Mechanical System
MIL-STD	Military Standard
NASA	National Aeronautics and Space Administration
NPT	National Pipe Thread
SLS	Space Launch System

Symbol	**Unit**	**Quantity**
a_n	[-]	points evaluating a sensor location
d	[m]	nominal diameter
E	[Pa]	Young's modulus
F	[N]	force
F_a	[N]	axial force
F_n	[N]	perpendicular force
g	$[m/s^2]$	gravitational acceleration
h	[m]	height
h_1	[m]	initial height
h_2	[m]	final height
l	[m]	engagement length
N	[-]	final score of a sensor
p	[Pa]	pressure
p_a	[Pa]	pressure caused by an axial force
p_s	[Pa]	contact pressure
p_1	[Pa]	initial pressure
p_2	[Pa]	final pressure
S	$[m^2]$	surface
u	$[m/s]$	fluid velocity
q	$[Pa]$	dynamic pressure
x_n	[-]	weight of location criteria
δ	[m]	radial interference
μ	[-]	coefficient of friction
ν	[-]	Poisson's ratio
ρ	$[kg/m^3]$	density