TAMPERE UNIVERSITY OF TECHNOLOGY
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PASI HAKONEN
FIREARM SUPPRESSORS – STRUCTURES AND ALTERNATIVE MATERIALS
Master of Science Thesis

Examiner: Professor Tuomo Tiainen
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TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Materiaalitekniikan koulutusohjelma
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Joka vuosi lukuisat metsästäjät, ampumaharrastajat ja varusmiehet kärsivät tinnituksesta ja eriasteisista kuulovaurioista. Suuri osa näistä ongelmista johtuu käsiaseiden laukausäänille altistumisesta ja epäonnistuneesta kuulonsuojauksesta ja ne olisivat vältettävissä asianmukaisilla aseisiin asennettavilla äänenvaimentimilla.

Painava teräsvaimennin voi tehdä aseesta kömpelön käsiteltävän ja raskaan kantaa pitkiä matkoja, mikä voi osaltaan selittää sen miksi vaimentimien käyttö ei ole yleistynyt vielä kattavaksi. Tässä diplomityössä pyritään löytämään tähän ongelmaan ratkaisu kevyempien materiaalivaihtoehtojen avulla. Tutkimus alkoi kirjallisuusselvityksellä, jonka pohjalta suoritettiin materiaalivalinta sopivien vaihtoehtoisten materiaalien löytämiseksi. Löydetyistä materiaalivaihtoehdoista valittiin kiinnostavimmat, joista valmistettiin prototyyppi testiammuntoihin.

Ensimmäinen testi keskittyi hiilikuitukomposiitin soveltuvuuteen vaimentimen ulkokuoreksi. Testissä havaittiin materiaalin kestävän huomattavasti suurempia lämpökuormia kuin alkuperäiset ennakkokäsitykset ja odotukset antoivat ymmärtää. Hiilikuitukomposiittivaimennin halkesi vasta kestettyään huomattavasti vaativampia olosuhteita kuin mihin kyseinen vaimenninprototyyppi oli tarkoitettu. Testin tulokset olivat lupaavia hiilikuidun soveltuvuuden suhteen mutta aikaongelmat estivät perusteellisen testaamisen ja lopulliset tulokset jäivät suuntaa-antaviksi. Prototyyppien rakentaminen ja testaaminen olivat vielä diplomityön kirjoittamisen aikana kesken ja ne jäivät odottamaan sopivaa testaamisajankohtaa.

Tutkimuksen selkein lopputulos on hiilikuitukomposiittien odotuksia parempi kestävyys äänenvaimentimissa. Lisätutkimusta tarvitaan hiilikuitukomposiittien ja anodisoidun alumiinin yhdistämisestä kiväärikaliiberisten äänenvaimentimien rakenteessa.

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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Each year several hunters, conscripts and sport shooters suffer from tinnitus and other problems with their hearing. A great part of these problems are resulting from the exposure to noise from small arms fire without adequate hearing protection. Many of these hearing problems could have been avoided with the proper use of fire arm suppressors.

A heavy steel suppressor may turn a rifle unwieldy and uncomfortable to carry and therefore less tempting to use. This thesis aimed for solving this problem by exploring lighter alternative materials for suppressor use. The research began with a literary study on the subject and on that basis it was continued by exploring possible alternative materials with a computer aided selection process. These materials were tested by building a prototype suppressor and by testing the material suitability with real fire testing.

The carbon fiber composites which were subjected to first test proved to withstand heat to much greater extent that what was originally expected. The material ruptured only after considerably heavier exposure than the suppressor was intended to endure. The results of the tests showed promise for the carbon fiber composites, but they failed to provide conclusive evidence as timing problems prevented extensive testing. The fabrication and prototype testing processes are still underway and they wait for future testing possibilities.

The main conclusion from this study is that future research and testing are still needed to verify the suitability of the combination of carbon fiber composite and anodized aluminum in rifle caliber suppressors. The preliminary results are very promising.

PREFACE

This thesis is written on the basis of the research on firearm suppressors conducted in Tampere University of Technology Department of Materials Science, in behalf of Oricopa Oy. The aim of the research was to improve already existing products with lighter material alternatives. This thesis contains theoretical background on firearm suppressors and on the computer-based process of finding alternative materials. The design process from first prototypes to future design possibilities is also described in the thesis. This document is intended as a basis for further research into the subject and to provide insight from material engineering perspective.

I would like to thank my professor Tuomo Tiainen for his valuable input and expertise and my instructor Mikko Nieminen for his reflection and for the endless supply of ideas for the research project. I would also like to acknowledge the personnel of Oricopa Oy, especially Taito Martiskainen and Vesa Saviahde for their insight and knowledge on the subject.

Writing this thesis would have never been possible without my family who has supported me through my studies and I want to thank them for all they have done and said. Still the most important person through this whole ordeal has been my wife Maija who found new ways to inspire me and helped me where I would not have had the strength to continue alone.

TABLE OF CONTENTS

ABRREVIATIONS AND NOTATION

A-duration	The time between the beginning of impulsive pressure increase and the return of the pressure to the ambient level.
First round pop	A phenomenon with certain suppressor types where the unburnt gunpowder ignites within the suppressor during first discharge.
Baffle	A baffle is a structural part in a suppressor that guides the expanding propellant gas to slow the gas discharge from the suppressor.
Ballistic crack	A projectile travelling at supersonic velocities produces a loud noise during flight. This is known as ballistic crack.
Caliber	Caliber refers to the diameter of the bore of a firearm. Caliber can either be announced in fractions of an inch (.308 and .50) or in millimeters (7.62 and 12.7, correspondingly).
Centerfire	A cartridge type where the primer is located in the center of the cartridge base. A high pressure cartridge used in most of the modern firearms.
CES	Cambridge Engineering Selector is a software designed to aid the process of finding possible materials and manufacturing processes for different applications.
Inconel	A registered trademark of Special Metals Corporation. A family of nickel-chromium superalloys.
Muzzle blast	Alternative name for muzzle report.
Muzzle brake	A device installed to the muzzle of a weapon that diverts and redirects propellant gas backwards to reduce the recoil.
Muzzle report	The sound caused by expanding propellant gas.
Reflex suppressor	A suppressor design where a significant part of the suppressor extends back over the muzzle to form a big primary expansion chamber.
Rimfire	A low pressure cartridge type used in some pistols and small caliber rifles.
Rise time	A property of a sound level measuring device that describes how quickly the device reacts to sound pressure changes.
Silencer	A device usually attached to the muzzle of a gun to suppress the muzzle report.
SPL	Sound pressure level, measured in decibels, describes the pressure variation caused by a sound source.
Suppressor	A more formal term used of weapon silencers.
Zeroing a weapon	Calibration of weapon sights and optics.

1. INTRODUCTION

Anyone who has experienced tinnitus knows how annoying it can be, especially if it is a constant nuisance. Hunters and recreational shooters are familiar with hearing problems as a study shows that every 5 years of recreational shooting increases chances of permanent hearing damage by 7% [1]. Hunting requires constant awareness of the surroundings and hearing protectors are easily left out to maintain situational awareness. This easily explains why older shooters may have problems with their hearing. In cases like hunting where earplugs and other hearing protectors are cumbersome other ways to protect the hearing of shooters and observers becomes increasingly important. Firearm suppressors offer a possible solution to such situations.

The most important aspect in the common civilian usage of suppressors is the protection of the hearing of the weapon operator and anyone in the vicinity. As the muzzle report of a rifle caliber weapon may exceed sound pressure levels of over 160 dB in the vicinity of the weapon, it poses a clear health hazard to the hearing of the shooter and everyone else in the proximity. With rifle caliber weapons a suppressor can be used to decrease the peak sound levels to 140 dB and below, which is considered as a limit when an impulsive sound produces hearing damage [2]. The suppressor also works in other ways besides than just damping the muzzle report. It influences the shooting experience and even enhances accuracy in some cases.

Suppressors provide an excellent way to protect the surroundings of shooting ranges from noise pollution. According to reference [2], the noise damping with structural changes in the shooting range requires significantly bigger investments as compared to the damping provided by suppressors. These facts alone already pose a valuable reason for the use and development of suppressors for civilian and military service. The internal structure of suppressors has been a noticeable target for research in history and there have been clear advancements in efficiency and size. [3]

In contrast alternative materials for suppressors have been studied less and the materials used in silencers rely heavily on traditional steels as the usage circumstances set significant requirements on the materials. The flow speed of air near the gun barrel can exceed speed of sound by a factor of three, while temperature can rise as high as 1000°C and the gas pressure can achieve levels from 200 to 600 times the atmospheric pressure. [4] These circumstances set great demands on the used materials. However, some research work has been carried out also on materials and as a result titanium, high temperature superalloys and carbon fiber composites have been used in modern suppressors. [3]

2. PRINCIPLES OF SOUND SUPPRESSION

In order to understand the methods used to suppress sound, one must first understand what sound is. Sound has been described as pressure, density and temperature variations which progress through a medium in waves. The wave characteristic of sound is responsible for such phenomena as scattering, absorption, refraction, interference, diffraction and reflection which play major role in the way sound behaves. The speed of sound is largely dependent on the sound medium where the waves propagate and on the surrounding conditions. Temperature, pressure and other outside factors influence the interactions between sound waves and particles. [5]

In order to suppress a sound, several methods can be used. Placing obstacles in the path of sound waves, using absorbing materials, specific structures and even electronic damping are possible. Yet the easiest way of reducing noise is distance. Shooting ranges are often located far from residential areas where the noise pollution does not influence living conditions. However, shooting ranges near cities might not have the option for distant location and other solutions for sound suppression are required. [2, 5]

Human hearing is considered to range from 20 Hz to 20 kHz frequencies, but the ear is more tuned to certain frequencies. The human hearing is most sensitive around the 1000 Hz frequency while sounds below 100 Hz require more intensity to be heard. The way human hearing responds to different frequencies is seen in **Figure 1**. The figure shows how the low frequency sounds require vastly stronger sound pressure levels to be perceived by the human ear, which means that the low frequency sound requires more energy to be audible. [6]

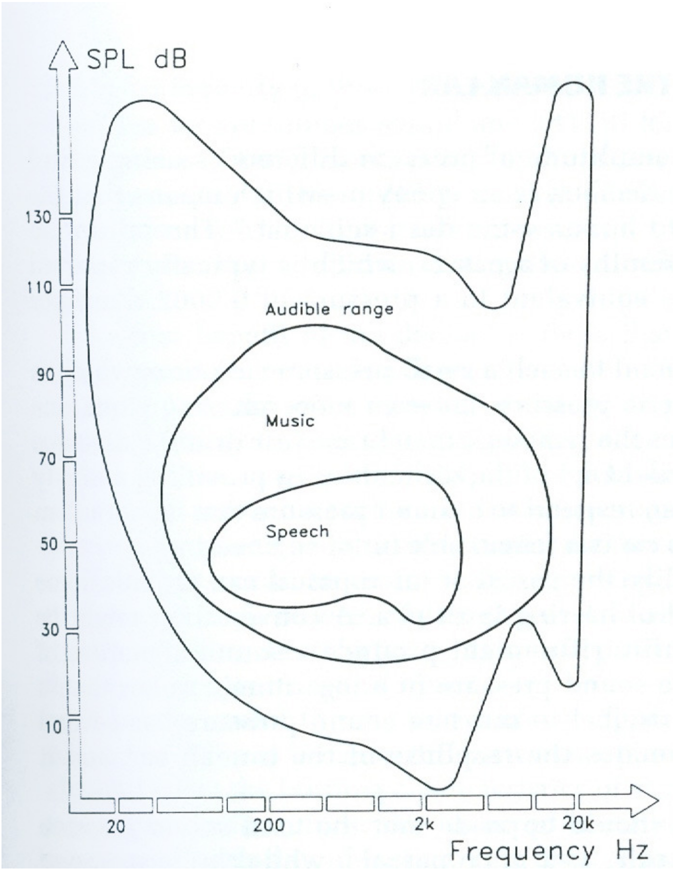

Figure 1 *The human hearing responds differently to sounds depending on the frequency range and sound pressure level (SPL). [7]*

This has an influence on how the human ear interprets a firearm discharge. Sounds around the 1000 Hz will sound more intense and therefore the greatest suppression is needed near the 1000 Hz range. **Figure 2** shows an idealized shot impulse and its Fourier spectrum. The impulse is idealized as in real situations the surrounding area creates reflections that affect the recording of the impulse. The peak energy in firearm noise varies between 1000 and 2000 Hz frequencies, just around the frequencies where the human hearing is the most sensitive. [7, 8]

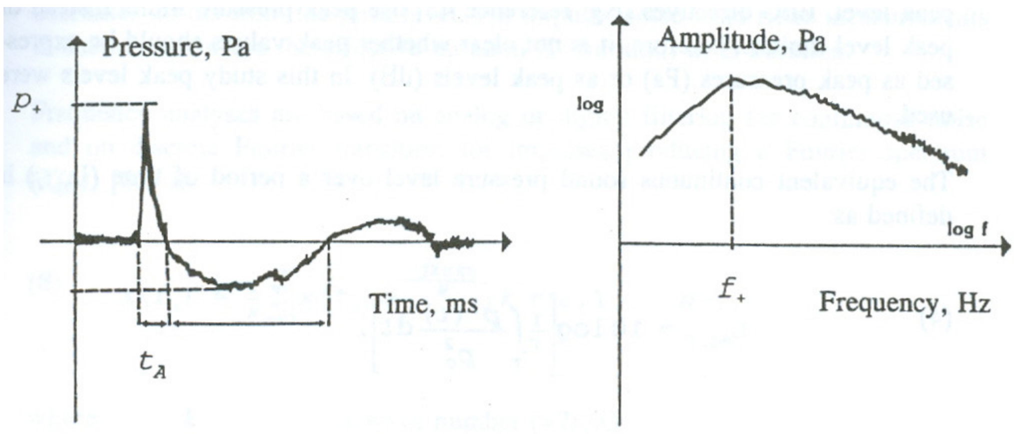

Figure 2 *An ideal shot impulse and its Fourier spectrum. The p_+ indicates peak pressure (Pa), t_a is the A-duration (ms) and f_+ the frequency of the highest amplitude. [8]*

2.1. Reasons for sound suppressors

The muzzle report is the single loudest sound source associated with firing a hand weapon. Depending on caliber, ammunition, environment, air pressure, temperature, used weapon and numerous other factors, the sound levels generated by the muzzle report usually exceed or brush close to safety limits. As an example the sound signature of a 7.62 caliber assault rifle can be lowered from 160 dB to 140dB and below which is considered as a risk limit in Europe. [2]

Earmuffs can turn out cumbersome and earplugs may distort sound distractingly during hunting. Sound suppressors provide an alternative way to protect the hearing of the hunter and those around him. The military service requires that trainers have constant communication with conscripts during exercises, especially when firearms are involved.

2.1.1. Health issues

The European Union has stated 140 dB as the peak noise level allowed with impulsive noise. An impulsive sound louder than 140 dB is considered to cause damage to hearing. When the duration of the noise increases, a smaller sound level is required to cause permanent damage. This comes to play in indoor shooting ranges or ranges with shooting shelters. The echo of the muzzle blast arrives so fast that the sound impulse seems to lengthen in duration and becomes more dangerous to hearing. [2, 6, 9]

Damage caused to hearing organs lowers the hearing threshold of the ear permanently. This manifests as a loss of hearing and affects the whole life of the person. The loss of hearing is most evident with older shooters who do not wear proper ear protection and military personnel who are subject to loud noises for extended durations during their workdays. Even sound levels of 85-90 dB have been found to induce hearing loss if a person is exposed for long periods of time to such levels. Workers who are exposed to sound levels over 85 dB in their working environment are entitled to hearing protectors. [9, 10]

Extreme sounds produce pain, disorientation and eventually even death. A deadly sound level is considered to be around 220 dB. The logarithmic scale used in the decibel scale means that the sound level of 220 dB corresponds to about 2 MPa of pressure. [3, 11]

2.1.2. Hunting

Hunting situations often require that the hunter has full use of all of his senses. Earmuffs and earplugs may hinder the hearing too much and even active hearing protectors may distort the noises enough so that some hunters rather leave them in the car. Further annoyance may follow as large muffs prevent fast aiming in quick situations, as they collide with the stock of the weapon. Therefore unfortunately a large number of hunters risk their hearing. In cases like these, suppressors would offer a considerable protection both to the hunters themselves and to any animals taking part in the hunting. [12]

A notable effect provided also by a suppressor is the damping of the recoil of a weapon. Especially younger and less experienced shooters may flinch in the anticipation of the recoil and miss a shot because of this. A suppressor has a similar effect as a muzzle brake. A silencer doesn't direct the propellant gases sideways or backwards towards the shooter, but forces a more controlled gas release that leads to smaller recoil. Muzzle brakes also increase the noise exposure of the shooter conversely to a suppressor. Also the flash of the gun is suppressed which may help in dim light hunting environments. Additionally there have been reports that suppressors confuse the prey to some degree and allow more careful placement of shots. This results in fewer wounded animals and more controlled hunting situations. [7, 13, 14, 15]

2.1.3. Military service

Hearing damage is a common problem during military service both with the conscripts and the instructors. Each year the central military hospital was reported to treat around 100 conscripts with hearing problems and Finnish Health Department reports about 200-300 acute hearing traumas yearly. Heavy machinery, explosions, heavy weapons and hand weapon fire are all possible sources for hearing damage. [10, 16]

During training earmuffs place limits on communication between the trainer and conscripts. Orders need to be issued with sufficient volume so that everyone registers the commands. This becomes even more important with firearms involved in the training. Suppressors might provide an alternative for earmuffs and provide a better communication during training. [9]

2.2. Noise sources

Discharging a hand gun produces noise from numerous sources. The most distinct is of course the expanding cloud of propellant gases, known as a muzzle report, which often masks other sounds. The bullet travelling above the speed of sound produces a distinct noise called the ballistic crack which is considered as unavoidable with supersonic projectiles. The cycling operation of the gun is surprisingly loud but harder to hear with the dominant muzzle report occurring at the same time. Lastly the impact of the bullet produces its own distinct sound, which can be heard even without a suppressor as the muzzle report has time to pass before the impact noise reaches the observer. Some suppressors also produce an additional sound known as the first round pop. When dealing with suppressors, the muzzle report is the main concern as a suppressor has only minimal effect on the other sound sources. [7]

2.2.1. Muzzle report

Muzzle report is caused by the expanding propellant gases combined with the air propelled from the barrel by the accelerating bullet. These gas shock waves form a unified shock front that is observed as the muzzle report associated with the weapons sound signature. [4]

The damping effect of a suppressor influences mainly just the muzzle report. The coherence of the expanding gas cloud is broken by the suppressor structure and the energy of the propellant gas is spread out to a longer time interval, thus causing a drop in the peak sound pressure. Oddly enough, while most of the pressure release is divided to a longer stretch of time, the peak sound level is actually shorter in duration. This is why there are several devices to measure the unsuppressed gunshot sound pressure level, but only a handful of facilities that can reliably measure the sound pressure levels of suppressed gunshots as the short peak level require exceptionally rapid response from the measurement devices. [7]

The domination of the muzzle blast is evident when comparing **Figure 3** and **Figure 4**. Both plots are recorded in the front of the shooter so that the bullet flight sound reaches the microphone before the muzzle blast. First figure shows the gunshot from an assault rifle without a suppressor. The muzzle blast is clearly more dominating and people rarely notice bullet flight sound when firing unsuppressed weapons. In **Figure 4** the ballistic crack has not changed in intensity but the suppressed muzzle report is now less dominating than the ballistic crack. This also gives a limit to the engineering of weapon suppressors. With a good suppressor the ballistic crack is louder than the muzzle blast, and suppressing the muzzle report further becomes pointless. The only way a suppressor could affect the ballistic crack is by lowering the speed of the projectile, but this poses more problems, such as a limited variety of cartridges that would function properly with the suppressor and limited accuracy in some cases. [7]

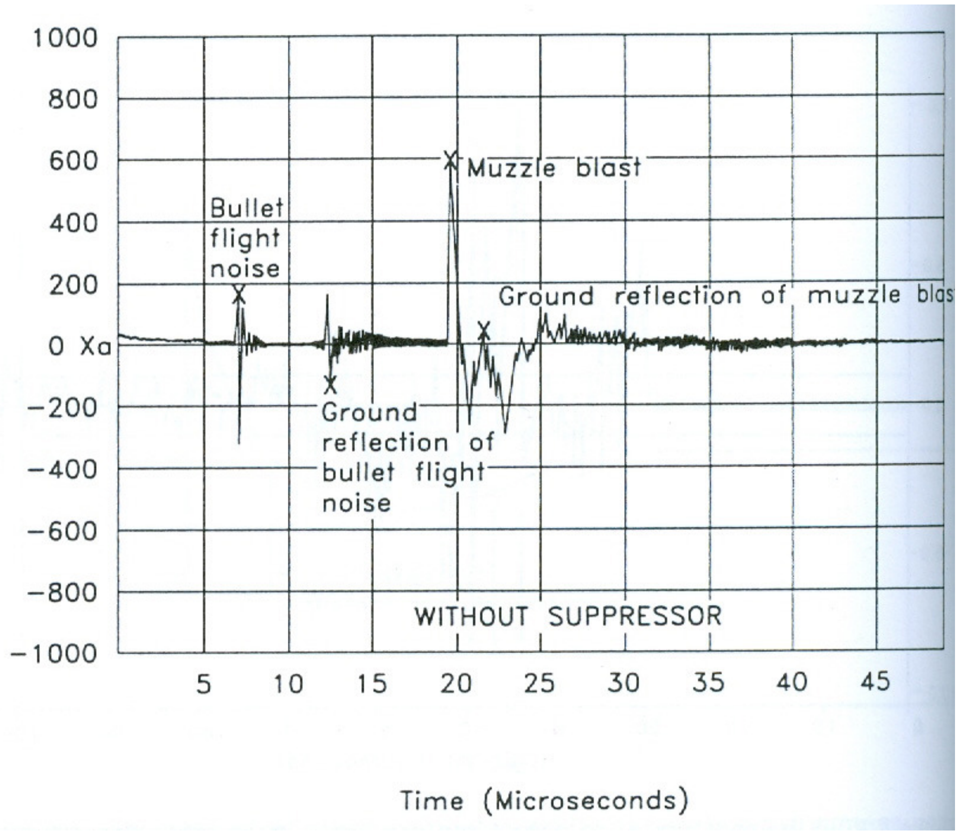

Figure 3 *A pressure versus time plot of an unsuppressed gunshot. [7]*

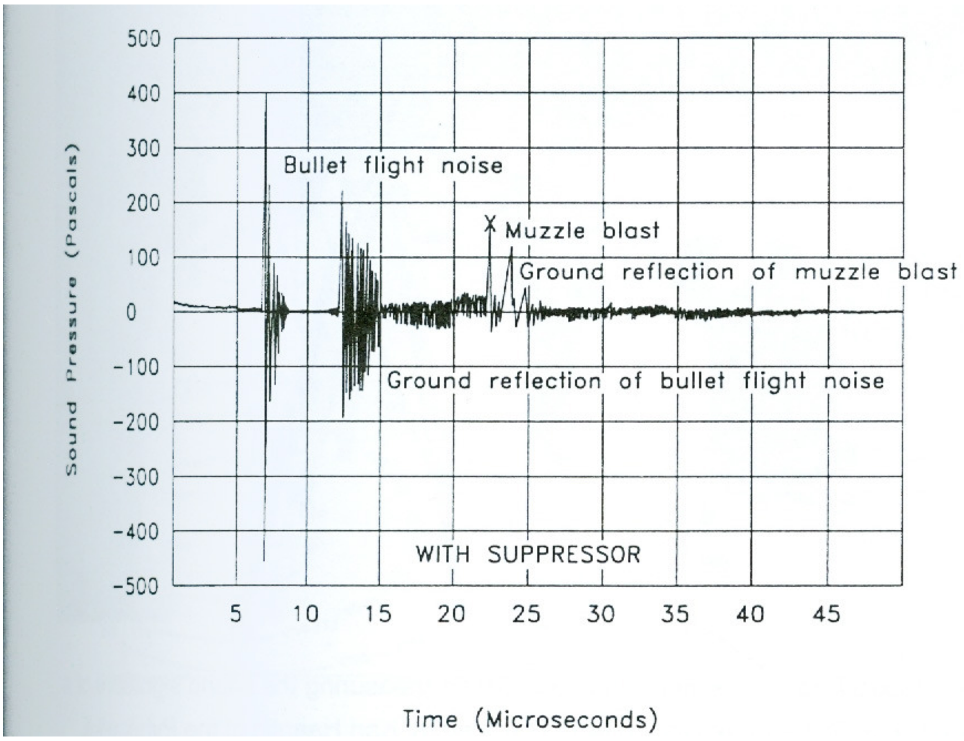

Figure 4 *A pressure versus time plot of a suppressed gunshot. Notice the difference in y-axis scale when compared with* ***Figure 3****. [7]*

2.2.2. Ballistic crack

An object travelling faster than the speed of sound produces a shock front which expands behind the flying object and is observed as a sharp noise. This is known as the ballistic crack. The flight sound of a bullet travelling with supersonic speed can in itself exceed the European risk level of 140 dB when reflected from objects and surfaces back toward the shooter. This results in a compelling argument for the use of other hearing protectors alongside suppressors when firing in spaces with large and uniform reflecting surfaces. Even without large echo surfaces the ballistic crack may represent a hearing hazard as repetitive impulsive sounds exceeding levels of 110 dB have been reported to cause hearing loss. [4, 7, 11]

The relation between bullet speed and the sound level produced by the ballistic crack in air is seen in **Figure 5**. Increase in bullet flight speed is observed as a louder ballistic flight noise. Near the speed of sound the flight sound increases rapidly and levels out after around 400 m/s. The difference in sound pressure levels between subsonic and supersonic projectiles is significant. Projectile shape has only a minimal influence on the flight sound. The results were obtained by using the same weapon and projectile and by increasing the propellant load gradually. [7]

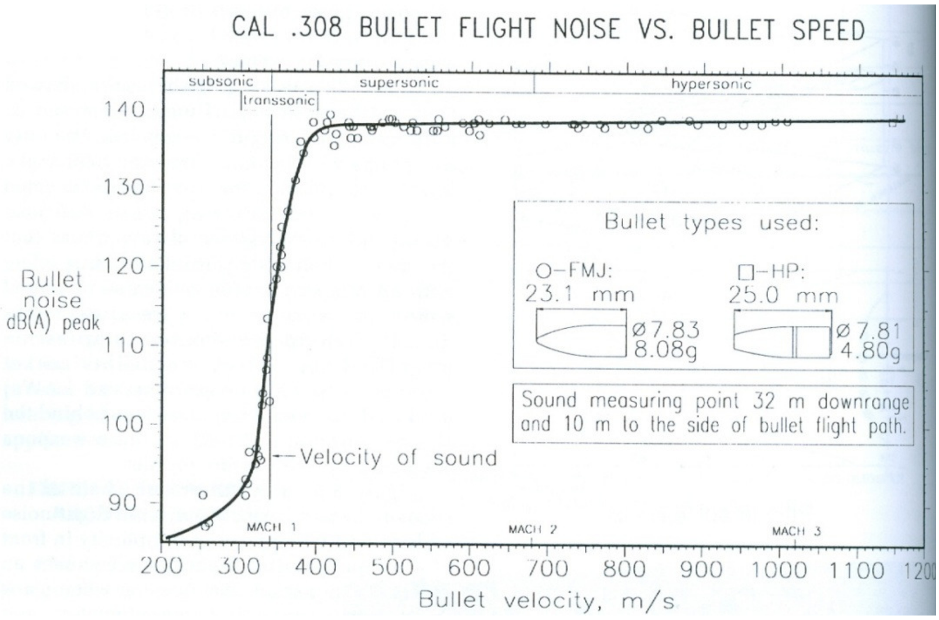

Figure 5 *The flight noise of bullets increases dramatically when the bullet overcomes the speed of sound in air. [7]*

2.2.3. Other sound sources

The action of a firearm produces more sound than what is normally thought. The louder muzzle report and ballistic crack mask other sounds which are a part of the weapon cycling when fired. This is easily observed by loading a rifle with a used cartridge and pulling the trigger. The hammer fall of an M14 rifle can exceed 108 dB within 2 meters from the weapon. [7]

Sometimes when firing several shots some suppressors perform worse on the first shot than on the following discharges. The first discharge is noticeably louder and is known as the first round pop. When the weapon is discharged first time, the suppressor is filled with oxygen rich air. This, combined with the pressure and heat within the suppressor, may cause the unburned propellant, which is a part of the expanding gases, to ignite inside the suppressor. With the second and third shot the suppressor is filled with propellant gases and the oxygen content in the gas is not sufficient to ignite the unburned propellant in the following shots. [13]

A noticeable sound involved also in discharging a firearm is the bullet hit sound that is largely dependent on the target. Hitting metal targets, breaking glass and even bullet striking flesh are reported to produce loud and distinctive sounds which may play a major role if the aim is to hide the fact that a shot has been fired during covert military operations. [7]

2.3. Elimination of noise

Work safety protocols demand that workers are provided with hearing protectors when the work place exposes them to loud noises. Hearing damage is not the only health hazard connected to loud noises. Sleeping disturbances, hypertension and heart diseases have all been linked to excessive noise exposure. Therefore the noise elimination has become increasingly important in engineering and everyday life. [5, 17]

Protection from noise can be achieved with several different ways when firearms are considered. The more traditional way to protect oneself from impulsive noise from firearms has been ear protection. Earmuffs, earplugs and active ear protectors are a common sight in firing ranges. Hearing protectors provide a good protection but the protection is limited to only a single person. When the aim is to provide protection for the surrounding environment, structural design and noise absorbing constructions must be considered. Noise walls, sound absorptive lining in firing shelters and foliage all provide noise absorption and protect the surroundings of firing ranges. Similar constructions are the noise walls near motorways which protect housing from the constant noise of traffic. [2, 7, 9]

Where ear protection provides aid for the shooter and people nearby and noise absorbing constructions protect the surroundings, suppressors provide these both. Limiting the sound exposure of a firearm produces benefits both to the shooter and the surrounding environment. Limiting a shooting range only to weapons with suppressors would provide a noticeably smaller safety area around the range as well as savings from noise absorbing structures. [2]

2.3.1. Protective equipment

Consumers have a wide range of personal protective equipment available to shield their hearing from excessive noise. Earmuffs and different kinds of earplugs ensure that everyone can find the best option for him- or herself. Some research has even been carried out for producing a noise helmet to protect against low frequency noise for military personnel and airfield operators who are exposed to intense low frequency noise. [7, 9]

Earmuffs are an effective protection against noise but they have their own problems. Concerning the good sides, earmuffs and earplugs suppress noise from all sources, not just the muzzle report as a suppressor does. They provide a good level of protection and are available in reasonable prices. Additionally with active earmuffs the loud noises can be cut off with only minimal loss of other sounds so communication problems related to standard ear muffs are avoidable. The drawbacks of earmuffs are that they may hinder the shooters ability to quickly acquire a good aim as large muffs collide with the stock of the weapon. Another drawback is that hearing protectors limit the hunter's ability to detect game by hearing. Even active earmuffs may distort the sounds of approaching game so that locating the source becomes hard. Another noticeable fact is that earmuffs don't provide any protection to the surroundings. Other hunters and any dogs involved in the hunt are still subject to the full noise of the discharge. [9]

2.3.2. Protection of the environment

When considering shooting ranges the noise pollution can be lowered with several ways. The shooting range can of course be located in remote areas to protect humans from noise and sometimes enclosing the range indoors can be used as well. Both are options when a new range is being founded but when improving existing ranges the options are fewer. Three main ways available at this point are using protective equipment, building noise walls and structures to capture the noise and finally the use of suppressors. [2]

It's considered that 65 dB is a reasonable sound level limit allowed in houses near shooting ranges. This means that the shooting range has either to spend considerable amount of money to build sound barriers or that a sufficiently large area around the range is reserved for the attenuation of shots. Another option is the use of subsonic loads and sound suppressors. With shotguns the use of suppressors and subsonic cartridges produces a suppression of -12 dB which doesn't compare well with rifle suppressors, but still manages to decrease the required space of a shooting range to 1/16th of the original as seen in **Figure 6**. This opens up a number of possibilities for new shooting ranges in more heavily populated areas. [2]

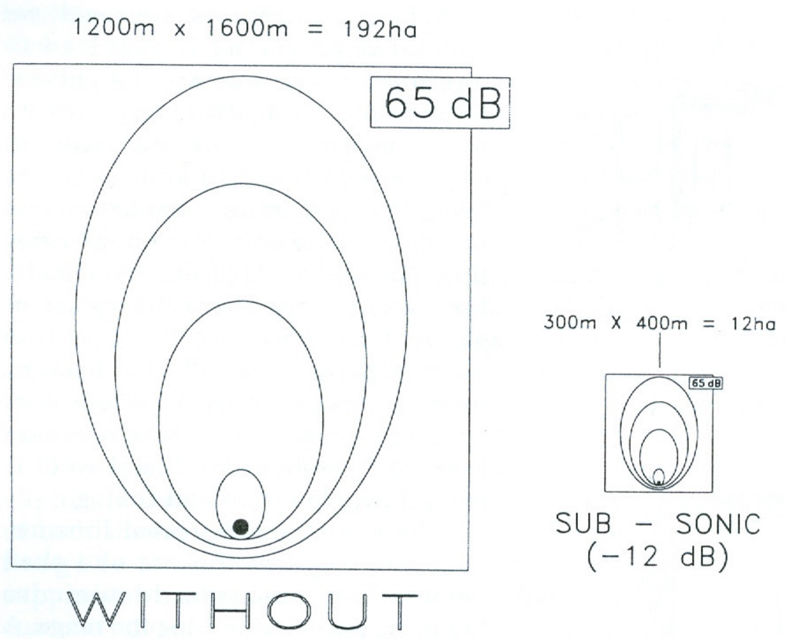

Figure 6 *The space required around a shotgun shooting range without sound suppression from suppressors and subsonic loads and with the suppression methods in use. [7]*

2.3.3. Noise damping structures in shooting ranges

Shooting ranges have different kinds of structures which influence the behavior of sound waves. Structures intended to protect the surrounding environment from shooting noise consist of noise walls, shelters, foliage, and other possible noise barriers. Noise walls usually surround the back of the range and act as safety measures and as noise control. The attenuation provided by a noise wall ranges from 5 to 10 dB near the range and from 0 to 7 dB within a kilometer from the shooting range. Within 20 meters from the shooter a shooting shelter provides attenuation of 3-15 dB, depending on the shooting direction and an attenuation of 0-4 dB within a kilometer. The effect of foliage on shooting noise is less consistent and rarely seen as an active attempt to provide attenuation. [6]

Structures intended to protect the shooter and possible trainers are seldom used in outdoor ranges and they mostly consist of absorptive surface materials used in shooting shelter walls and roofs. **Figure 7** shows a possible structure which could be utilized in shooting ranges to enhance noise attenuation. [7]

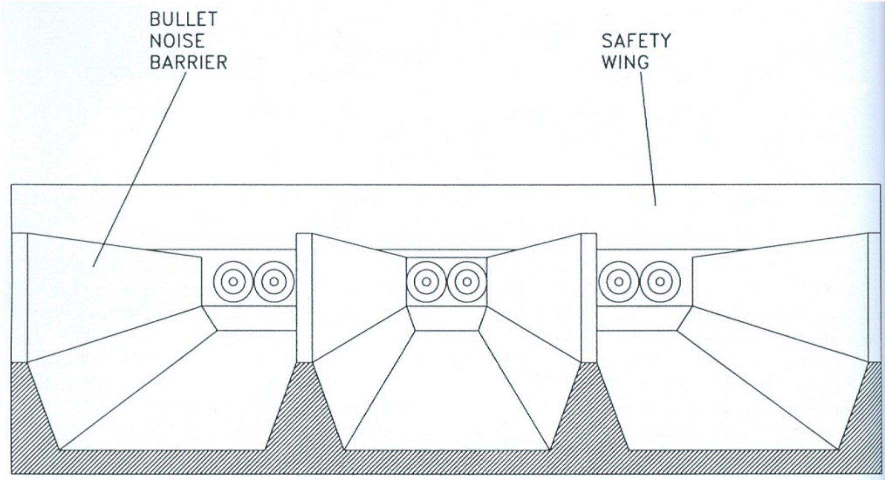

Figure 7 *Noise barriers for effective elimination of sound leaving the shooting range. [7]*

Shooting shelters provide protection from wind and rain as well as attenuate noise from the weapon fire. With unsuppressed weapons the shooting shelter extends the time for which the shooter and observers are exposed to peak sound pressures. Sound reflected from hard wooden or concrete surfaces increases the risk of hearing damage. Therefore ranges intended for unsuppressed weapons should take advantage of absorptive materials in the shelter roof and walls. This provides protection to both the participants and surrounding environment. Suppressed weapons benefit less from the attenuation of absorptive shelter materials. The peak sound pressure is lower and shorter in duration and main sound exposure results from the ballistic crack. **Figure 8** illustrates the difference. [7]

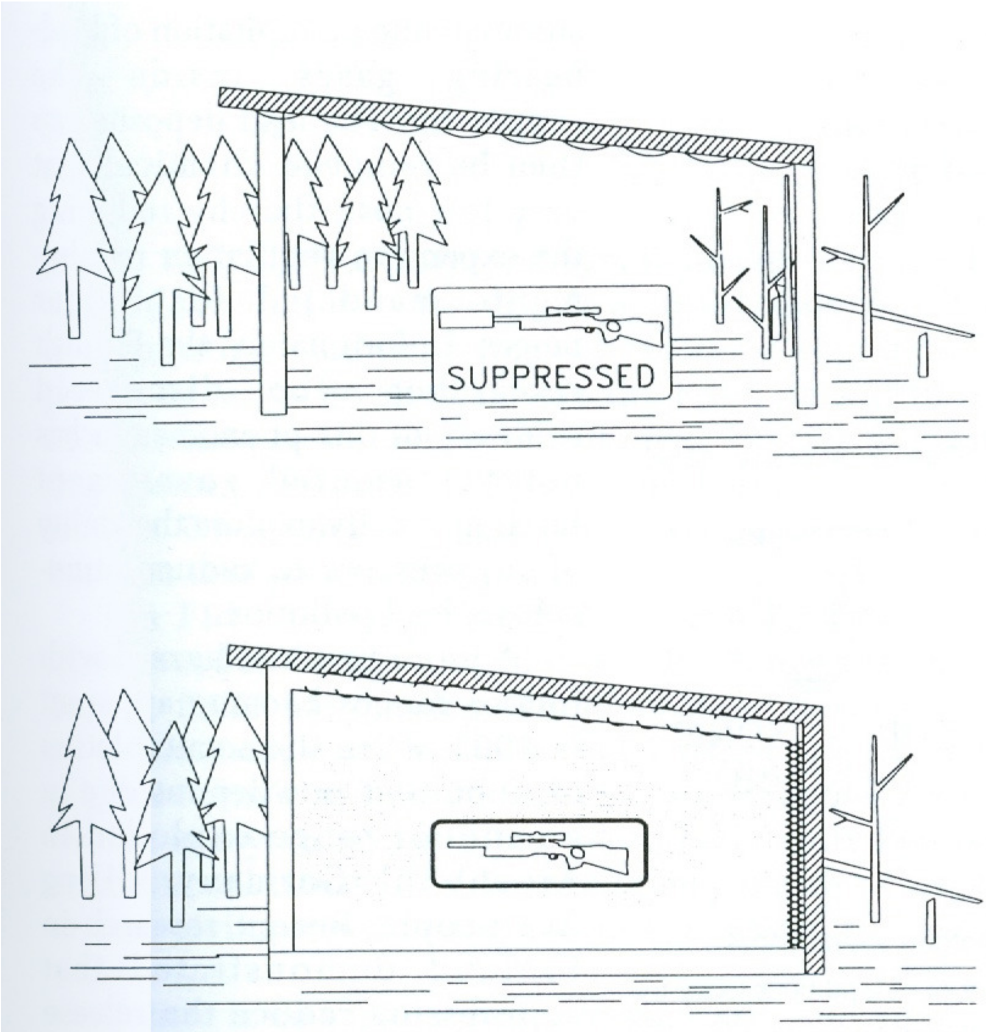

Figure 8 To reduce noise pollution the use of thick and absorptive materials is encouraged with unsuppressed weapons. With suppressed weapons an open structure with a roof is sufficient. [7]

2.3.4. Industrial sound suppressors

Suppressors found in industrial use like air ducts and car exhaust noise control share common features with firearm suppressors. Two main factors in industrial sound attenuation are absorbing materials and wave guidance. Absorptive materials are often porous with open cells, fibrous and possibly soft materials. Sound waves attenuate in such materials as pressure variations and gas viscosity turn coherent waves into turbulent flow and heat. Porous foam panels in concert halls are the clearest examples of the material. [5]

Wave guidance is the second major method for attenuation and more often seen with car mufflers and air ducts. Sound in wave guides like pipes and air ducts travels easily far, which is why almost every single air ventilation system has some kind of silencer or suppressor. Easiest way to provide attenuation is a sudden change in the duct cross section and in the following expansion chamber. This discontinuation divests energy form the sound wave and reflects part of it towards the source. Reflected sound waves interact and distort sound waves coming from the source and provide attenuation. [5]

A common acoustical structure found in acoustic design is the Helmholtz resonator. Helmholtz resonator is a structure where a larger chamber is connected to the rest of the system by a neck with smaller diameter. This kind of structure works as an acoustic spring and it can be used to identify sound tones and eliminate them. The most common example of a Helmholtz resonator is an open bottle when blowing gently across the mouth of a glass bottle. [5, 18]

The ideas behind expansion chambers and Helmholtz resonators can be seen in **Figure 9**. Car mufflers utilize expansion chambers to let sound waves reflect and cancel each other. The Helmholtz resonator is used in the muffler's resonator chamber which is tuned to attenuate certain frequencies and get the best effect on the most important part of the noise spectrum. [19]

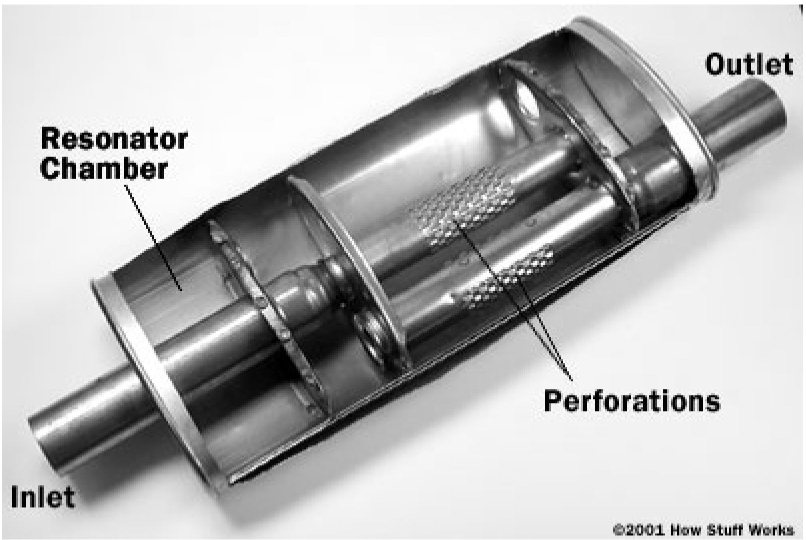

Figure 9 *A cut open view of a car muffler. [19]*

2.3.5. Suppressor structure elements

Firearm suppressors rely partly on same principles as other industrial suppressors. Diverting gas flow with different channels and prohibiting free flow of gas with baffle structures are among the most used methods. Common structure elements in suppressors are also expansion chambers, wire mesh, stepped or threaded surfaces and reflection discs. [7]

A baffle is in its simplest form a disc with a hole in the center for the bullet to pass through. The bullet seals the chamber behind it for a moment as it passes through the hole in baffle. Propellant gases following or overtaking the bullet are reflected and diverted. More advanced versions of baffles are conical in shape to further enhance the diversion of gases and may contain channels or grooves to utilize the gas flow against the expanding gas cloud. For example a gas stream may be diverted across the bullet path right behind the bullet to push the following stream into an expansion chamber. [7]

Expansion chambers are empty spaces inside the suppressor which provide the expanding gas cloud with space to consume its energy via expansion, heat transfer and turbulence. Especially reflex designs rely on large primary expansion chambers as the sleeve extending over the barrel allows free space. Expansion chambers also allow sound waves to reflect back towards the source for added attenuation and turbulence. [7]

Surface area increases heat diffusion between expanding gas and surrounding suppressor structure. Cooling down the propellant gas is one way to rob energy from the expanding gas and to provide attenuation. Wire mesh is a good element when surface area is needed and a wire mesh filling in expansion chambers is an element which has been seen since the earliest suppressor models. The same idea is behind fully threaded outer shells and stepped cone baffles where otherwise normal slanted wall is replaced with surface modification which increases the surface area available for contact with the gas. Additional effect found with modified surfaces is increase in turbulence. Turbulence forms circular flows within the expanding gas and plays a major role in sound attenuation. [3, 5, 7]

Some suppressors are designed to utilize additional medium for optimal performance. These are mostly seen with pistol caliber suppressors and are known as “wet cans”. The suppressor is filled with different kinds of liquid or foam substances which increase the heat transfer and sound attenuation. Wet suppressors can be designed to even smaller dimensions but their performance is less optimal if used dry. A negative aspect is that the substance might not always be available and also during discharge part of the liquid substance may end up on the shooter. Any hazardous liquids might pose a health hazard for the operator. [7, 20]

THE AIM OF THE WORK

The aim of the research project was to improve an existing suppressor design by replacing most if not all of the existing suppressor materials with lightweight alternatives which could still operate under the demanding conditions a suppressor experiences.

The search for alternative materials was conducted with the aid of a computer software designed for material selection. The main goal of the software was to provide multiple alternative materials from which the best candidates could be chosen for use in suppressor components. The final aim of the study was to test these components by building a prototype suppressor to be tested in live fire conditions to determine their final suitability.

3. SUPPRESSOR PROTOTYPES

The design of a new suppressor prototype was started on top of an already existing suppressor. The previous model was a reflex type steel suppressor with a robust design. The new prototype was aiming for lighter materials and structural solutions which would work with several materials. Particular interest was addressed towards carbon fiber composites and aluminum alloys for their light weight, mechanical properties and availability.

The design process started on the outer shell of the initial structure and worked from there inwards. New materials raised questions especially on joining the parts made from different materials together so that the whole suppressor would withstand the load. For example the high thermal expansion of aluminum might cause stresses and failure when combined with other materials as the temperature variations may be significant within the suppressor.

3.1. Structures and designs

First patents related to suppressors are dated to 1899. J. Borrensen and S. Sigbjornsen filed patents on expansion chambers and baffles, the same ideas which are still found in modern suppressors. Although the first patents were filed in 1899, even older attempts and designs of suppressors have been recorded. The first commercially successful suppressor was the Maxim Model 1908, developed by the Hiram Percey Maxim. [7]

Suppressors can be divided roughly into three groups by their structure. More traditional suppressors are attached to the end of the barrel and they extend outwards. This kind of suppressor usually consists of expansion chambers, baffles and in some cases wire mesh. There are several good sides in the design. For example, the suppressor is compatible with several different weapons with only minimal work as the barrel rarely limits the use. In some cases the barrel might even be shortened to retain the original handling characteristics of the weapon. The suppressor is usually easy to attach and several quick lock mechanisms are available for suppressors in this variety. The Maxim model 1910, one of the first commercial suppressors ever, in **Figure 10** and the more modern Vaimeco .30 SX in **Figure 11** are good examples of this category. The Maxim suppressor has a closed structure and any maintenance to the suppressor is very limited. The Vaimeco .30 suppressor is made of anodized aluminum which provides a lightweight structure with only a few detachable parts which enables easy maintenance. [7]

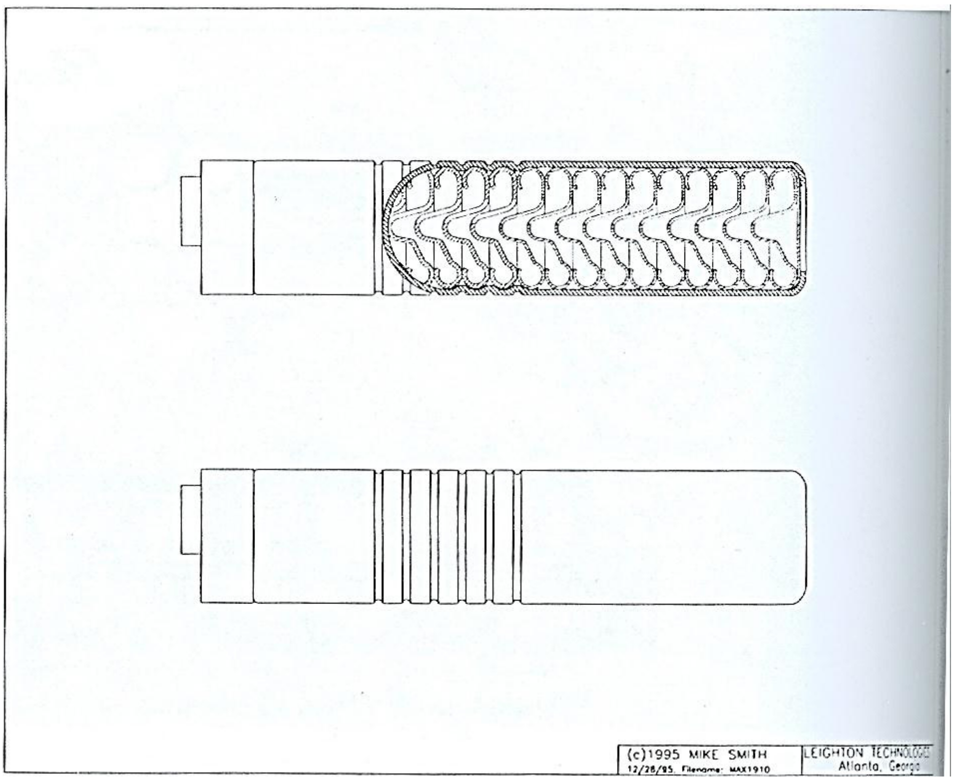

Figure 10 *A Maxim Model 1910 .44 suppressor for center fire weapons. [7]*

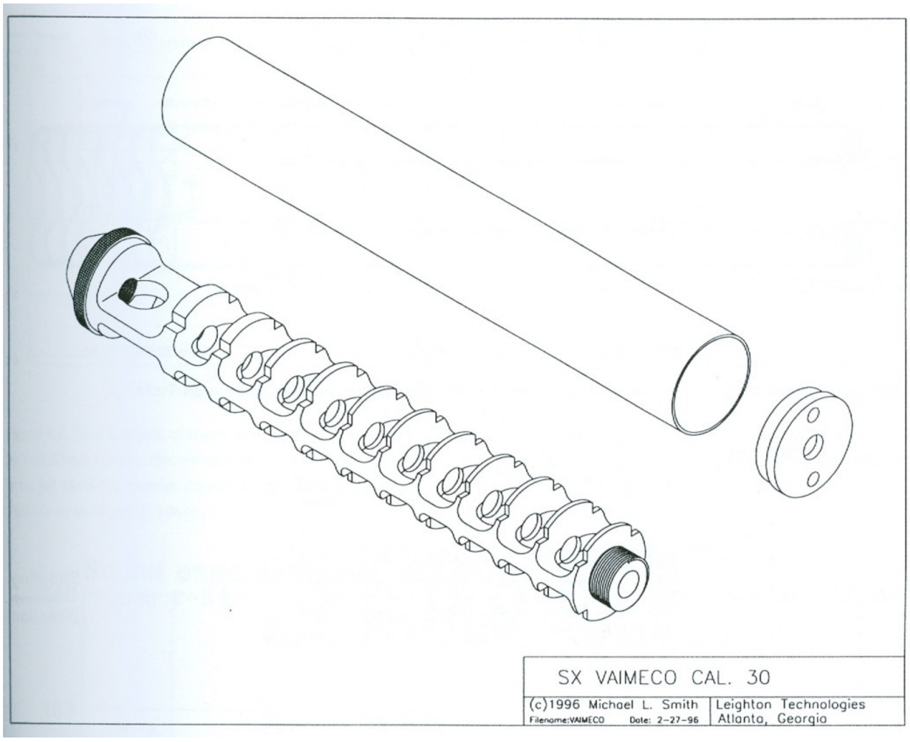

Figure 11 *Vaimeco .30 SX suppressor with a limited number of parts to enable easy maintenance. [7]*

Another traditional suppressor, the Hush Puppy used by U.S. Navy, uses polymer wipes for extra attenuation efficiency. The wipes are seen in **Figure 12** as parts with cross shaped cut in the surface. The wipes were efficient in providing suppression and slowing down the bullet to subsonic velocities. The drawbacks were the highly reduced accuracy and the limited lifetime of the polymer wipes. Polymer wipes have almost disappeared from U.S. civilian markets due to the problematic legislation which makes replaceable parts within suppressors extremely expensive. Disappearance from civilian markets also severely hinders research on the subject. Other countries with less limiting legislation have still continued the research to some extent. [7]

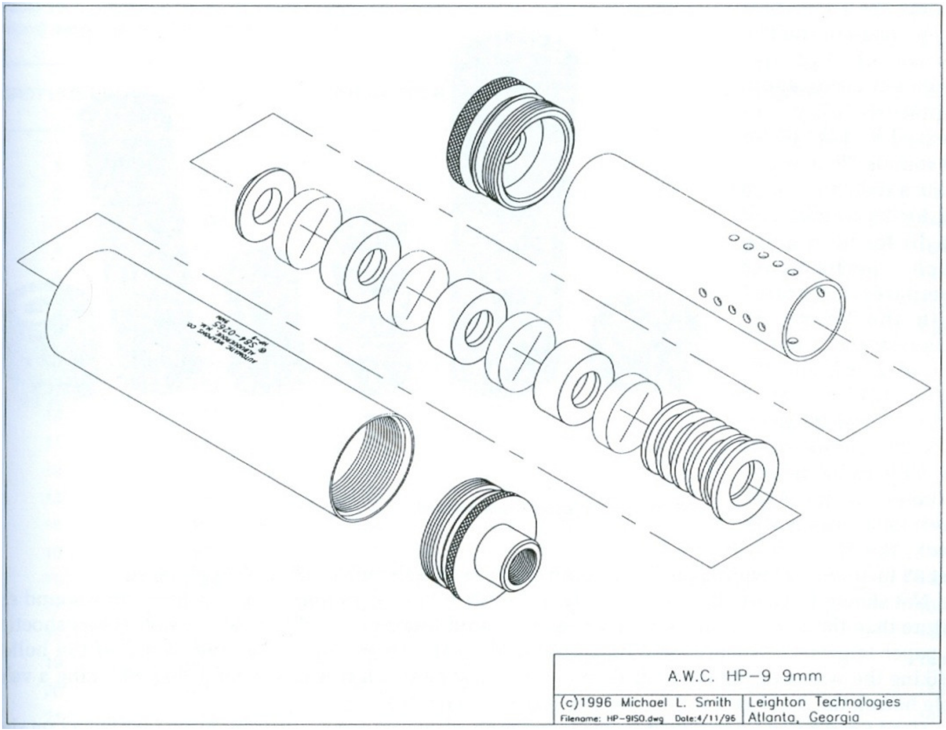

Figure 12 *A second generation clone of the "Hush Puppy" suppressor. [7]*

The second group is known as reflex suppressors. The idea is that the suppressor extends back over the barrel of the weapon like a sleeve instead of protruding forwards. This enables the use of massive primary expansion chambers and the shorter barrel length is easier to use and operate. Reflex designs also offer more durable and robust structures, as less stress is placed on the barrel due to the two attachment points for the suppressor. One point of attachment is usually utilizing threads at the end of the barrel similarly to traditional designs and the second attachment point is usually located at the back of the suppressor where it surrounds the weapon barrel. The BR-Tuote .50 suppressor seen in **Figure 13** is a good example of the reflex design. It consists of a large main expansion chamber and a small coaxial insert that plays the role of baffles. The insert doesn't provide the best possible sound reduction, but the main purpose of a suppressor on a .50 caliber rifle is to reduce the muzzle blast and recoil and to hide the muzzle flash instead of silence. The suppressed sound level is still around 161 dB. [3]

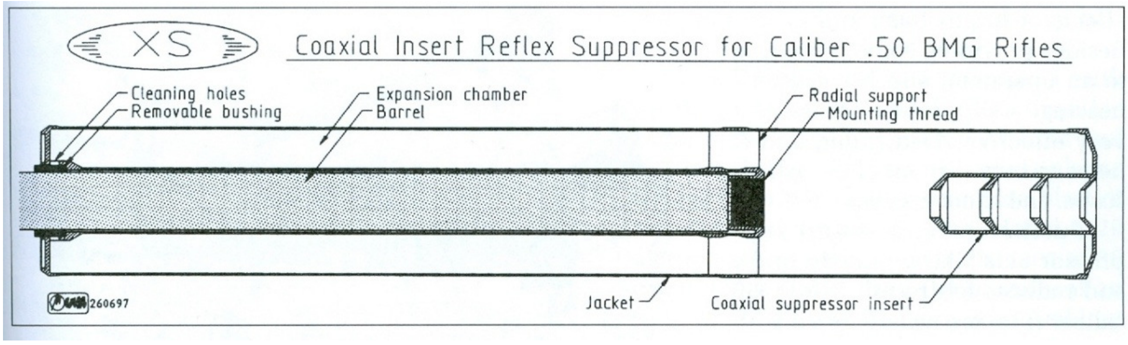

Figure 13 *.50 BMG caliber from BR-tuote consists mainly of a large expansion chamber and small baffles. [3]*

Another example of the robust reflex design is the BR-tuote TX8 seen in **Figure 14**. The steel structure offers durability and strength even under high stress situations like rapid fire. The construction is not meant for disassembly and any cleaning has to be done by submerging the suppressor in solvents. On the other hand, the steel structure requires very little maintenance. The TX-8 relies on large primary expansion chamber and on a limited number of baffles. The primary blast baffle is provided with a deflection cone that further disrupts the forward flow of expanding gases. [3, 21]

Figure 14 *A cut out of the Br-Tuote TX-8 reflex rifle suppressor attached onto a gun barrel. [21]*

The third suppressor group is known as integral suppressors. Integral suppressors are built into the firearm and require a lot more modifications to the weapon than the previous two groups. Integral suppressor design takes the idea of reflex suppressor and develops it further. The suppressor envelopes the entire barrel and becomes an integral part of the weapon. A weapon with integral silencer design cannot be used unsuppressed without further serious modifications. An integral silencer acts as a huge expansion chamber around the barrel. Several ports are often installed into the barrel itself so that expanding propellant gas could be diverted from the barrel. The bullet speed decreases significantly, all the way to subsonic velocities if needed. **Figure 15** shows the integrally suppressed rifle AWC R 10 to illustrate the design. The expansion chamber around the barrel is divided into two different chambers by a spacer in the barrel. The ventilation on the barrel reduces the pressure behind the projectile slowing it down to subsonic velocities and eliminates the ballistic crack. The large expansion chamber design also attenuates the muzzle report. The decrease in bullet velocity limits the number of usable cartridges for the weapon. This suppressor design could provide a net sound reduction of 28 dB. [7]

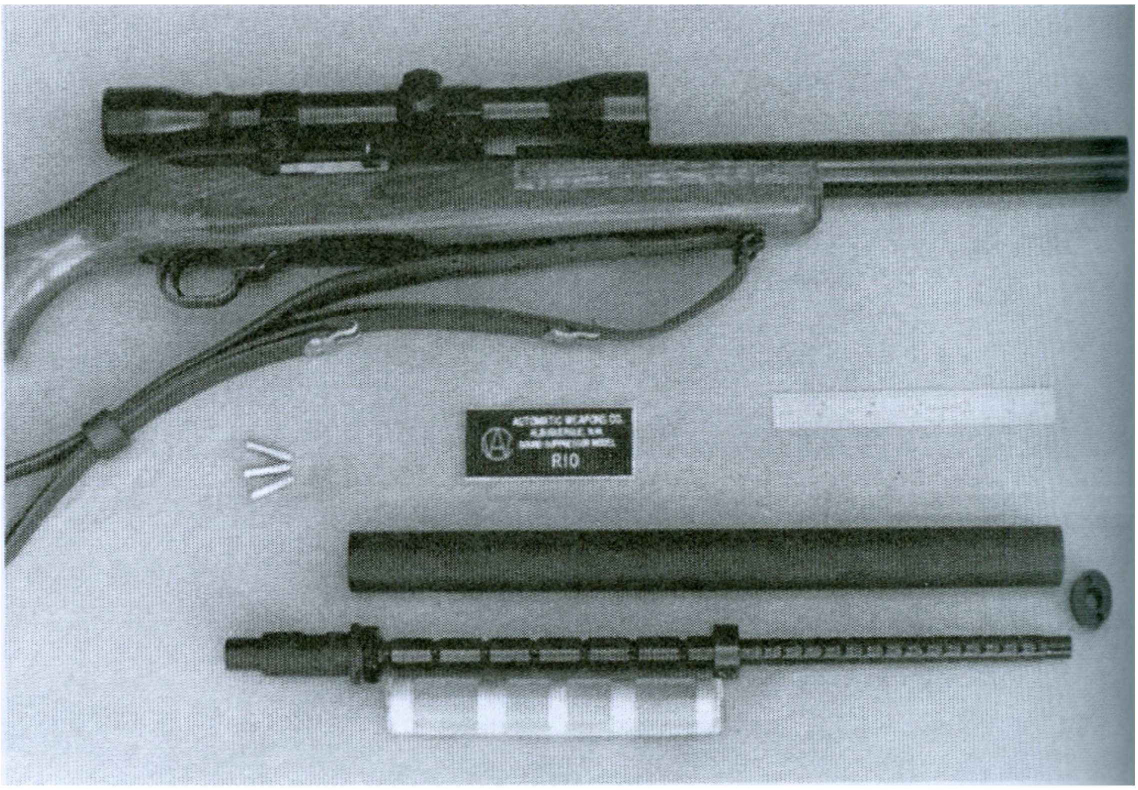

Figure 15 *The integrally suppressed rifle AWC R10 with modified barrel and stock to house the silencer sleeve. The modified barrel is at the bottom of the picture and the suppressor sleeve above it. [7]*

3.1.1. Initial structure

The design process started from an already existing steel-based design. The initial design was a reflex type suppressor with one main expansion chamber and seven smaller chambers separated with steel baffles. The baffles are fixed with welded support rods to the part attaching the suppressor to the weapons barrel. The design is sturdy and robust, but the maintenance possibilities are limited. The main disadvantage with the initial design was the weight. A steel suppressor weighing between 0.5 – 1 kg is a noticeable increase in the weight of the weapon, especially if it has to be carried over longer distances.

3.1.2. First prototype

The first prototype was designed primarily to test the carbon fiber strengthened polymer matrix composite as the outer shell material. The internal components were almost identical to the initial structure with only some exceptions to allow the attachment of the outer shell without altering the carbon fiber tube. The outer shell was a carbon fiber composite tube which was attached to the internal structure by compressing it between end caps. The first prototype can be seen as disassembled in **Figure 16**.

Figure 16 *The first prototype as disassembled. The internal structure was mostly unchanged as compared to the initial design, because the testing was focused on the carbon fiber outer shell. At the bottom is the internal steel structure and above it the carbon fiber outer shell and steel end cap.*

3.1.3. The second prototype

The second prototype consists of a carbon fiber outer shell with metallic inserts at both ends and of an anodized aluminum internal structure. Metallic inserts in the outer shell enable a wider variety of internal designs as there is no need to apply pressure to the outer shell from both ends for the suppressor to remain compact. The threaded metallic inserts are visible in **Figure 17**.

Figure 17 Metallic inserts of the carbon fiber composite outer shell in the second prototype.

Although the outer shell of the second prototype was finished when this was written, the internal structure was still under design. A design draft of the second prototype is seen in **Figure 18**. The aim of the design is to allow the disassembly without specialized tools for easy maintenance and the minimization of welding. The baffles of the design are single modules and replaceable to compensate the likely quicker deterioration of aluminum parts when compared with the original steel structure. The biggest challenges considering this design are how well the aluminum can replace the steel and the eventual problems with manufacturing the structure.

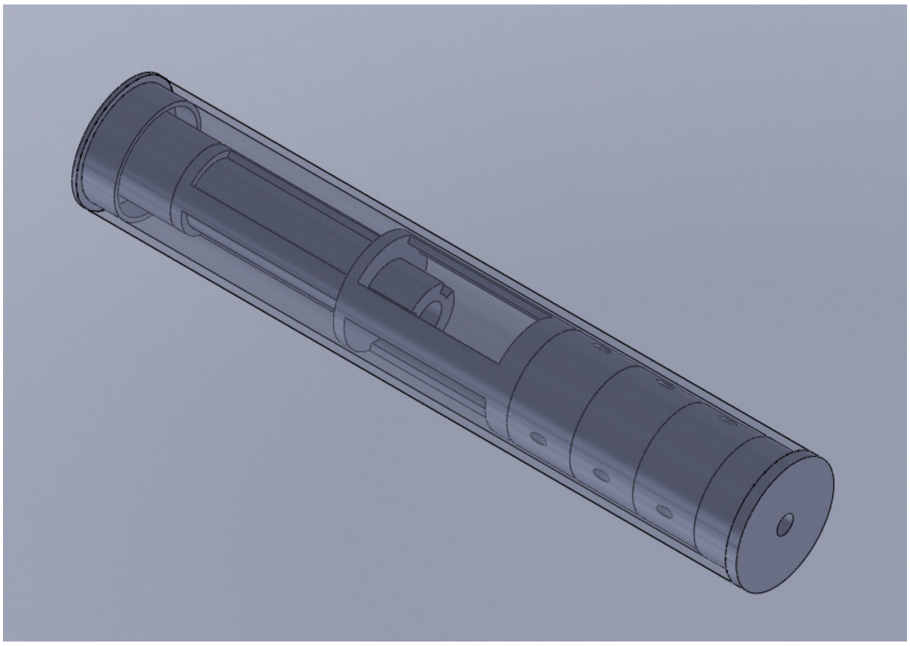

Figure 18 *A design draft of the second prototype.*

3.1.4. Future prototypes

The testing of the second prototype will show where the future development should be directed. If the structure of the second prototype turns out to be durable enough to work with rifle caliber weapons, the next logical aim would be to increase the sound damping properties. This could be achieved by modifying the shape and number of baffles and by increasing the size of the primary expansion chamber. Diverting a bigger part of the propulsion gas towards the back of the suppressor could also add to the damping effect.

3.2. Materials

The materials of suppressors play central role in the construction. Wrong material selection might result in poor performance, reduced service time or even in failure with serious consequences. Sudden changes in external conditions during discharge set a variety of requirements to the materials. Even when a material might otherwise be suitable for use in suppressors, the compatibility with other materials and fabrication problems may limit its usability. All these things have to be taken into consideration during the design process.

3.2.1. Material requirements

When a rifle caliber weapon is discharged the conditions inside and around the barrel and muzzle change rapidly. At 200 microseconds the bullet has already left the barrel and the propellant gases expand and accelerate to high speed. The temperature of the propellant gases flowing from the barrel can achieve levels as high as 1300 °K. The pressure of the expanding gas cloud can be as high as 60 MPa and the speed of the flowing gas and possible debris like unburned propellant is reported to be around 1000-

1400 m/s. It is clear that conditions like these set a wide range of requirements on the material which needs to endure in suppressor applications. [4]

The weapons used in hunting and outdoor shooting ranges are also exposed to rain, ultraviolet light, wear, collisions and other related conditions. The chemical composition of gunpowder residue and propellant gas might turn out to be hazardous for the materials.

3.2.2. Materials used in suppressors

The materials used in suppressors are dominantly metals. Easy access, reasonable price, wide variety of fabrication processes and durability are properties which have played a major role in the selection. The most common metals are stainless steels in suppressors for weapons using centerfire cartridges and aluminum in suppressors for rimfire cartridge weapons where the gas pressure is lower. The ease of fabrication and low weight of aluminum make it an excellent material in places where its mechanical properties are sufficient. With larger calibers, aluminum lacks abrasive wear resistance and high temperature strength to withstand prolonged use. [3]

Tests have been performed on the use of ceramic materials in baffles to utilize the abrasion and heat resistance of the material. Unfortunately the fragility and low thermal shock resistance have limited the use of ceramics. Rapid and intensive temperature variations and impulsive pressure shocks limit the use of more exotic materials like plastics. Therefore material research has focused into more specialized metals. Titanium has been found to work in suppressors and the only limiting factors for its wider use have been the price of the material and fabrication problems. [3]

Steel

Even though different materials are becoming more common in rifle caliber suppressors, steel still holds the dominant position. Easy fabrication, wide variety of different alloys and high strength properties still weigh much in the selection. For smaller manufacturers the low price of the material and wide availability may also play a great role. Drawbacks of the material are its density and weight. A suppressor made out of steel may weigh around 0.5-1 kg which is not much if the weapon is used for practicing shooting but a hunter rarely wants to carry any extra weight.

When used with sport shooting or during practicing a steel suppressor heats up rather fast. Even though the heat might not damage the suppressor it may still produce problems. A hot object produces optical distortions as the air above it heats up. This in turn may cause problems in aiming as the aim line is located right above the suppressor. Steels have a wide variety of alloys and modifications available for use. Most of the steels used in suppressors are of stainless type. Corrosion resistance provided by the chromium is useful if the weapon is used under wet conditions. [7]

Aluminium

Aluminum is used in suppressors for smaller caliber weapons. Aluminum itself is soft and has limited mechanical properties as compared to steels. In suppressors the materials are subject to thermal stresses, violent pressure variations and abrasive wear from unburned propellant particles and this shortens the life span of aluminum parts. Aluminum parts are usually anodized to grow a thick protective oxide layer on the surface. Aluminum may also create problems when used in combination with other materials as the thermal expansion of aluminum tends to be greater than that of many other materials used in silencers. This may create a problem when aluminum parts are tightly fitted inside other materials and the materials expand at different rates during heating. [3]

The benefits of aluminum include its good availability, light weight, cost efficiency and many manufacturing possibilities. Light weight becomes more important than extensive heat resistance or excellent mechanical properties, when the weapon is used, for instance, in hunting. Hunting situations rarely require extensive numbers of shots to be fired in close succession. Smaller thermal stresses enable the use of aluminum parts and provide a more pleasant hunting experience with less weight encumbering the weapon during travel and aiming.

Carbon fiber composite

Carbon fiber composites consist of a polymer matrix and carbon fiber particles or fibers for reinforcement. The material is strong of light weight and it is often seen in aerospace applications and in high end sports equipment. Anything from tennis rackets to airplane fuselages are made out of carbon fiber composites. [22]

Carbon fiber is used in suppressors mainly with pistol caliber weapons. This is because the polymer matrix in carbon fiber composites is susceptible against the combination of heat and mechanical stress and the peak temperatures and pressures stay lower with pistol caliber weapons. Continuous fire will cause melting of the matrix material and extensive deterioration of the matrix may result in serious damage to both the suppressor and the weapon. The benefits of carbon fiber composites come from the light weight of the material combined with good mechanical properties. [7]

The manufacturing process of carbon fiber composite materials and components introduces to the design of parts some limits, which the traditional metallic components can ignore. For instance, any shaving or grinding which damages the carbon fibers may result in a significant decrease in mechanical properties. This means that parts made out of carbon fiber composites must be manufactured as close to the final shape as possible to minimize the damage to the fibers during shaping. [22]

Titanium

Titanium is a light weight metal with a multitude of uses. Titanium and its alloys can be found in aerospace, chemical industry, high end sports equipment and even in medical applications. It is not uncommon for the head of a golf club or for a medical implant used in bone surgery to be made from titanium alloys. Good mechanical properties and excellent chemical properties combined with the light weight are the key features of the material. Titanium forms a passive oxide layer on the surface which makes the material inert under many demanding corrosive conditions. The drawback is the challenging manufacturing process. Especially hot titanium is highly reactive with the environment. Therefore titanium can only be melted either in inert atmosphere or in vacuum. The use of titanium in suppressors is gaining popularity, but manufacturing costs still keep titanium suppressors as a high end solution. [3, 23, 24]

Other materials

There have been studies on other possible materials for suppressor construction. Research on ceramic materials showed that more common ceramics tend to be too brittle to withstand the heat and pressure shocks and the abrasive effect of unburned powder, especially under rapid fire. Polymer materials have been used mostly as rubber wipes which the bullet punches through and as the matrix of composite materials. The rubber wipe technology had adverse effect on bullet velocity and accuracy but provided excellent damping effect. The drawback was that the wipes wore down in 10-20 shots. Composite materials have been mostly limited to carbon fiber composite outer casings in pistol caliber suppressors. [3]

3.2.3. Search for alternative materials

The search for new alternative materials for suppressors requires either clear knowledge on the conditions the materials need to withstand or knowledge on several materials that are already used in the application. With exact requirements the search for possible materials for the application becomes easier. If the requirements are not definite and there is available only a list of materials already found, the process becomes more challenging, as the requirements are formed by finding properties common to the known materials and by defining which of these properties are critical for the application.

The criteria used for materials in suppressor applications are dependent on what kind of firearm the suppressor is intended for. A .22 caliber pistol suppressor doesn’t require as high strength and hardness as a .308 caliber suppressor for a hunting rifle due to the fact that the gunpowder load and pressure of the propellant gases are smaller. Even higher requirements are placed on the heat and abrasion resistance of the material used in a 7.62 assault rifle suppressor which is subjected to rapid fire. With lower requirements comes a broader pool of materials to choose from.

The suppressor on which this study concentrates is meant for hunting and target practice weapons of possibly .308 caliber. This sets definite strength requirements on the material due to the high pressures involved. Hunting weapons rarely require high service temperature from the suppressor material as the number of shots fired in a hunting situation rarely exceeds three to four shots. Zeroing the weapon or practice shooting might cause some heat accumulation, but long intervals between shots also reduce the effect of heat shock which is dangerous for many brittle materials like ceramics.

Material selection software

New materials were searched for with the Cambridge Engineering Selector (CES) software. The software compares given requirements to a database of materials and rules out materials which cannot fulfill the set requirements. The selection process was twofold. First part of the process involved finding a set of requirements which accepted materials which are known to work with suppressors and ruled out materials which would not withstand the preset circumstances. The second part was to explore the material groups the software recommended for the application and to see which of them were viable and interesting for further research.

The CES software offers two options for filtering and selection of materials. Filtering based on values and filtering based on graphical selection maps. The value based limits can be used to define such characteristics as resistance to oxidation in sea water or resistance to ultraviolet radiation. Graphical material selection maps are more versatile tools where the user defines one or two material properties that act as axes of the selection maps. The software then plots different material groups on the map according to their material properties. A larger size of a material group means more variance on the material properties of the select material group. The user is then able to define certain areas or parts of the selection map that fulfill the needed requirements.

In this study the desired materials were selected by first using a value based filter to define some ground requirements the materials should pass and after that the remaining material pool was further defined with a series of material selection maps. Each selection map removed a number of materials from the pool of available materials which could not fulfill the needed requirements. The most common way to use the selection maps in this study was to plot a map of two defining characteristics and then choose two materials which were known to function in suppressors and draw a limiting line between these two materials. Materials which fell on the wrong side of the selection line were eliminated from the pool of available materials. To clarify the selection process, the areas which were excluded from material pool are colored light red on the selection maps.

Chemical and thermal requirements

The search for new possible materials began with defining some lower limits for environmental resistance which would not rule out any materials already found in use with suppressors. Finally a combination which required reasonable resistance from the materials without ruling out viable materials was found. The average resistance requirements to flammability and corrosion resistance in fresh water and sea water were set and less strict requirements were placed on wear resistance, oxidation at 500°C and the resistance against organic solvents. Higher resistance to oxidation would have been preferable, but under closer examination this did not form a bigger problem. Oxygen content within the suppressor decreases when the weapon is discharged as the propellant gas replaces fresh air. Therefore high temperature oxidation is less likely to occur.

The next requirement for candidate materials was the temperature which the materials would have to withstand under normal operation. Propellant gases reaching 1000°C gave the theoretical maximum limit. This, however, was a too strict requirement as under normal operation a hunting weapon suppressor would not face rapid fire and the suppressor material would require very extensive use to reach the same temperature as the propellant gases. Solution was found by finding a limit which accepted most materials seen in suppressor applications. The limit was set to 180°C. The selected temperature limit and maximum service temperatures of different materials are shown in **Figure 19**. Known suppressor materials were highlighted to show how they relate to each other. Steel obtained a clear advantage to the other materials when the heat resistance was considered.

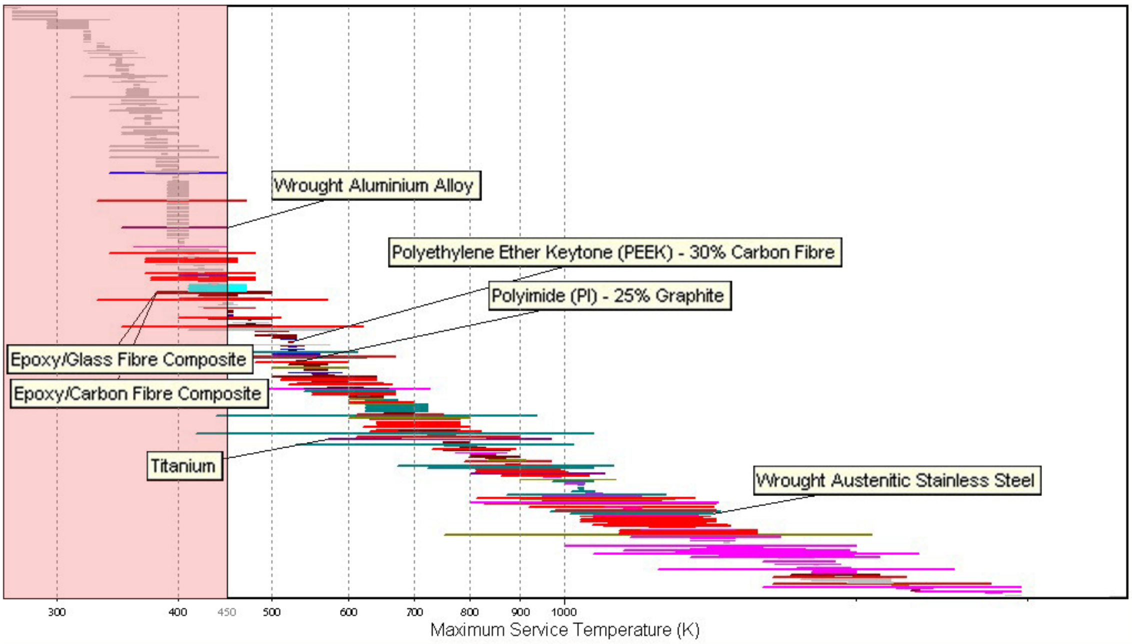

***Figure 19** Selected maximum service temperature range and materials known to be used with suppressors applications. [25]*

Heat resistance was not the only thermal demand which the material needed to fulfill. Many ceramic materials, for instance, meet the 450°K requirement but would still not work properly under real conditions. This had been established by previous researchers as the rapid temperature changes and abrasive wear managed to demolish tungsten carbide inserts in suppressor tests with rapid fire weapons [3]. A way to describe a materials ability to withstand rapidly changing temperatures was found by considering the thermal shock resistance. Thermal shock resistance is best defined as the relation between the normalized strength and the linear expansion coefficient of a material. Materials that break easily from thermal shocks have a high linear expansion coefficient and small normalized strength. In other words the material distorts considerably under thermal strain but cannot withstand the strong internal stress caused by this distortion. The internal strength is dependent on different properties with different material groups. Metals and polymers are defined by their ultimate tensile yield strength, ceramics by their modulus of rupture and composites by their tensile strength. Different properties are used as the different material groups experience failure different ways. Whereas brittle ceramics crack and composite materials tear from delamination or matrix failure, metals and elastomers deform until failure occurs.

However, the differences in thermal shock resistance are rather small between the materials under scrutiny for suppressor applications. Only ceramics and ice would be excluded if thermal shock were used as a filtering factor. Instead of thermal shock a better factor for thermal stability was found from thermal distortion. This is best described using the material properties of thermal expansion and thermal conductivity. High thermal expansion produces strain in the material as temperature changes, whereas high thermal conductivity levels out the temperature variations faster through the material. With high thermal expansion and low thermal conductivity the material expands and contracts strongly as temperature increases, but the strain is limited to local areas. This leads to significant internal stress states. Low thermal expansion and high conductivity leads to smaller changes in dimensions even with large temperature variations and the changes are spread more evenly. Consequently the internal stresses stay at minimum. A filtering relation between these two factors was found by using materials already found in suppressors as reference. The division between materials which seemed plausible alternatives for their thermal distortion resistance is shown in **Figure 20**. The dividing line filtered materials with high thermal expansion and low thermal conductivity out of the material pool. The dividing line was set to include both epoxy/glass fiber composites and polyimide material groups, but exclude material groups with worse thermal distortion properties. The materials that were excluded are the ones that located in the light red area. Materials known in suppressor applications are highlighted in the picture. Material groups marked with grey have been filtered out in previous limiting stages. [3, 26]

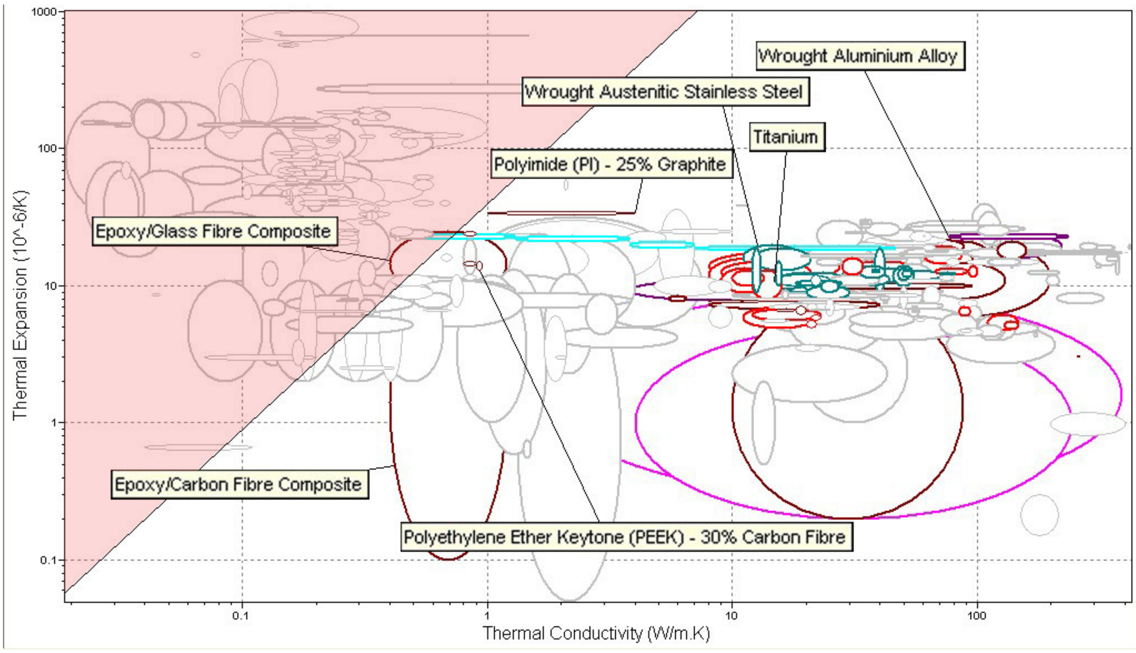

Figure 20 *Thermal expansion versus thermal conductivity of materials. The highlighted materials are known to be used with suppressors. [25]*

Mechanical requirements

After the thermal properties were used for filtering, mechanical properties became a topic of interest. Stiffness and impact resistance were the first mechanical properties required from the materials. High stiffness was needed to ensure that the expanding propellant gases would not distort the structure too much to block the projectile path at any point. The blocked path would have resulted even in the best case in some degree of damage to the suppressor structure and in a clear loss of accuracy. At worst the blocked bullet path could have led to explosive failure of the suppressor and damage to both the weapon and the shooter. Impact resistance ruled out materials which are too brittle to withstand rougher circumstances experienced in hunting trips as well as the blast wave of the propellant gases. Impact resistance is best described in this kind of application by comparing materials fracture toughness to its Young’s modulus. High Young’s modulus relates to stiffer materials and high fracture toughness coefficient relates to material’s ability to withstand fracturing stress. **Figure 21** shows how this relation was used to filter out materials too susceptible to impact fractures. Known suppressor materials are highlighted and named in the figure. The dividing line was drawn so that material groups Polyethylene Ether Keytone and Wrought Austenitic Stainless Steel would be included but materials with worse relationship between fracture toughness and Young’s modulus than these two were excluded.

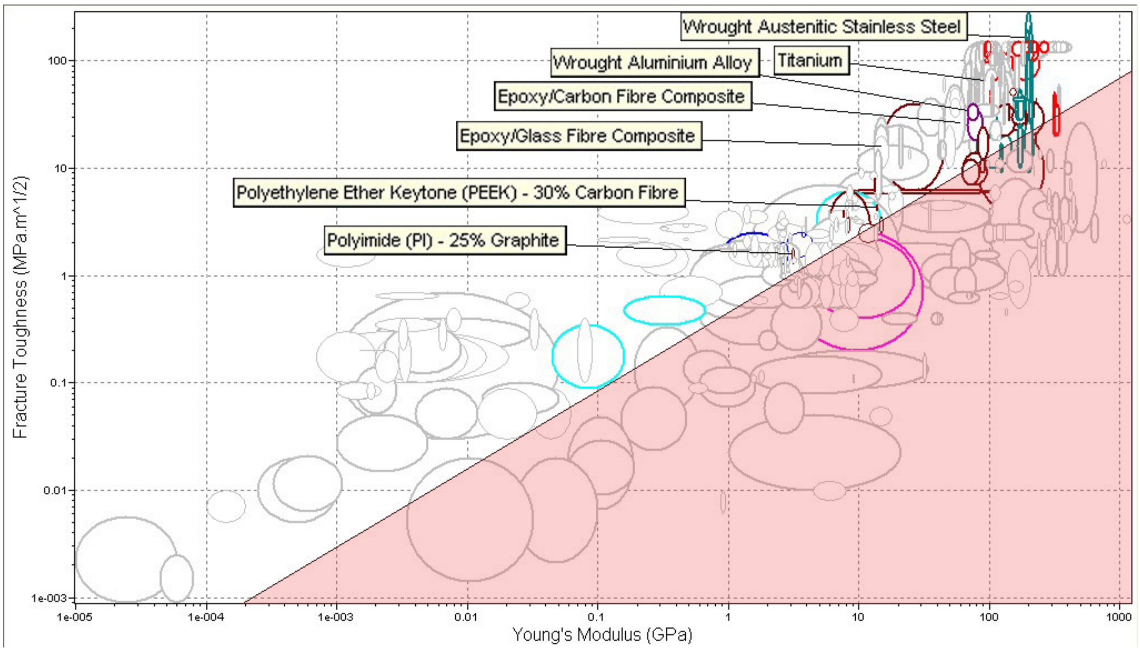

Figure 21 *Fracture toughness versus Young's modulus describing materials ability to withstand impact loads. [25]*

Stiffness of material is tied to its Young's modulus which describes the amount of strain produced by certain stress. Stiffer materials deform less under stress and have a higher Young's modulus. This in itself may not be sufficient when the application is looking for stiffness with minimal weight. Mass sensitive high stiffness applications therefore prefer to use the relation between Young's modulus and material density to find optimal materials. This relation was used in **Figure 22** to filter materials that wouldn't provide enough stiffness or would require too much weight to produce good results. The materials used as anchor points for dividing line were Polyimide and Wrought Austenitic Stainless Steel.

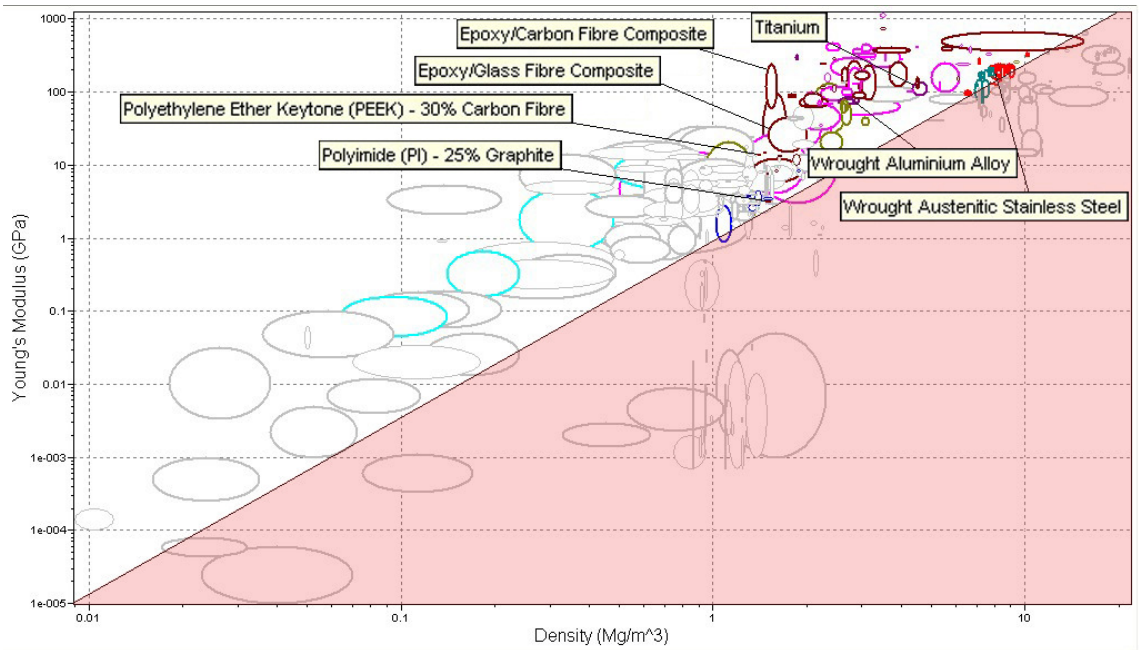

Figure 22 *Material stiffness represented by Young's modulus versus material density. [25]*

After applying the cumulative list of limiting filters to all materials which were in the CES database, a pool of 72 materials remained. The alternatives could be divided into smaller groups. Steels and cast irons, polymer matrix composites, aluminum alloys, high temperature superalloys, titanium alloys and nickel alloys formed the largest groups. The next filtering operation was to consider the possible costs and availability of the materials. For example aluminum fiber within aluminum matrix may provide the needed properties but the costs and availability ruled the material out of the pool.

The filtering process for removing the most expensive and exotic materials out of the pool as they would not be viable options for a commercial product due to their high price is shown in **Figure 23**. The limiting price was set to around 60 GBP (the program uses pounds as the default currency) per kilogram. The price versus kilogram comparison is not the best one to rank the materials for viability as the density and other properties should also be considered before any ranking is reasonable.

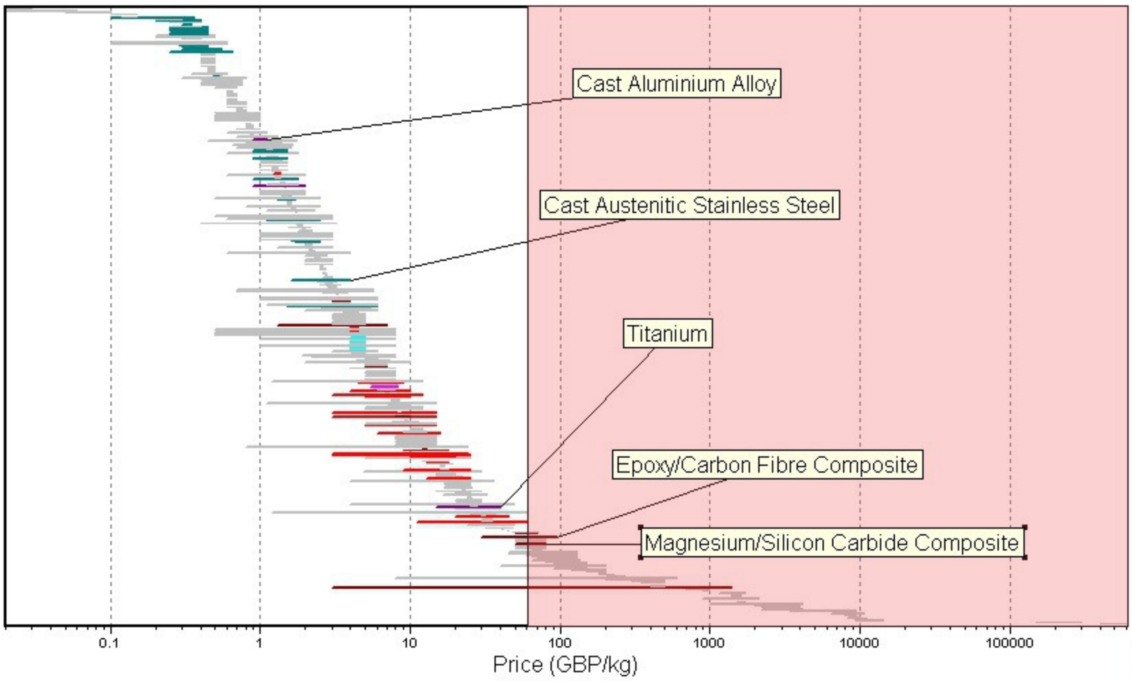

Figure 23 *Price per kilogram-filtering aims for removing too exotic alternatives out of the material pool. [25]*

After filtering out most exotic alternatives, a pool of 64 material groups remained. The pool of interesting materials could further be reduced by removing the material groups that were already used with suppressors as the intention was to find new alternative materials. This took out many aluminum alloys and steels, carbon fiber composite with traditional epoxy resin and titanium.

The remaining material groups worth of closer inspection included aluminum bronze, aluminum/silicon carbide composite, nickel tungsten alloy, chromium nickel alloy, cobalt superalloy, zirconium of several grades, nickel alloys, magnesium/silicon carbide composite, molybdenum alloys and polyimide graphite composite.

Filtering results

The CES software provided also data sheets on material properties which provided an opportunity to compare candidate materials with each other with more precision. The following material descriptions and properties were provided by the software for the materials listed above.

Aluminum bronze is a copper-aluminum alloy. It is used where high strength is needed in combination with corrosion resistance. The alloy is found in marine and chemical applications, pumps, valve gears, chain condensers and heat exchangers for acids and salts. The benefits would have made the alloy a viable alternative, but the density of the material which is only slightly smaller than that of cast austenitic steel yielded the same problems that the original suppressor had. Weight savings would be only minimal, if steel were to be replaced with aluminum bronze as the suppressor material. The material could be considered for use in selected parts like the first baffle which takes majority of the wear and strain. The formability and welding properties of aluminum bronze would also limit its use. Aluminum bronze parts are usually cast and the casting process of the material is demanding.

Aluminum/silicon carbide composite is a metal matrix composite which means that the material has an extremely wide price range and a wide variety of compositions. The material is used in electronics packaging, pistons, engine parts, mountain bike frames and precision instruments. The ceramic silicon carbide is used to counterweigh the high thermal expansion coefficient of aluminum and it can be used to tailor the expansion to a specific range, if needed. Otherwise the material is stronger than aluminum and has better mechanical properties. Unfortunately the low maximum service temperature and limited ductility makes it unsuitable for suppressor application.

Nickel alloys are found in applications where high heat resistance and oxidation resistance are needed. Nickel alloys like Inconel are used in furnace shields, gas turbines, combustion liners, chemical plant hardware and also in suppressors. Inconel blast baffles are found in some high end suppressors where steel has not been sufficient to withstand the circumstances, like in rapid fire weapons. Density which is comparable with steel limited its viability to anything else than single parts like primary blast baffles for this research. [3, 27]

Cobalt superalloys are alloys used in high temperature applications with cobalt as the main constituent element. They are found in aerospace engines, turbine blades, afterburner parts, furnace parts and combustion chambers. Excellent chemical resistance and mechanical properties would have made them viable for applications like suppressors. The major drawback of the material group was the high density. When being even heavier than steel, there would have been no point in using the material in larger extent. Even use in smaller parts would have been unreasonable, as less dense and cheaper alternatives were available.

Zirconium is in its pure form a transition metal, but rarely used as unalloyed. Zirconium alloys have excellent chemical properties and are used with chemical processing equipment, heat exchangers, pipes and pumps. Small trace particles of zirconium can be a fire hazard and toxic if ingested in large quantities. Zirconium has limited weldability and can be welded only to titanium, vanadium and niobium. For this application the limited possibilities of obtaining and joining zirconium parts formed a problem. Zirconium is lighter than steel but still not light enough to be considered for major components.

Magnesium/silicon carbide composite is in some respect similar to aluminum/silicon carbide composite. Magnesium-based composite has slightly better mechanical properties and is lighter than the aluminum-based composite, but it has slightly weaker thermal properties including maximum service temperature. Magnesium/silicon carbide composite can be found in aerospace applications, pistons, rods and rocker arms, even in special horse shoes. The material was an interesting competitor for aluminum in major structural elements for suppressor applications even with the high price of magnesium composites. The weaker thermal properties would have required separate testing before anything definite for its usability could be stated.

Molybdenum alloys are extremely hard materials, used with high temperature applications. Molybdenum is found in nuclear reactors, die casting cores, radiation shields and in aerospace parts. Excellent mechanical and chemical properties are hampered by the high density of the material, which is around 20-25 % higher than that of steel. Molybdenum is considered highly toxic which also limits its use. For this study molybdenum could have been considered only in minor parts and even there lighter alternatives would have been available.

Polyimide carbon is a carbon fiber composite with a polymer matrix designed for higher temperature applications. Mechanical properties of polyimide matrix and more traditional epoxy matrix composites are somewhat similar. The difference comes from better thermal properties. Maximum service temperature difference between the two carbon fiber composites is at least 10% in favor of the polyimide matrix composite. All in all the carbon fiber composite with polyimide matrix was deemed as an interesting material for further studies.

4. PROTOTYPE TESTING

Suppressor performance testing usually focuses on measuring the sound attenuation which they provide. This measurement is performed at specific places around the weapon during discharge and usually more than one microphone is used in order to get a more complete picture on the propagation of the sound impulse around the weapon. Tests are also performed with only a single microphone, but these give only a limited description of the suppressor performance. The tests usually follow the procedures defined in U.S. Army standard MIL-STD-1474C to produce reliable and comparable results.

The typical placing of microphones is shown in **Figure 24**. The use of multiple microphones provides a more complete picture on the performance of the suppressor. The most important microphone placement is right next to the shooter (A), to measure the sound pressures the shooter's ear is subjected to. Microphones located at the back (E) and to the side (D) of the shooter show how the surroundings are affected by the discharge noise. Usually strongest damping is found in the direction directly behind the shooter (E). The side microphone (D) measures how a fellow shooter in a firing range might observe the discharge. Finally the microphones at the front of the shooter (B and C) provide info on how the attenuation in the frontal sector is affected by the suppressor. The frontal sector is subject to greatest sound pressure levels during discharge and suppressors rarely can influence these levels to any great extent. This is a result of the bullet flight noise becoming a dominant sound source. [7, 28]

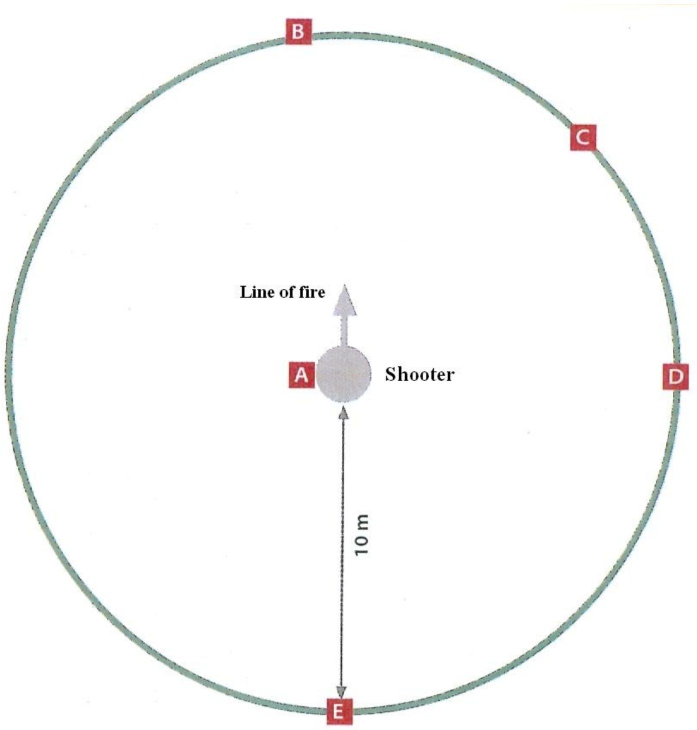

Figure 24 *A schematic presentation of the usual placement of microphones during the measurement of suppressor performance. [29]*

Sound pressure level measurement is often connected to occupational safety, where the way by which the human hearing reacts to different sounds plays a great role. The different audible range of varying frequencies has led to the development of different weighing systems seen in **Figure 25**. The weighing systems are basically a set of filters which modify the actual sound impulse by both amplifying some frequencies and suppressing other frequencies. The weighing systems are used to simulate how the human hearing interprets the noise of different frequencies under different circumstances and they are used in sound measuring implements.

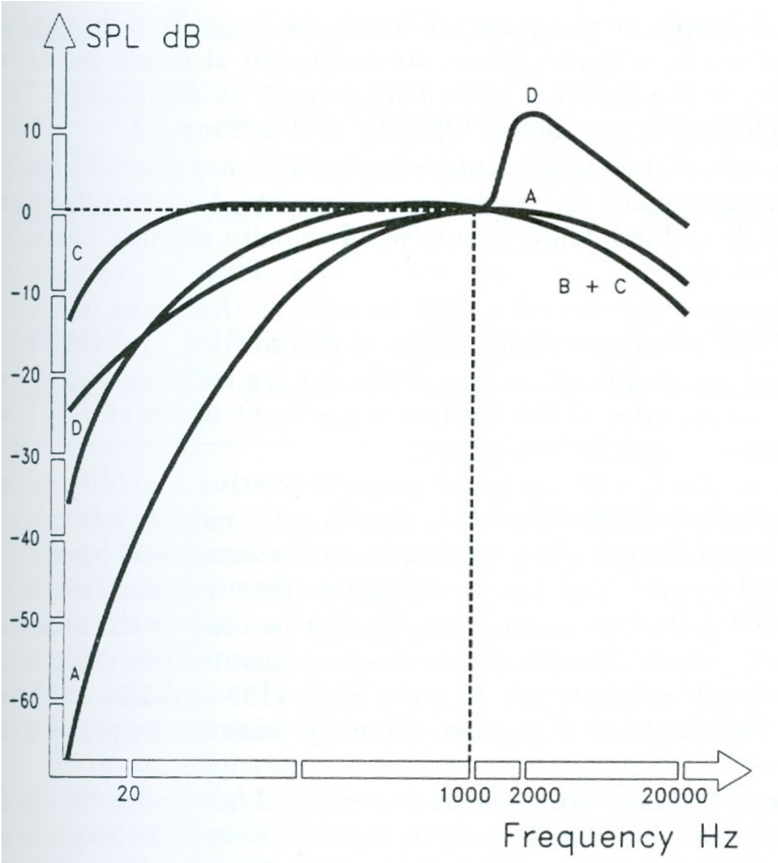

***Figure 25** Different weighing systems used with sound level measurement. [7]*

The human hearing is most sensitive around the 1000 to 2000 Hz frequency range which is evident in **Figure 1**. Therefore any noise outside that range would require more sound pressure for the human ear to react to it. The A-weighing simulates this by damping any noise outside that range. As the A-weighing is best interpreting the human hearing it is the most commonly used system with occupational safety measurements. C-weighing provides less attenuation of low frequency noise and it is also often seen in sound measurement equipment. When measuring suppressed weapons, the C-weighing is often used to provide a better idea on the effects which a specific suppressor has on the weapons sound signature. B-weighing plays a middle ground between A and C and is somewhat rare in sound measurements. D-weighing can be seen from time to time but is more closely related to the measurement of aircraft noise and it is not a relevant filtering system in this case. [7]

4.1. Testing equipment

Available measuring equipment form a significant factor in the accurate measurement of sound characteristics of silenced weapons. Normal unsuppressed hand weapon sound characteristics are measurable with a large variety of equipment as long as they can withstand the sound pressures involved.

A suppressed weapon signature on the other hand forms an additional challenge to measuring. The peak sound pressure of a suppressed weapon is considerably shorter in duration than that of an unsuppressed one. This requires that the used measuring equipment has to be fast enough to react to the short impulse with sufficient accuracy.

The reaction time is best represented by the rise time capability. A rise time of 20 microseconds for the whole system is deemed as necessary to achieve reliable readings. Slower rise time means that the peak pressure is long past the microphone before the system even responds and this might yield as large as a 10dB difference in readings. [7]

4.2. Suppressor test

Originally this study was intended to contain several live firing tests which would concentrate on the performance of materials under firearm suppressor conditions. Unfortunately only one test was managed to carry within the time limits of the work.

4.2.1. Real fire test

The first prototype was tested in an indoor shooting range. The range was built within a cave and the range itself was long and narrow. The test arrangements were not meant for measuring the sound damping abilities of the suppressor, but to test the endurance of the carbon fiber outer shell. The suppressor and the weapon were fixed to a shooting bench and closed into a chamber where the weapon could be discharged and observed behind a safety glass.

The first prototype raised suspicion on whether it could withstand normal firearm conditions as the epoxy matrix is not a material commonly seen in high temperature and pressure applications. The aim of the first test was to find out whether carbon fiber composite could be used as outer shell material in rifle caliber suppressors. In order to test this the suppressor was first subjected to conditions which a normal hunting weapon suppressor might face and after that to conditions which far exceed those circumstances to find out how much the suppressor would really endure. The first prototype was attached to a test weapon, which in turn was attached to a test firing bench. The first test was conducted with a RK62 7.62 caliber assault rifle. The test began with two groups of four single rounds and one group of ten single rounds, which were followed by the visual confirmation of the outer shell integrity. A hunting weapon suppressor might go through such conditions during zeroing or target practice with the exception that hunting weapons rarely hold clips larger than 5 shots.

As consecutive single shots proved to have no visual effect on the carbon fiber material it was decided that the material integrity and endurance would be tested under rapid fire circumstances. As normal live fire circumstances did not show any deficiencies in the suppressor, the test continued by testing abnormal circumstances such as continued short burst fire. A clip of 30 rounds which was fired in quick bursts of two to three shots proved that the outer casing of the suppressor was not sufficiently tight as propellant gas leaked between the top cap and the outer shell. This leakage was strong enough to cause damage to the carbon fiber composite shown in **Figure 26**.

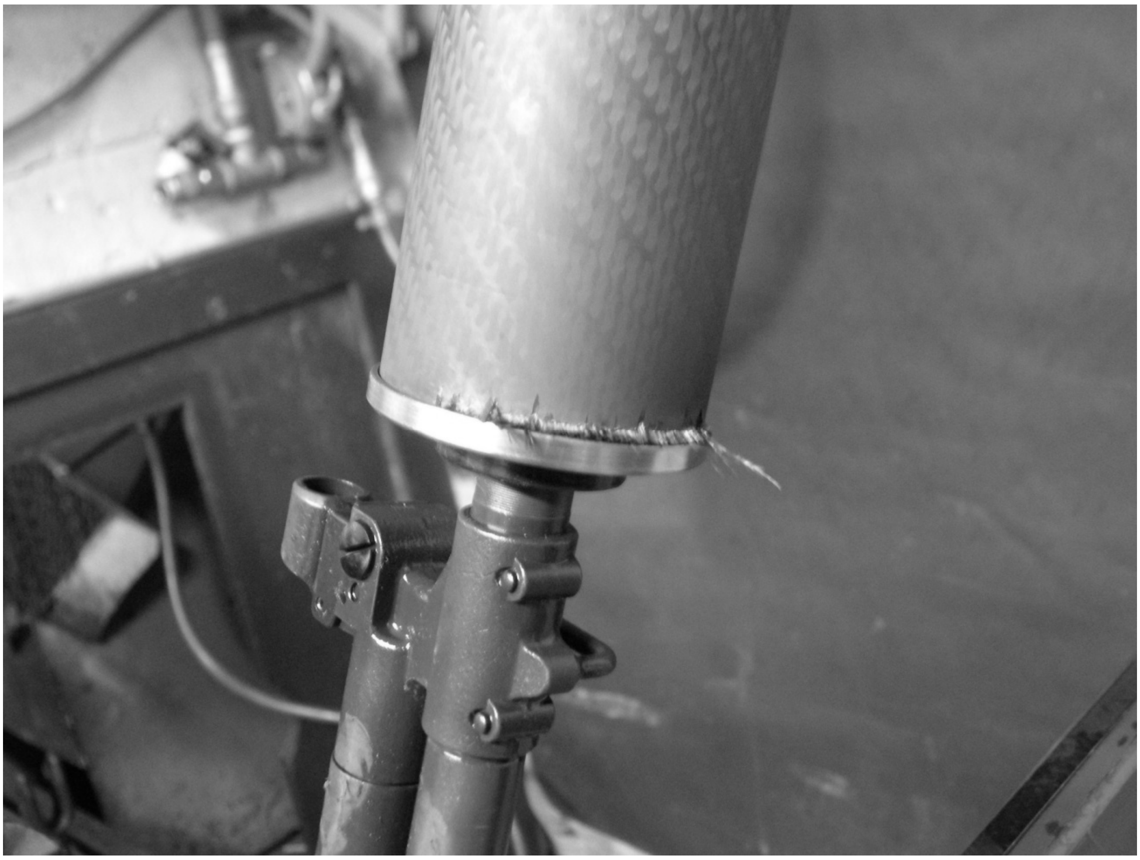

Figure 26 *Damage caused to the suppressor outer shell by propellant gas leak between the end cap and outer shell.*

The prototype was repaired by cutting off the damaged segment of the carbon fiber tube and reassembling the suppressor. As the gas leak was most likely a result of poor fitting between the outer casing and end cap and not due to material deficiency, the full thermal stress endurance potential of the material was still a question. Therefore test continued by subjecting the suppressor to further rapid fire. After 60 rounds of short bursts the suppressor casing started to show signs of alteration. The gas leakage did not manifest itself again but the material darkened which was deduced as a sign of the carbon fiber epoxy matrix reaching its thermal damage temperature. After this first visual alteration the suppressor still withstood about 35 rounds of rapid fire in short bursts before rupturing. The suppressor burst along a fairly straight line on the carbon fiber outer shell and flew several meters from the weapon. The rupture is shown in **Figure 27**. The first test proved the ability of the carbon fiber composite to withstand a lot more heat strain than the normal use as a hunting suppressor would require.

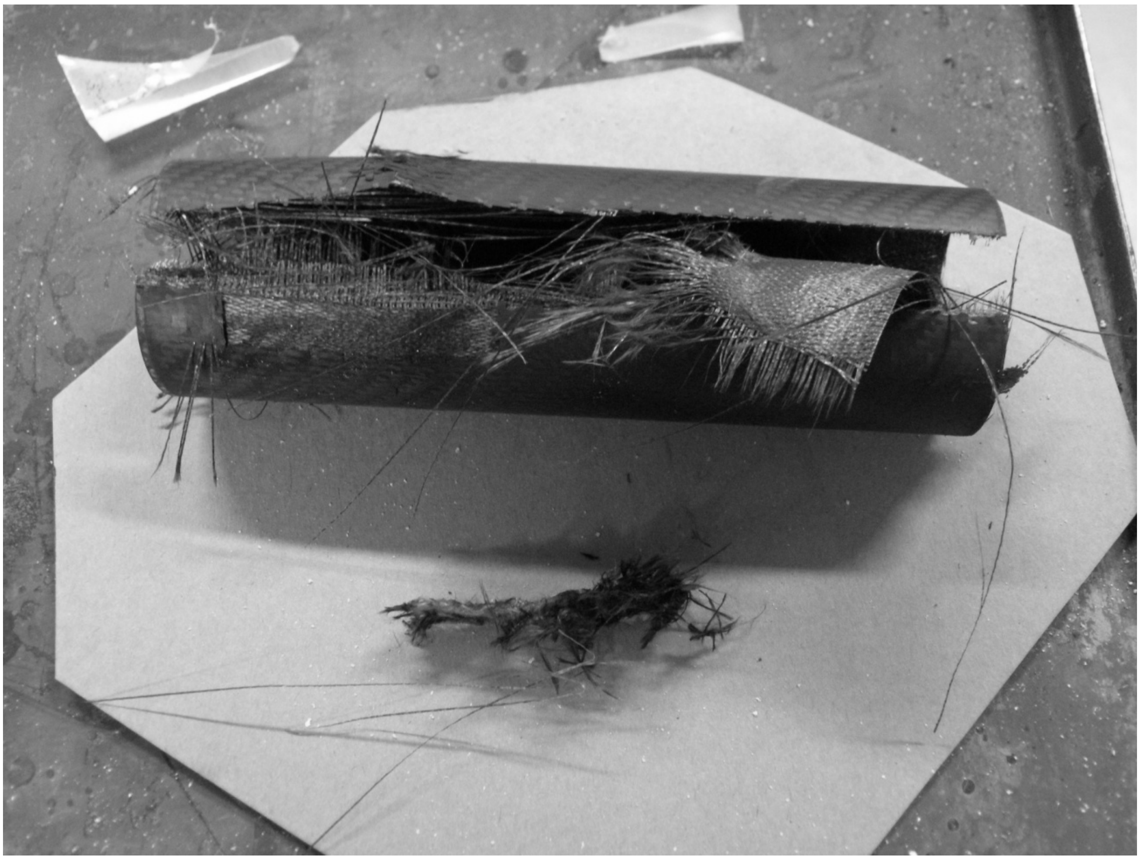

Figure 27 *The ruptured first prototype. The rupture progressed along a fairly straight line on the suppressor outer shell.*

5. RESULTS AND DISCUSSION

The results of this study stand more on a theoretical foundation than on empirical evidence as due to time issues only one live fire test could be accomplished. The results of this test, however, are promising for carbon fiber composites and their use in suppressors. The outer shell of the first prototype proved to be able to withstand a considerable amount of heat before the structural integrity of the shell was compromised sufficiently to cause rupture.

While the heat resistance was proved to be promising the test also revealed a notable issue with the materials susceptibility to fraying under strong gas flow. This can be countered by ensuring that the edges of carbon fiber parts are not subject to direct gas flow or leaks or by providing some kind of protection against fraying.

Another issue which the test revealed is how any contact between the inner metallic structure and outer shell increase the heat transfer to the carbon fiber component. The steel baffles were designed to rest against the outer shell and during testing the heat buildup was clearly more evident in areas which had a contact with the baffles when compared to other areas of the outer shell. Even with a change of baffle materials from steel to aluminum the issue would most likely prevail as aluminum has even higher thermal conductivity than steel. Therefore the contacts between inner metallic structure and any carbon fiber components should be minimized. Even if an aluminum part might not have immediate contact with a carbon fiber composite material prior to discharge, it is possible for the situation to change during firing with the high thermal expansion of aluminum.

The first test concentrated upon the validity of carbon fiber as a suppressor material in the outer shell of the prototype. The second step is to improve the internal structure and find a construction that works with lighter materials like aluminum. These modifications are easy to test in the same testing environment and with the same equipment as used with the first test. For obtaining more complete results also different caliber weapons should be used. The assault rifle cartridge is shorter than those used in some hunting rifles and therefore the increased propellant gas pressure might cause damaging issues in hunting rifles.

Finding a working structural solution may require several prototypes and tests and even though the testing environment used in the first test was not optimal for measuring the effect the suppressor has on shot signature, a rudimentary approximation of the effect is still possible. A single decibel measurement device could be fitted inside the testing area to measure the values from an unsuppressed discharge, from the prototype suppressors and from a commercial competitor. By comparing these values a rude approximation can be derived whether the suppressor attenuates the weapon signature to any extent. The close walls and strong echo of the shooting range make it almost impossible to measure the sound signature any further.

When the suppressor design is sufficiently advanced and the sound attenuation requires more attention, a more open testing environment is required. An open field shooting range would be near ideal to provide comparable values and microphone placement should follow **Figure 24**. It is also worth considering that the suppressors might work quite differently when used with different weapons and different cartridges even if the caliber remained the same. Therefore the future tests would benefit from several different testing weapons and from the use of multiple different cartridges. The subsonic ammunition should also be included, as it is used in some cases to control the weapon signature even further.

6. CONCLUSIONS

The aim of this study was to improve an existing suppressor product by finding alternative materials which are suitable for suppressor conditions and provide some advantage over the previously used steel. The theoretical process found several possible alternatives which would be worth of a closer look. Polymer matrix carbon fiber composite and anodized aluminum turned out to be the most interesting alternatives. As the company Oricopa Oy already has contacts with carbon fiber composite manufacturers, they would also form the most available options to test in a prototype. The carbon fiber composite was proved to have potential as a possible replacement for steel when used as the material for the outer casing of the suppressor.

The research did not fulfill all of its goals as the time issues did not allow the testing of anodized aluminum in the internal structure and possible combinations of aluminum parts with carbon fiber composite components. Theoretical designs were created for possible future testing and prototype construction.

As carbon fiber composites are somewhat a rarity in rifle caliber suppressors these results find promise for the material and encourage for further research on the subject. Light and strong suppressor designs with easy maintenance and reasonable manufacturing costs would be welcomed among hunters and sport shooters.

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