Signe Johanne Engebråten

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Master's thesis in Mechanical Engineering
Supervisor: Kjell Kolsaker
June 2020

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NTNU
Norwegian University of Science and Technology
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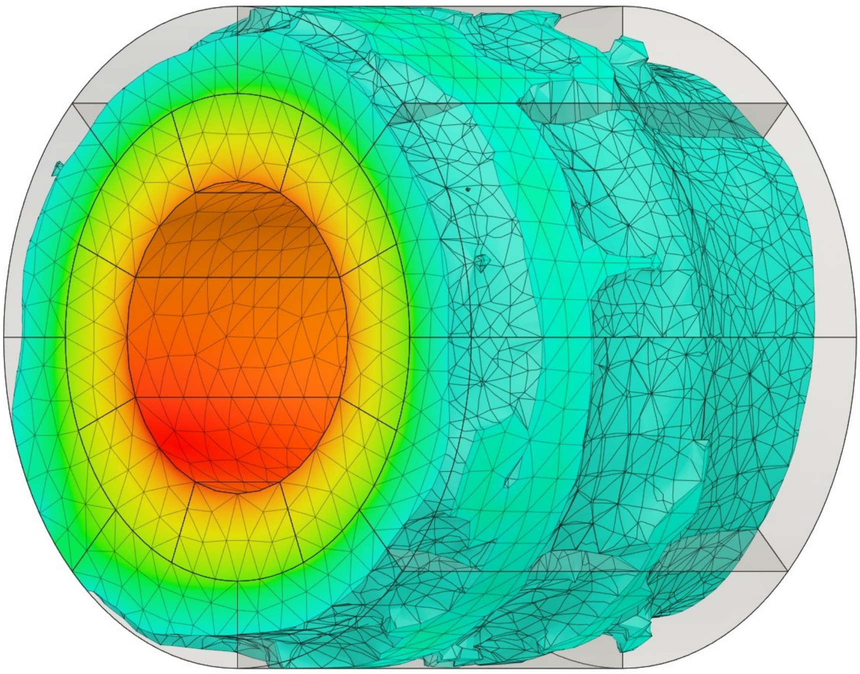

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Abstract

This study deals with a problem of a high temperature combustor design for a cyclical powerplant presented by the partner company OGPro. The study builds upon a preliminary work completed in autumn of 2019 that investigated the existing engineering solutions and literature, and identified non-traditional materials that may be used in the construction of a combustor that can sustain the conditions proposed. This study assesses the problems and literature on the implementation of non-traditional materials such as ceramics proposed in the preliminary work. This study proposes methods, tools, and a coherent industry friendly approach that allows the partner company to modify or adapt the solutions and methods developed here to a finalized design. One approach and accompanying solution presented and evaluated here showed favorable results on the use of actively cooled ceramics in high temperature combustors.

Sammendrag

Denne studien tar for seg et problem med design av et forbrenningskammer for forbrenning ved høye temperaturer i et syklisk kraftverk presentert av partnerselskapet OGPro. Studien bygger på et forarbeid som ble fullført høsten 2019 som undersøkte de eksisterende tekniske løsningene og litteraturen, og identifiserte ikke-tradisjonelle materialer som kunne brukes i konstruksjonen av et forbrenningskammer som kan opprettholde de foreslåtte forholdene. Denne studien vurderer problemene og litteraturen om implementering av ikke-tradisjonelle materialer som keramiske stoffer som var foreslått i forarbeidet. Denne studien foreslår metoder, verktøy og en sammenhengende bransjevennlig tilnærming som gjør det mulig for partnerselskapet å endre eller tilpasse løsningene og metodene som er utviklet her til et ferdig design. En metode og tilhørende løsning presentert og evaluert her viste gunstige resultater for bruk av aktivt avkjølt keramikk i forbrenningskammer ved høye temperaturer.

Preface

The partnered company OGPro presents a problem of high temperature combustion and the design of a combustor or piston bore to be used in these conditions. The conditions presented are more similar to the conditions seen in the leading edges of supersonic and hypersonic aircraft, than in common piston based powerplants.

It is uncertain whether or not a potential solution can be found that would satisfy the performance criteria provided by the partner company. As such it is important to retain flexibility and the opportunity to pivot to alternative solutions, by failing early in the design and optimization process. Therefore, a preliminary study completed in autumn 2019 investigated potential material candidates that may be used, the extent of the literature of applied thermodynamics at the conditions specified, existing solutions, and material candidates, to create a foundation for further work. This study builds upon that foundation, and in the same manner investigates the potential solutions that may be utilized while retaining the greatest possible amount of flexibility through modularity in the final solutions.

The problem presented by the partner company is also a part of a greater design concept, much of which is confidential due to intellectual property concerns. The solutions developed here therefore need to adaptable to a final design that at the time of writing remains unknown.

No assumptions can be made about the resources the partner company may have at their disposal for further work, such as the work required for final integration of the solutions developed here into the final design. As such, the solutions and methods developed in this study cannot rely on technical tools or methods that are not available for the partner company at a later date. Rather, reliance on inexpensive, readily available tools has to remain a primary focus, to maintain an industry friendly approach and generate results that may be utilized in practice.

I extend my sincerest gratitude to professor Kolsaker for offering a great deal of support and guidance with respect to handling the difficulties presented due to the confidentiality concerns of the partner company. Additionally, I would extend my gratitude for the understanding and unwavering support with completing the thesis during the pandemic of spring of 2020.

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List of Abbreviations and Terms

CAD	Computer Assisted Design
CAE	Computer Assisted Engineering
CAM	Computer Assisted Manufacturing
CGI	Compacted Graphite Iron
CNC	Computer Numerical Control
EDM	Electron Discharge Machining
EDWC	Electron Discharge Wire Cutting
OGPRO	OGPRO AS - The Partnered Company
UHTC	Ultra-High Temperature Ceramics
UHPP	Ultra-High efficiency Hydrogen Power Plant
UHPP Core	Cyclical Piston Power Plant in the UHPP

List of Symbols

Δ	Change
ε	Emissivity
σ	Stefan-Boltzmanns constant
ω	Cyclic Rate
A	Area
b	Piston bore diameter
C	Correction factor
h	Heat Transfer Coefficient
k	Thermal Conductivity
L	Length
P	Pressure
Q	Heat Rate
R	Resistance
r	Radius
s	Piston stroke length
T	Temperature
V	Volume
x	Molar fraction

1 Introduction

The following study is a design and development study, and as such is structured differently than is common in other academic works, in order to make the work performed easier to follow. For clarity, the structure of the study and a summary of each primary section is presented in this introduction.

2. The Preliminary Study

Section 2 is a preliminary study that details the problems that the partner company presented and required solutions for. It builds on a preliminary study that was completed in autumn 2019.

The section reiterates a large part of the work performed in the preliminary study, including the literature study that was performed at the time to understand what technical solutions currently exist for the type of problem presented here. Especially relevant are considerations of why those technical solutions are not directly applicable to this problem. Additionally, the work presented several technical solutions and materials more commonly used in other industries that are relevant in developing technical solutions for this problem.

The section also contains an overview of the existing scientific literature including thermodynamic models that were available for use with estimating important effects relevant to the problem presented, and considerations that have to be made when utilizing these thermodynamic models.

Lastly, the feasibility analysis performed in the preliminary work is reiterated, and some promising solutions and results from the preliminary work are presented, along with a path for how these results may be utilized, and have been utilized, in this study.

3. In Depth Problem Analysis

Section 3 builds upon the preliminary study and assesses the requirements for utilizing the possible solutions that were found in the preliminary study, and the potential problems such solutions may encounter. Both performance related concerns and serviceability and operability concerns are considered and presented in this section, with some potential solutions from the literature presented for the relevant problems.

4. Designing and Optimizing the Solution

Section 4 contains the process of designing and developing a solution with the problem presented in mind. It entails the basic design of the solution proposed, considering the problems and solutions for those problems discussed in Section 3. It then goes on to optimize, dimension and assess the performance of the design using low impact simulations in CAD software.

5. Conclusion

This section contains the conclusion of this design and development study, detailing quickly the progress that has been made toward achieving a potential workable solution for the presented problem.

6. Future Work

This section contains recommendations for future work, split into three possible groups. The first group details recommendations for future work based on the perceived shortcomings in the literature, that proved problematic through this work, such as lacking availability of models describing a particular problem.

The second group details recommendations for future work based upon perceived shortcomings in this work itself, and the results obtained, such as through simplifications in the modeling of different effects of problems, or lack of analysis of certain problems.

The third group details recommendations for future work based upon known shortcomings in this work, that is problems that were not solved during the course of this design and development study due to a focus on the specific problem of high temperature combustion and its associated effects and sub problems. These problems will likely be required to be solved before the solutions developed here are implemented, but they were not necessary to consider in detail in this study.

2 The Preliminary Study

The problem presented by the partner company OGPro for this study contains a multitude of variables, with the "hard problem" of high temperature as the primary focus. This study builds on a previous preliminary work assessing the feasibility of the design through an in-depth investigation of the existing literature. This preliminary work, which is reiterated in part through Section 2, showed promise and indicated the problem was solvable, but the results produced were uncertain due to the limited scope of the study.

2.1 UHPP Core

An ultra-high efficiency hydrogen powerplant has been proposed by the company OGPro. The thermal powerplant is proposed to generate electrical power with high electrical conversion efficiency up to 20% higher than the existing contemporary designs. OGPro propose to achieve a higher efficiency than contemporary solutions by innovation in the combustion system and the power conversion units. The portion of the ultra-high efficiency powerplant discussed in this study, is a portion of the sub component referred to by the partner company as the UHPP Core, a cyclical piston based powerplant operating at high pressures and temperatures.

2.1.1 The Properties and Current Design of the UHPP Core

The current design of the powerplant is a work in progress, as such, a lot of the properties and specifics of the design are expected to change. Some properties are also not known due to confidentiality concerns. A few basic properties are however disclosed for the purposes of this work, and they are all described in as much detail as is available and required, in the following section.

The powerplants piston bore and piston are referred to collectively as the UHPP Core by the partnered company. The piston bore is cylindrical, with a bore or diameter of **b** = 0.287m. The relation between the piston bore and the stroke length is a 1/10 ratio. That is to say, the total length of movement for the piston, or the stroke length, within the cylinder is 10 times the diameter, which yields **s** = 2.87m.

The combustion cycle is assumed to be somewhat simplified for ease of calculation and simulation in this work. The powerplant ingests pure atmospheric air, and this air is assumed to be a pure mixture of N_2 and O_2 such that $\mathbf{x}_{\mathbf{O_2}} = 0.21$ and $\mathbf{x}_{\mathbf{N_2}} = 0.79$, where x denotes the molar fraction of each component in the gaseous mixture. It compresses the working fluid to a compressed volume of **V** = 0.185m^3, where the pressure is $\mathbf{P_{initial}}$ = 25Bara and temperature is $\mathbf{T_{initial}}$ = 635K. The powerplant then injects a combustible fuel, in this case gaseous hydrogen. The volume, pressure and temperature are all assumed not to change while the fuel injection occurs. The powerplant then combusts the mixture instantaneously, and the temperature and pressure increase to $\mathbf{P_{combustion}}$ = 385Bara and $\mathbf{T_{combustion}}$ = 3850K respectively, while the engine retains the constant volume. The cylinder then retracts, producing work in a power-stroke. The engine operates at a cyclical rate of **ω** = 100rpm, completing 100 full compression and power strokes within one minute. The piston cylinder, or relevant parts of it that require the cooling, are assumed to be actively cooled throughout the entire process.

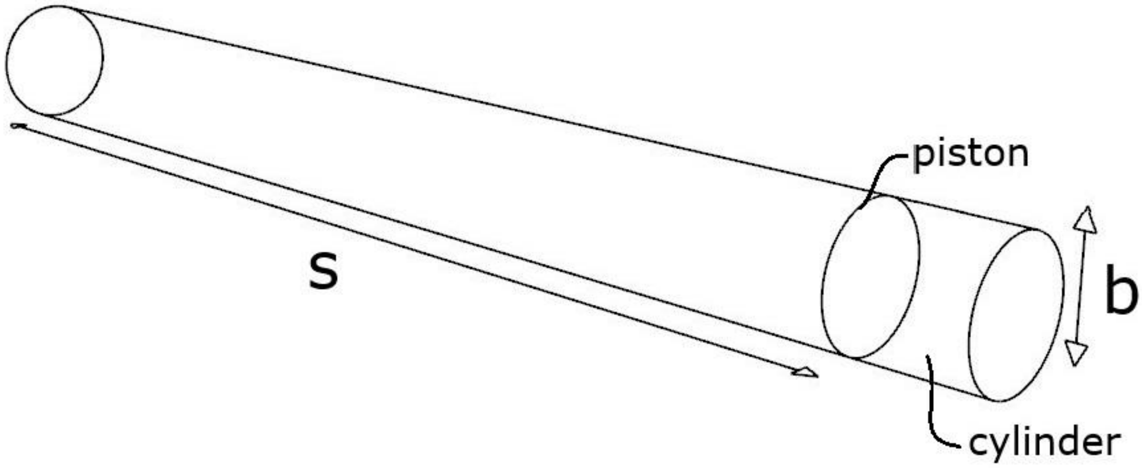

Figure 1: Labeled Powerplant Geometry

2.2 The Existing Literature

An investigation into the available literature was required to look into the existing knowledge on the design methodology, the design specifics, and the materials in common use in powerplant designs today. When this engineering knowhow and science is known, it is significantly easier to see where it is lacking and research is required. As such the design proposed in this work can be limited to the constraints and established engineering knowhow of the literature to the greatest possible extent, limiting the work to where it is actually required.

2.2.1 The Relevant Materials Science

Traditionally, internal combustion engines have from their inception been constructed of metallic alloys, such as cast iron or aluminum alloys (Myagkov et al., 2014). These materials place significant constraints on engines due to the necessary size and weight of the components.

In recent years, more advanced materials have been developed. These include advanced alloys and composites (Myagkov et al., 2014). Myagkov et al. describe in their study; "Advanced and conventional internal combustion engine materials", the potential advantages of new materials, and the disadvantages of materials that are currently in widespread use.

Engine blocks and by extension piston bores and the combustion cavities are normally made from cast iron or aluminum alloys (Myagkov et al., 2014). Perlitic gray cast iron such as ASTM A48, is in common use. According to the MatWeb database, and data provided there by a manufacturer, Dura-Bar, of the following alloys, A48 has a maximum service temperature of 922K (Dura-Bar). Additionally, high strength ductile cast irons, such as 65-45-12, are also used, which again have a maximum service temperature of approximately 922K (Dura-Bar).

In their introduction, Myagkov et al. (2014) describe the problems with current materials in conventional engines. The designs of internal combustion engines are continuously being improved to ensure enhanced specific power output, mainly through increasing the compression ratio in cylinders and the mean effective pressure through turbo charging, high pressure fuel injection, better organization of the air/fuel mixing process and improved combustion strategies.

Furthermore, they describe that advanced lightweight materials with high specific strength are necessary to withstand both the increased dynamic and thermal loading which result from these advancements. Advancements in the materials used for engine design make reductions in engine dimensions, weight and other properties possible, as well as potentially increasing their durability.

They go on to describe some of the newest materials, such as compacted graphite iron (CGI), that could potentially be used. This material is currently in widespread use, with over 500’000 CGI engines being produced annually. This material offers reduced wall thickness at current pressure loads, or, alternatively, increased operating pressures at current design, increased hardness, reduced cylinder bore dimensions and more.

2.2.2 Potential Problems with the Current Solutions

Given the low cyclical rate of the engine that is the focus of this study, the high temperature within the cylinder is retained for a significant amount of time, compared to currently conventional engines. Contemporary engines, even if they do not utilize a four-stroke design, which permits additional internal cooling on the intake and exhaust strokes, also typically operate at cyclical rates on the order of 20-50 times higher than this powerplant. As a result, the high temperature within the cylinder usually occurs momentarily, before the pressure and temperature is lowered due to the movement of the piston. In addition, in systems where the cyclical rate is high, rapidly fluctuating dynamic conditions approach the conditions more typically seen in steady state systems. This is due to a systems thermal inertia caused by its heat capacity and the time delay associated with conducting heat through a solid medium. When temperatures fluctuate rapidly, the system reacts too slowly to reach equilibrium within a single cycle (Incropera et al., 2017).

The specifics of this difference between the engine that is evaluated and contemporary engines could be determined in more detail with use of methods for transient heat transfer as described by Incropera et al. (2017), but for this initial evaluation, given the significant difference in the cyclical rate and the combustion temperature, a worst-case scenario of steady state heat transfer where the wall temperature can approach the combustion temperature, is assumed.

The materials presented earlier all offer potential benefits for engine design, ranging from weight and insulation, to ease of manufacture. However, these materials offer specific solutions to problems that are prevalent in contemporary engines, not the engine which is presented in this case. A solution then needs to be found to bridge the gap between the problems in this engine, and the known and advanced materials science currently employed in contemporary engines. In this way, the existing engineering knowledge and knowhow used for other engines can be taken advantage of.

As is evident from the properties presented by Myagkov et al. (2014) and MatWeb (Dura-Bar, Dura-Bar), the primary property that makes these materials unsuitable for the cylinder design of the engine presented here, is this engine’s particularly high combustion temperature. This presents the potential shape of the solution, as all that is necessary is finding a material that can survive sustained exposure to this high temperature, while also insulating the remaining portions of the engine from the combustion. In that way, conventional materials, such as cast irons and aluminum alloys (Myagkov et al., 2014) can be employed for all sections of the engine that are not directly exposed to the unusually high combustion temperature.

2.2.3 Ceramics and Ceramic Composites

In 1984, Tovell published "Ceramics and the Reciprocating Combustion Engine" (Tovell, 1984), within which, they describe the use and benefits of ceramics in internal combustion engines. They describe that patents for using ceramics in internal combustion engines have been present since the early days of oil engines.

Though the study is old, they go on to describe that up until the point of writing, ceramics have not been commonly used in gasoline or diesel engines, with the exception of uses such as spark plug insulators (Tovell, 1984). As newer studies and textbooks also describe, this is also the case more recently (Incropera et al., 2017, Myagkov et al., 2014), where ceramics have been used in some limited capacity for cylinder bore liners, and their use as high temperature insulators for combustors has been proposed (Gasch et al., 2005, Myagkov et al., 2014, Tovell, 1984).

In this engine, the proposed solution then is the use of aircraft and spacecraft grade ceramics, such as the class of ceramics referred to as Ultra High Temperature Ceramics, described by Gasch et al. (2005) as originally intended for applications such as high temperature shielding for the leading edges of spacecraft and high-speed aircraft. Due to their refractory properties, and high temperature operability, these ceramic composites offer a potential solution to the harsh conditions inside of this particular engine, if the conventional materials are found to be insufficient.

2.2.3.1 Ultra High Temperature Ceramics

Ultra-High Temperature Ceramics are class of ceramics containing mainly ceramic borides, carbides and nitrides, as described by Gasch, Ellerby and Johnson in "Handbook of Ceramic Composites" (Gasch et al., 2005). They are characterized by high melting points, chemical inertness and relatively good oxidation resistance (Gasch et al., 2005). The work on UHTC's was originally conducted by the US Air Force in the 1960's and the 1970's, and much of the work has been primarily funded and published through NASA, the US Navy and the US Air Force (Gasch et al., 2005). The applications for high temperature materials with high melting temperatures and high resistances to oxidation, are best described by Gasch et al. (2005);

> The need for high temperature materials that can operate with no or limited oxidation or ablation at temperatures greater than 3000K has driven the development of UHTC materials. The potential applications for UHTCs span a wide number of needs arising from future military, industrial and space-based projects. Potential industrial applications for UHTCs include use in foundry or refractory processing of materials. Their chemical inertness makes them ideal for molten metal crucibles, thermowell tubes for steel refining and as parts for electrical devices such as heaters and igniters.[9]
>
> The military and aerospace applications for UHTCs range from rocket nozzle inserts and air augmented propulsion system components to leading edges and nose caps for future hypersonic re-entry vehicles.[9-12] … the successful design of a sharp hypersonic vehicle requires the development of new materials with higher temperature capabilities than the current state-of-the-art materials can provide. Ultra-High Temperature Ceramics are a family of materials that are promising candidates for meeting such requirements.[13–14] (Gasch, Ellerby and Johnson, 2005, p.209)

Refractory compounds such as UHTC's exhibit a large service temperature range. This is due to a multitude of properties they have, including the low coefficient of thermal expansion, very high melting temperatures, and perhaps more importantly, a high resistance to oxidation even at high temperatures (Gasch et al., 2005).

Boride ceramics typically include the highest resistance to oxidation over those of carbides and nitrides. This makes them more applicable in situations where the fuel or reactants are more corrosive than those that are assumed in this initial evaluation, such as if the oxidizer in the engine, currently pure air, was to be replaced with pure oxygen. However, the borides also typically prove the least suitable of this class of ceramics, due to their unusually high thermal conductivity (Gasch et al., 2005). Given the desire to use these ceramics as insulating liners in the construction of the cylinder, such that more affordable and more manageable materials, like those used in contemporary engines can be used, it may be desirable to utilize a material with a lower thermal conductivity. While carbides and nitrides exhibit lower resistance to oxidation over borides, they also exhibit lower thermal conductivities (Gasch et al., 2005).

2.2.3.2 Problems With The Use of Ceramic Composites

Non-ceramics are however still necessary. Notably ceramics have several shortcomings, largely stemming from properties that are otherwise beneficial in their application as high temperature thermal insulators. Their high hardness makes them brittle and potentially unsuitable for pressure retention applications where they are placed under tension (Gasch et al., 2005, Tovell, 1984), such as, in this case, an unsupported cylinder bore pressurized to a high internal pressure. The high hardness in some cases makes them unsuitable to be machined and manufactured using conventional processes (Gasch et al., 2005). For this reason, fabrication of UHTC's has typically been accomplished by hot pressing and sintering (Gasch et al., 2005). For conventional machining, diamond tooling is typically required, although Electron Discharge Machining (EDM) has been used successfully (Gasch et al., 2005).

The materials may also be susceptible to thermal shock, given their high hardness and brittle failure mode (Tovell, 1984, Gasch et al., 2005, Myagkov et al., 2014). Though the materials exhibit low coefficients of thermal expansion, their hardness may be high enough that these materials would prove unsuitable for use in applications where they are exposed to cyclical thermal loads. In this application however, the materials may be more suitable than in contemporary engines, due to the low cyclical rate of this engine. Other materials, such as metals and composites may therefore be necessary to support and absorb mechanical stresses that the ceramic composites may be unsuited to support.

2.2.4 Physics of Heat Transfer at Elevated Temperatures

Although the literature on the mechanisms and physics of heat transfer in general is extensive, the physics and mechanisms of heat transfer at very high temperatures is in many cases somewhat limited. Relevant source material for temperatures in excess of 3000K is largely unavailable. Though correlations have been developed for models that utilize a single heat transfer coefficient, such as the one developed by Woschni (1967) for the heat transfer at the internal surface of conventional combustion engines, most of these are tuned to the properties and specifics of the internal combustion engines commonly in use today. These do not exhibit the same temperature and pressure conditions, as well as the low speed that is relevant for this system.

2.2.4.1 The Thermal-Electrical Network Analogy

The thermal-electrical network analogy is a method that has been developed such that heat transfer can be calculated as if it were electric current. This method offers multiple benefits when calculating heat transfer. Among others, it allows heat transfer calculations to be made on complicated networks where the heat can be transferred on multiple paths, for example from a hot solid block of material and to the surroundings by both convection and radiation simultaneously, or through a wall of multiple layers, where each layer has separate thermal conductive properties. The method requires that the method of heat transfer can be reformulated to the general form of heat transfer across a thermal resistance, which is as noted by Incropera et al. (2017);

$$Q = \frac{\Delta T}{R}$$

Once the thermal resistances can be expressed on this form, they can be treated the same way as is done in electrical network analysis to calculate currents. There are expressions for how to treat parallel resistances to heat transfer, and also how to treat heat transfer across multiple resistances in series.

2.2.4.2 Radiation

Due to the geometry of the problem, the cylinder is believed to form a black body cavity as described by Incropera et al. (2017). The Stefan-Boltzmann Law then describes the heat transfer by radiation from the hot combustion gases into the wall (Incropera et al., 2017). However, this law as originally formulated, is more applicable to the radiative heat transfer between solid bodies.

An expansion upon it was developed originally by Hottel and Egbert (Hottel, 1927, Incropera et al., 2017), which also produced emissivity charts for various gases and reformulated the law such that it is readily applicable to heat transfer by radiation between a solid body and a gas (Hottel and Egbert, 1941, Incropera et al., 2017).

$$h_{Radiation} = \frac{\varepsilon_{gas} \cdot \sigma \cdot (T_1^4 - T_2^4)}{T_1 - T_2}$$

Where the subscripts 1 and 2 indicate the areas or objects in between which heat transfer occurs, **ε** denotes the emissivity of the gas, and **σ** is the Boltzmann Constant.

Using the general formula for resistance to heat transfer in the electrical-thermal analogy, an expression for the resistance to radiative heat transfer based on Hottel and Egberts model can be formulated as;

$$R_{Radiation} = \frac{(T_1 - T_2)}{A \cdot \left(\varepsilon_{gas} \cdot \sigma \cdot (T_1^4 - T_2^4)\right)}$$

Where the area **A** here denotes the surface area of that the heat transfer by radiation occurs through.

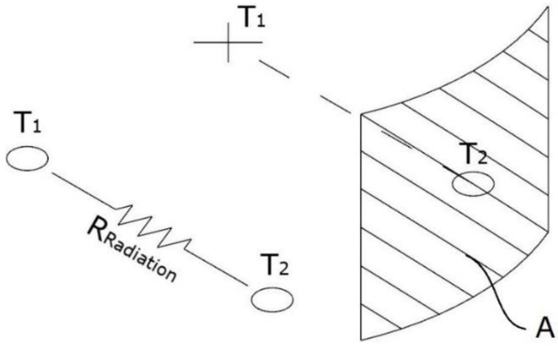

Figure 2: Resistance to heat transfer by radiation.

In this case, the emissivity of the gas is unknown, and only some properties of the fuels and the combustion products are known. Hottel and Egbert originally developed a general model for the gray gas emissivity of combustion products, in their work "The Radiation of Furnace gases" (Hottel and Egbert, 1941). Hottel and Egberts results, however, are only applicable in a narrow range of temperatures and pressures. Later, more comprehensive data about the emissivity of gases has been concatenated in databases, such as the HITEMP-2010 database (Alberti et al., 2016). The data here however is hard to access, and not readily applicable to the original correlations and methods developed by Hottel and Egbert.

Alberti, Weber, and Mancini have re-created Hottel's emissivity charts for water vapor, and other common combustion products (Alberti et al., 2016, Alberti et al., 2018). These exhibit higher ranges of validity both in terms of pressure and temperature, and yield much more accurate results than those previously provided from the correlations by Hottel and Egbert (1941). Though Alberti, Weber and Mancini's work (Alberti et al., 2018) have later expanded upon its ranges of validity, these new ranges of validity do not quite overlap, both in pressure and temperature, with those given for this powerplant. As such, the magnitude of heat transferred by radiation is at best uncertain, at worst unknown, as there exists no databases or tools with ranges of validity sufficiently high as to be completely applicable to this powerplant.

2.2.4.3 Convection

Heat transfer by convection is well established and understood in the literature. This method of heat transfer is typically modeled by Newton's law of cooling.

$$Q = h \cdot A \cdot \Delta T$$

Using the general formula for resistance to heat transfer in the electrical-thermal analogy (Incropera et al., 2017), an expression for the thermal resistance to convection can be formulated as;

$$R_{Conv} = \frac{1}{h_{Conv} \cdot A}$$

Where **h** is the coefficient of heat transfer, and **A** is the area over which the heat transfer is occurring, in this case, the internal surface of the cylinder at the time of combustion.

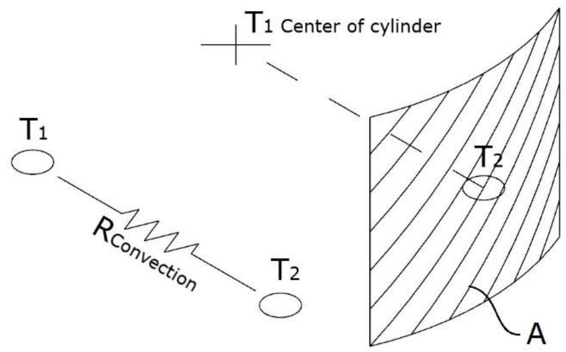

Figure 3: Thermal resistance to heat transfer by convection.

However, one important unknown in this model is the magnitude or expression for the coefficient of heat transfer. Tables of heat transfer coefficients for different situations exists and these tables of heat transfer coefficients largely describe heat transfer by forced and natural convection in tubes and heat exchangers. Additionally, in the few cases where heat transfer coefficients for similar situations as the one at issue here are available, they typically have ranges of applicability that do not include the properties of this particular engine.

In the case of internal combustion engines, many methods have been developed for the determination of the heat transfer coefficients. Most of those methods are tuned to yield very good results that accurately model the heat transfer in current combustion engines. Unfortunately, in this case due to the novel nature of the powerplant proposed here, they are unlikely to yield results that are realistic for this problem.

For the convective heat transfer coefficient, the model developed and published by Woschni in 1967 was used. Woschni's model was preceded by Annand and Nusselt, which developed broader correlations that had been in use until Woschni's model was available (Woschni, 1967). Woschni's heat transfer model is a universally applicable model of the heat transfer occurring in an internal combustion engine. It takes into account the properties of the engine, such as the piston speed, its dimensions, pressure and temperature, in order to calculate the heat transfer coefficient from the hot gas to the wall (Woschni, 1967). As a result, it is not necessary to resort to a simplified theoretical model, that may have limited applicability or errors in its modeling of the physical processes.

Though Woschni's heat transfer model is significantly more accurate than the first models of this type developed using the work of Nusselt, and the later improvements upon those models by Annand, Woschni does note that the model is not entirely accurate for several reasons. It has been found that the model overestimates the heat transfer during combustion, and may require tuning in order to yield accurate results for contemporary engines, it is however highly tunable with the use of three tuning constants. Later models however deviate from the universally applicable approach of Woschni's model and may therefore have limited applicability for this system.

Woschni's heat transfer model includes the effects of radiation in the tuned constants as provided in their original article, and they discuss the validity of this inclusion. It is assumed by Woschni that the inclusion is valid for the relevant engines that the model is tuned for, as the proportion of heat transfer by radiation rarely exceeded 20% of all heat transferred

(Woschni, 1967). Therefore, the heat transfer by radiation is included in the heat transfer model as an increase in the heat transfer proportional to the heat transfer by purely convective means.

Given that the model is specifically tuned to the conventional engines and situations investigated by Woschni, and perhaps more importantly, those that were present in the literature at the time of Woschni's findings, it may be necessary to reexamine the applicability of the proportional inclusion of the effects of radiation into the convective heat transfer coefficient. The heat transfer by convection may therefore be reduced by some constant correction factor, applied directly to the coefficient of heat transfer.

2.2.4.4 Conduction

The expression for resistance to thermal conduction in cylindrical walls is well established, and defined by Incropera et al (2017) as;

$$R_{cond} = \frac{ln(\, r_{outer}/r_{inner}\,)}{2 \cdot pi \cdot L \cdot k}$$

Where r here denotes the radius from the center of the cylinder, L the length in the axial direction of the cylinder, and k the thermal conductivity. In this expression, the thermal conductivity is the remaining unknown, and dependent on the material to be evaluated, not on any physical processes that are to be investigated.

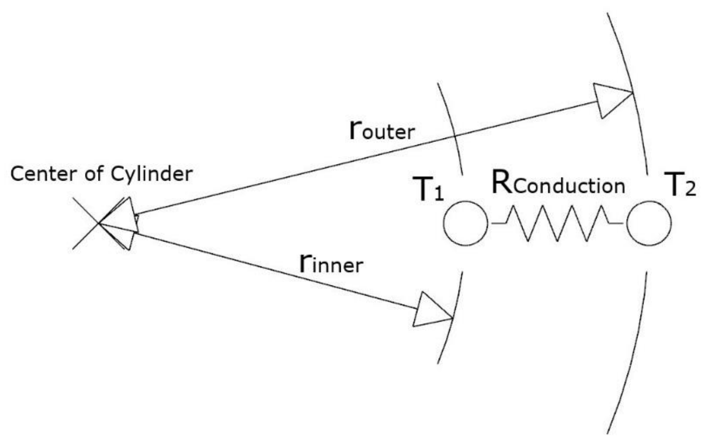

Figure 4: Thermal resistance to heat transfer by conduction.

Though many of the relevant materials discussed within this work are ceramics and ceramic composites, which exhibit strong refractory properties, there is still some temperature variability of the properties of the materials. As such, it is important to determine the properties of these materials at the temperatures at which they are simulated in the model.

The primary property that exhibits temperature variability with ceramics and ultra-high temperature ceramics in particular is their thermal conductivity with respect to temperature. In most cases the variability of the material's thermal conductivity with respect to temperature is given in the relevant source studies along with other properties, such as melting temperature and maximum service temperature. The temperature variability in ranges that were not specified in the data may have to be interpolated and extrapolated based upon the available data.

Thermal conductivity is a result of the combination of both phonon and electron transfer (Incropera et al., 2017, Gasch et al., 2005), and as such the thermal conductivity does not exhibit a necessarily linear change with temperature (Gasch et al., 2005). It is however generally assumed that given the data available, the thermal conductivity can be interpolated linearly between two adjacent points of data or as a linear extrapolation where the data is unavailable at the temperatures required, though this is a potential source of inaccuracy that may not be possible to circumvent otherwise.

2.3 Introductory Simulations

The literature shows a series of materials that may be usable for the purpose of insulating the core of the powerplant, in particular, the UHTC group of ceramics and ceramic composites. But there is little data in the literature testing these materials under the circumstances suggested here, as actively cooled insulators in high temperature combustors. The UHTC group of ceramic materials present several potential material candidates. However, it may also be the case that none of these materials are suitable for the use case proposed here. As such, some form of testing is necessary.

There are many variables that need to be solved for simultaneously in this problem. The necessary wall thickness is unknown, the cooling duty is unknown and the material chosen, and the material properties required are also unknown. Solving for all of these unknowns simultaneously would be excessively time consuming, and the multitude of unknowns makes it impossible to simply chose a material by a ranked list of properties, such as their maximum service temperature. As such, some form of testing or prototyping is required.

The materials are unfortunately also costly, and developing test samples and testing hardware relevant to the proposed use case would be costly as well. It is therefore desirable to attempt to test or estimate the properties of the materials through simulations and computer aided calculations in order to find which materials may be more suitable for this use case, before physical prototyping or experimentation is considered.

As such, to be able to test these materials for their suitability as insulators in high temperature combustors, a simulation framework had to be developed such that the materials could be tested and suitable material candidates could be selected without requiring prototyping or high-fidelity simulations. This simulation framework was developed in the preliminary work, and it is repeated in short form for clarity in the following section.

2.3.1 Assumptions and Theory

Certain simplifications and assumptions had to be done in the model to permit fast and accessible modeling, and allow the breadth of materials that were evaluated to be evaluated within a given timeframe. The simplifications are both in terms of theoretical simplifications and assumptions, and simplifications necessary due to the way the model was implemented.

Steady state

Firstly, the model assumes steady state conditions and attempts to calculate the solution for steady state heat transfer. In general, this represents the worst-case conditions, and a non-steady state solution will generally as a rule, barring unusual circumstances, always be more manageable. As such this assumption offers no significant flaws that would make the solution developed here unusable. Instead, this assumption would likely result in the design being over-dimensioned, with a larger safety factor than intended.

Material properties only dependent on temperature

Secondly, of the material properties evaluated in this case the thermal conductivity is assumed to be dependent on temperature alone. The variation in the thermal conductivity is implemented with the variability described by (Gasch et al., 2005). Where data is not available for the entire range of temperatures required, extrapolated and interpolated values are assumed to be representative of the material properties.

Constant heat transfer

Lastly, the heat transfer through the material is assumed to be constant and specific. Heat transfer by cooling rarely occurs at a very specific heat transfer rate by design, with the exception of heat transfer due to electrical resistance. In practice, the heat transfer is more generally the result of a thermal gradient and the thermal resistance in between a hot and cold side. However, for the purposes of this model, defining the heat transfer rate as constant and plotting the results for many heat transfer rates in the same diagram provided a usable result that could be used to estimate the heat transfer rate required to achieve this thermal gradient, and also allows the cooling system to be dimensioned based on the diagrams.

Iterative steady state solutions

In order to form a solution vector, all the program has to do is solve the general formula for heat transfer across a network of thermal resistances. This is possible to calculate without specifying an outer boundary temperature at the outermost point in the wall. This successfully allowed the results for each material and heat transfer rate to be plotted without specifying the outer boundary temperature, which permits selection of material thickness, cooling rate, and determination of required cooling system temperature from the same simple output diagram.

This is possible due to the way the calculation is done in the program. The heat transfer rate **Q** is specified and the thermal resistance **R** between each temperature node **T** is known. This leaves one unknown for the program to solve for, which is the temperature gradient between each node. Once the temperature gradient in between each temperature node is known, one temperature in the entire temperature array needs to be specified for the absolute temperatures of each node to be known. Given that the combustion temperature is specified by the design properties, the combustion temperature in the center of the combustor can be used.

The result once each iteration is complete, is the temperature node vector, that lists the temperature at each node in the wall. The program repeated this calculation an unspecified amount of times, using the old temperature node vector as the initial guess, until it achieved convergence.

Achieving convergence and the stopping condition

The program needed to determine when a solution for the steady state heat transfer had converged. The iterations were stopped when a stopping condition was met. The stopping condition implemented simply calculated the maximum difference in between the old and the current result, and stopped the iterations when the change between the previous and current result was smaller than some specified limit. While other models have been developed that accelerate the convergence rate and may be able to achieve convergence faster or with fewer iterations than the implemented solution, these were not considered necessary, as the program as implemented is fairly lightweight and the iteration speed was sufficiently high.

Two solution sets

The program repeated the iteration process twice, producing two complete output diagrams per material. This was seen as necessary given the overinclusion of radiation in Woschni's heat transfer model, which is used for convection. Woschni's model scales the heat transfer by convection by approximately 1.2 times. As such, if the model is used to model convection it overestimates the heat transfer by approximately 20%. Therefore, in the top right corner of each diagram the program specified the correction factor both for heat transfer by radiation and heat transfer by convection. It produces two sets of outputs, one where all of the heat transfer by convection and radiation both are calculated by Woschni's heat transfer model alone, and one where the heat transfer calculated by Woschni's model is reduced by 20% to remove the inclusion of radiation, and the heat transfer by radiation as calculated from Hottel and Egberts models are included in full.

2.3.2 Potential Material Candidates

The program did not in any way rank or evaluate the materials on its own, it displayed the material properties in a way that allows easier comparison between the materials. As such, the materials still need to be evaluated, and promising candidates selected.

There are three primary problems that the insulating core is supposed to address, that the diagrams can be used to evaluate. The first problem that needed to be evaluated was whether or not the wall temperature at a required cooling rate was in excess of the maximum service temperature of the material. The second and related problem is how much lower the wall temperature is than the maximum service temperature. The third problem that needed to be evaluated was the slope of the thermal gradient within the wall. All of these problems should be evaluated together, as none but the first are strict requirements.

In the preliminary study, several materials had very high melting temperatures in excess of 3800K, which implies sufficiently high service temperatures. Tantalum Carbide and Hafnium Carbide both show promising results, and neither is significantly preferable over the other. They both exhibit thermal conductivities of approximately 20W/mK, which could permit a very small wall thickness or, alternatively a large wall thickness with very low cooling requirements, as is evident from Figure 5 and Figure 6.

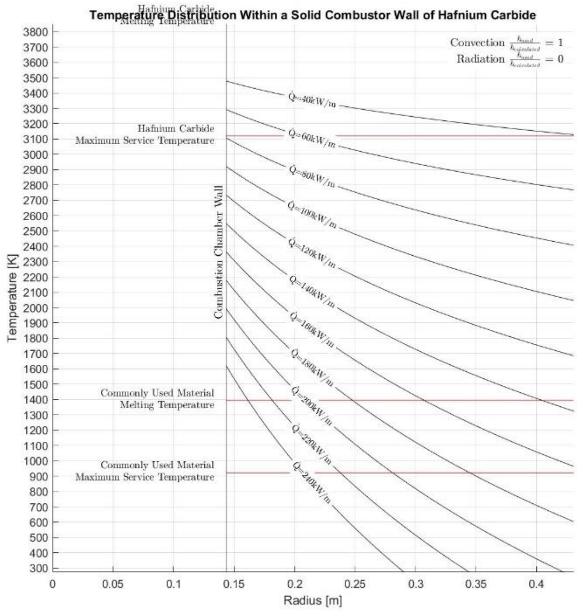

Figure 5: Hafnium Carbide (HfC) performance in preliminary study.

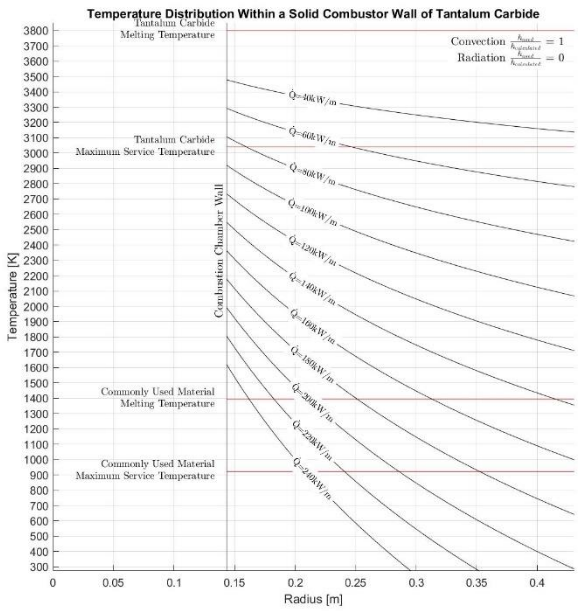

Figure 6: Tantalum Carbide (TaC) performance in preliminary study.

Further in-depth discussion of the results of the other materials can be found in the preliminary study. A material that was not discussed in depth in the preliminary study however, was Silicon Carbide (SiC). Silicon Carbide shows fairly decent properties but its properties are not as phenomenal as those of the other two carbides, so it was not presented in detail in the original report. Here however, due to the shifting focus towards feasibility and implementation, this material is particularly interesting due to its high availability (Callister, 2007) and high oxidation resistance (Gasch et al., 2005). The results for Silicon Carbide are shown in Figure 7.

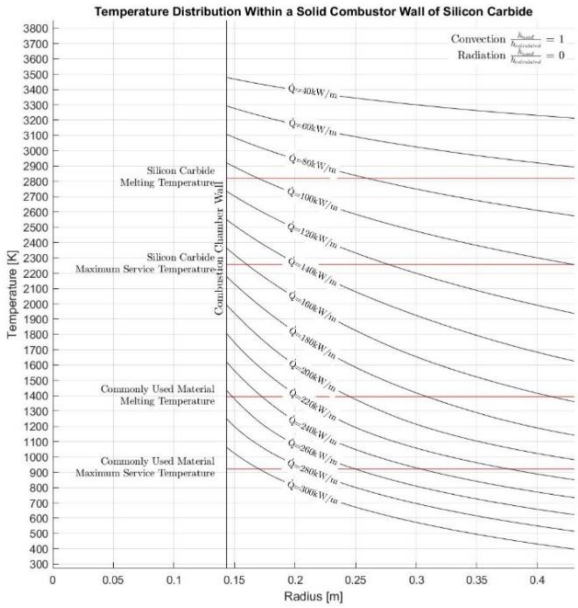

Figure 7: Silicon Carbide (SiC) performance in preliminary study.

2.4 Concluding the preliminary study

In summary, several studies helped gain an overview over the existing science and engineering knowhow on powerplant design, construction, and materials. The study showed models by which heat transfer at high temperature can be calculated, however, these models were unfortunately plagued with small regions of applicability that do not quite reach the absolute temperatures in question here.

Hafnium Carbide and Tantalum Carbide both showed very promising results due to their very high melting temperatures and high thermal conductivities, promising feasibility of either thin wall structures with aggressive cooling, or thick insulating walls with gentler cooling, the latter being made possible due to their high melting temperature. The study also showed Silicon Carbide as a potential material candidate, which shows particular promise due to its low cost, high availability and high resistance to exotic degrading effects such as oxidation.

Further on, potential material candidates need to be tested in simulations that include the specifics of the design of the combustor. However, before a design can be created and optimized, further understanding of the potential problems and pitfalls involved with the implementation of these materials is required.

3 In Depth Problem Analysis

Although there is one primary issue presented with the combustor, that of very high temperature combustion, that is not the limit of the issues that may be problematic in the implementation of any proposed solution. Other materials than those normally used can be selected that have service temperatures sufficiently high such that they can be used during sustained operations in the combustor. In the preliminary study, this was demonstrated, and reiterated in Section 2. This is not however a complete solution, as these materials have shortcomings that prevent them from being used to simply replace the existing materials in a current and established combustor design.

A solution has to be designed around the wall materials established in the preliminary study, in order to facilitate their use. In order to develop this solution, the problems faced in the utilization of the unique wall materials proposed here have to be properly analyzed and understood.

3.1 The Preliminary Solution

For the purposes of this analysis a basic preliminary structure of the combustor is assumed. This basic preliminary design assumption is based on the typical structure of combustors used in high end automotive applications, where an engine block of an easily manufacturable material is used, and a cylinder insert or cylinder sleeve can be inserted into the engine block if necessary (Myagkov et al., 2014). This basic structure has to be adapted slightly in order to be applicable to the problem discussed here.

The initial design is proposed to comprise a total of four major sets of components or sections. The parts or sections are shown on Figure 8, with a following explanation.

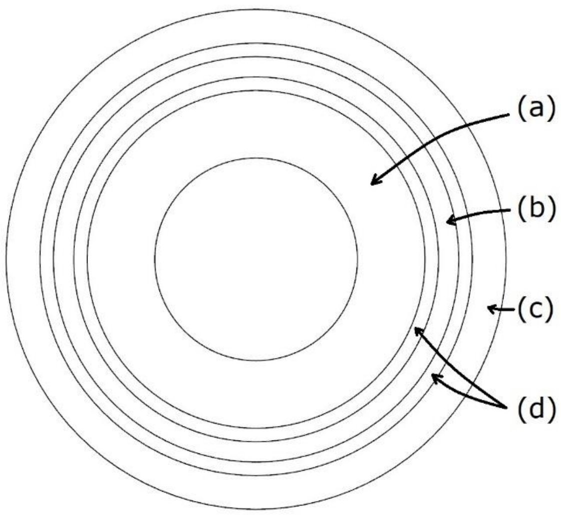

Figure 8: The Preliminary Shape of the Combustor Design. a) The Insulated Core, b) The Cooling System, c) The Combustor Housing, d) Other Mounting Hardware and Heat Spreaders.

- **a) Insulated Core**
  An insulated core that can provide a temperature resilient inner surface for the combustor, and provide a resistance to heat transfer through the combustor assembly, such that the outer surface and pressure retaining components can be manufactured from conventional materials, or even unconventional materials with favorable mechanical properties.

- **b) Cooling System**
  An active cooling system, that cools the combustor section, directly within the combustor housing. Active cooling is as previously described in Section 2 likely a necessary component in order to allow any materials to be used in the design of this particular combustor.

- **c) Combustor Housing**
  A combustor housing, that serves to connect the combustor with the remainder of the engine, such as the majority of the piston bore, and the cylinder head. This part is analogous to the engine block of a conventional piston engine design.

- **d) Mounting Hardware and Heat Spreaders**
  Mounting hardware or mating sections and other components inside the combustor, in order to mount the insulated inner core to the outer components, such as the cooling assembly, and the outer combustor housing. This component may also serve to spread or dissipate heat across the combustors internal volume.

3.2 Determination of the "Hard Problems"

Once the basic structure of the combustor is known, the problem has to be analyzed so that potential solutions can be developed. One useful intermediate step however, is to use the problem analysis to develop design criteria for which the potential solutions can be developed. The design criteria needs to be specified both for the combustor as a whole, and for each of its individual parts. The design criteria needs to be specified both in terms of the functionality of the combustor and its parts, and their collective performance when installed and in use. For the purposes of the next sections, the design criteria will be separated into these two distinct groups.

The first group of criteria discussed in Section 3.3 specifies design criteria based on different aspects of the functionality of the combustor or its parts, such as operability, and manufacturability. These design considerations have in common that they are not possible or easy to test without a prototype, but contain valuable considerations that needs to be accounted for in order to make a usable prototype regardless. The second group of criteria discussed in Section 3.4 specifies design criteria based on the performance of the combustor or parts of the combustor, such as maximum internal service temperature. This group of requirements includes performance specifications and criteria that are testable, and possible to simulate and optimize further in order to arrive at a satisfactory and functional solution.

3.3 Operability and Serviceability

Certain problems and associated design criteria have to be discussed in the evaluation of the technical solutions that are not directly testable in performance simulations, and may not even be testable until final implementation is completed and the product is implemented with a potential customer. These design criteria include quality of life considerations both in manufacture, installation and use of the finalized product, that serve to make the design possible to use and implement in its intended use case. They are all grouped and discussed in the following section.

3.3.1 Adaptability and Versatility

At the time of this work there is a significant amount of uncertainty as to many of the physical parameters of the completed system. The functional parameters such as cyclic rate, combustion temperature and similar are somewhat uncertain, the structure of components that the combustor is to interact with, such as piston heads, cylinder heads, cooling systems, and so on, are unknown. These uncertainties stem from a number of different causes. The design is in progress with significant work being done towards its development, and there is substantial secrecy surrounding the details of its design. Regardless of the cause, the adaptability and versatility of the solutions developed here need to be considered in the design of the combustor.

3.3.2 Manufacturability

All of the parts in the combustor need to be manufactured at least once. As was addressed in Section 2.1, the design may change due to changing physical properties of the powerplant, and this may happen repeatedly. It is therefore desirable that adaptable manufacturing processes are utilized to the greatest possible extent to minimize or remove the cost of retooling if or when the design changes.

Manufacturing processes that utilize purpose-built tooling should therefore be avoided as much as possible, and part designs or technical solutions that require such tooling should be discarded completely, if possible. Examples of manufacturing processes that require purpose-built tooling for each part geometry or design include injection molding, die casting, forging, and so on. These types of manufacturing processes are typically required or desirable for high volume manufacturing regardless, and would therefore not likely be cost effective to employ in the production of the parts for this system.

Housing, Supports, and other metal components

The outer housing, internal supports and heat spreaders for the combustor need to be produced by some method. As was mention in Section 2, it is desirable to produce the combustor with as much of the conventional processes utilized in conventional engine design as possible to take advantage of the extensive literature on their design and manufacture. As the manufacturing methods possibly to use with this in mind are very diverse, one of the most available and common manufacturing methods will be described in further detail.

Metals and metal alloys used for conventional engine designs, are commonly manufactured by conventional machining methods, on which the literature is well established. These manufacturing methods carry few limitations and are well suited to low volume manufacturing, and are therefore highly applicable here. Grover (2004) describe that the common feature of all machining processes is the use of a cutting tool to form a chip that is removed from the work part. To perform the cutting operation, relative motion is required between the tool and work. This relatively motion is achieved in most machining operations by means of a primary motion, called the cutting speed, and a secondary motion, called the feed. The shape of the tool and its penetration into the work surface, combined with these motions, produces the desired geometry of the resulting work surface.

Machined parts can either be rotational or non-rotational. A rotational work part has a cylindrical or disk-like shape. The characteristic operation that produces this part geometry is one where a stationary tool removes material from a rotating part. Alternatively, a part can be non-rotational or prismatic, where the material is removed by a rotating or linear moving tool on a typically stationary part.

Machining processes typically require some way to hold a precursor part while the part is manufactured. As such, space must be allotted in part design such that a part can be held and retained while it is machined. Additionally, tool access is a strict requirement for machining processes. Unlike with some non-traditional manufacturing processes, in order for a part to be produced through machining, the tool needs to be able to access and cut into the material, and chips need to be removed as well. As such, fully enclosed part geometries are normally not possible using this manufacturing method alone.

The Cooling System

The cooling system is another example of a part where it is desirable to utilize existing tooling, materials, or even wholesale parts to the greatest possible extent. It is also the most apparent example of one of the primary parts where the structure remains largely unknown, and detailed design may inhibit optimal design at a later date when the cooling system itself is designed.

Most cooling circuits are made using bent tubing. This is also assumed here, although many other options exist. This solution is affordable, easy to dimension, and there are many correlations and simple tools that can aid in the design, dimensioning and optimization of this sort of cooling system.

The Insulated Core

The insulated core is proposed in Section 2 to be constructed from ceramics. These materials are as described by Gasch et al. (2005) constructed through hot pressing and sintering. Further fabrication of the finished hot pressed and sintered part or precursor part can then be done using fabrication methods utilizing diamond tooling, which are usually grinding-based machining operations (Grover, 2004). Diamond tooling is usually a requirement due to the high hardness of the material (Gasch et al., 2005). Gasch et al. (2005) also describe the possibility of using electron discharge machining to process parts made from UHTC materials.

Grover (2004) describes the manufacturing process of hot pressed and sintered ceramics in detail, however, it is not guaranteed that the process described here mirrors the one used in the manufacturing of UHTC's as described by Gasch et al. (2005). However, a few broad conclusions can be drawn. Sintering and hot-pressing ceramics usually requires heating precursor powder or particulate to some temperature usually just beneath its melting temperature. The material is then injected into a pressing jig, where a press compacts the powder to some pre-specified and determined density and porosity. The material cools, and the part is extracted.

This manufacturing method puts limits on the geometry of the finished part, similar to the limits imposed on part designs in other forms of pressed powder manufacturing, such as powder metallurgy. The part designs that are possible to produce through these methods alone broadly fall into four categories, or classes of powdered metal parts. These are described by Grover (2004) referencing the Metal Powder Industries Foundation, and shown here in Figure 9.

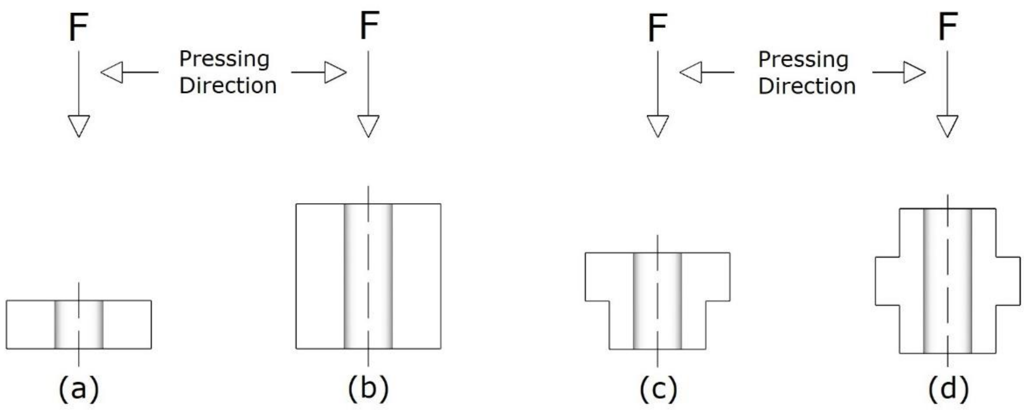

Figure 9: Possible Pressed Part Designs. a) Class 1 - Simple thin shapes that can be pressed from one direction. b) Class 2 - Simple but thicker shapes that require pressing from two directions. c) Class 3 - Two levels of thickness, pressed from two directions. d) Class 4 - Multiple levels of thickness pressed from two directions, with separate controls for each level to achieve proper densification throughout the compact.

Some part designs are also recommended to be avoided as they contain features that may be impossible to produce with these methods. They are also described in Grover (2004), again citing the Metal Powder Industries Foundation, and shown in Figure 10.

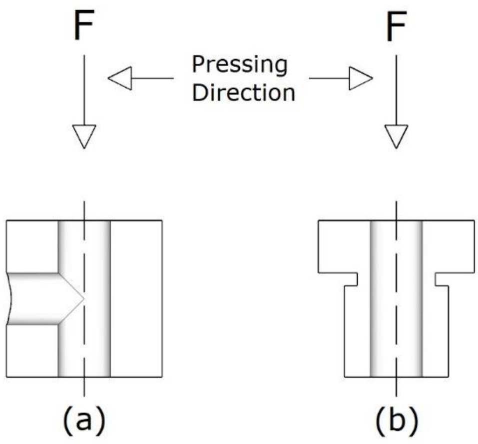

Figure 10: Impossible Pressed Part Designs. a) Side holes, b) Side undercuts. These features make part ejection impossible.

Once a part has been produced by sintering and hot pressing, it can however be further modified by grinding or electron discharge machining. As the former process is fairly well established and known, and its limitations are few, it is not considered necessary to describe limitations to it in further detail here. Electric Discharge Machining may however have some particular design limitations that should be discussed in further detail.

Grover (2004) describes Electric Discharge processes as processes that remove material by a series of discrete electrical discharges that cause localized temperatures high enough to melt or vaporize the material in the immediate vicinity of the discharge. There are two main processes in this category; electric discharge machining and wire electric discharge machining. Electric Discharge Machining uses a tool that can be optimized for a particular material removal operation, and cuts around the tool. When machining, the tool can move in any three dimensions, limited by tool holding the same way conventional machining processes are. This is different to Electric Discharge Wire Cutting, which functions the same way, but the tool utilized is a sacrificial wire that is fed through the material in a very similar manner to a traditional saw, where the tool can only be moved in two directions orthogonal to the cutting direction of the wire at any given time. As such, two-dimension part geometries are recommended for the latter, whereas three-dimensional part geometries are possible for the former.

3.3.3 Ease of Manufacture

The possibility of manufacture is however not the only criteria or concern related to manufacturability that should be addressed. Some parts may seem ideal in the theoretical sense, but may be unusable if they require an excessive amount of time or expense to actually manufacture. Additionally, because of the problems in designing technical solutions for prototypes previously mentioned in Section 3.3.1, these concerns are further amplified. The designs may need to be produced multiple times, or potentially modified and iterated upon an unknown number of times until a practical solution has been found. As such, the ease with which each part can be manufactured should also be addressed, both in terms of the time required to manufacture each part, and the cost involved with doing so.

Low volume production

There is no indication that the product discussed here, at least initially, will become a high-volume product. As such, the final design and the production methods it is designed to be produced with should favor production methods suitable for low volume production, and no parts of the design should be impossible to produce with such methods. However, this tends to be less of a restriction than the inverse would be, as high-volume production methods tend to be more restrictive in terms of the parts designs possible to produce with them, especially because the production methods suitable for low volume production, tend to include production methods suitable for rapid prototyping.

In terms of ease of manufacture, however, this may also be considered a detriment. Many high-volume production methods do offer significant benefits in terms of the speed with which any given volume of parts can be manufactured, and the low cost of manufacturing them. However, this would not necessarily be true for a low volume of parts manufactured on a high-volume assembly line. There are significant costs involved with establishing a high-volume assembly line, and a significant setup time. These processes also typically do not allow for substantial changes to the designs, which as discussed in Section 3.3.1 may be necessary due to changing part requirements or substantial changes in the design.

Components constructed from metals

While the methods suggested for producing the metallic components in the previous section are particularly suitable for one off or low volume production, they can however be further optimized. As the production processes suggested are reductive, material wastage should normally be minimized, by minimizing the amount of material that needs to be removed to the absolute minimum. However, this requirement is only beneficial if the material reduction could be achieved by utilizing a smaller precursor part or billet usually. Once the billet has been purchased to be used for the manufacture of a part, the material is bought and the cost is present whether material is removed or not.

Additionally, there is a cost incurred in machining time, that in a low volume production like this may be far more significant than the cost of the material for machining. This is especially true where complex or advanced machining tools are required, such as multi-axis CNC machining and similar processes. The cost can be reduced by utilizing parts designs that do not require advanced or costly machinery, or by reducing the time required to machine the part by decreasing the complexity of the geometry of the part.

Therefore, the minimum amount of material wastage, and the minimum machining time in a low volume production like the one required here, will be incurred if the smallest possible billet is acquired for machining, by designing parts that closely match the basic geometries available as precursors and billets, and decreasing complexity of the part geometry to the greatest possible extent.

Components constructed from ceramics

The sintering and hot-pressing processes as described originally by Grover (2004) and quoted in the previous section are costly and usually require dedicated tooling. Grover (2004) specify that minimum part order quantities of 10000 units are suggested, although exceptions exist. As the total number of combustors produced is not likely to approach 10000 units, at least not during development, it is unlikely that dedicated tooling will be suitable. Additionally, it would be very difficult to prototype using these materials with minimum order quantities on that scale. As a result, manufacturing methods should be chosen where dedicated hot-pressing tooling is not required.

This is likely to be possible if a precursor part in common manufacture is selected from an available manufacturer of the UHTC. This precursor part could have a multitude of different shapes or geometries, depending on what is available. It could then be manufactured to a more complex geometry using more available manufacturing methods, like Electric Discharge Machining (EDM), or Electric Discharge Wire Cutting (EDWC).

It is recommended that parts are designed with the limitations of Electric Discharge Wire Cutting in mind, as this process generally has more limitations than Electric Discharge Machining. Namely, Electric Discharge Wire Cutting can only produce two dimensional geometries as the "tool" can only move along two axes orthogonal to the direction of the wire. This requires the parts to be designed to have complex features only on or along two axes, similarily to the parts constraints typically placed on extruded parts. If this limitation is observed, it allows for either Electric Discharge Wire Cutting or Electric Discharge Machining to be used depending on the availability of either at the time of prototyping.

3.3.4 Repairability/Modifiability

Lastly, the repairability and modifiability of the finished design should be included in the design and problem analysis. Many independent factors and considerations indicate that the possibility of modifying or repairing the combustor during prototyping or even after installation may be necessary. Even if it is not necessary, there is generally little loss to producing a part such that affecting repairs to it or replacing it can be done easily and quickly regardless of the stage of production and implementation the part is in.

The requirement of adaptability and versatility

Firstly, the concerns raised in Section 3.3.1 regarding adaptability and versatility of the prototype are again apparent here. Unforeseen problems may arise, or design specifications may change during prototyping or early production that would require the replacement of a particular part or the modification of parts or large sections of the design.

Additionally, the powerplant may be installed in circumstances where removal and replacement of the entire powerplant may be unfeasible, such as offshore, on ships, or on oil and gas platforms. In these applications, down time may also be a serious issue, as such the speed at which the powerplant can be serviced and maintained is also important. Therefore, parts or sections of the combustor or powerplant may need to be serviced or replaced on site, as easily and quickly as possible.

These ends can be achieved in a multitude of ways. Primarily however, the methods with which they can be achieved describe what not to do, rather than what specifically to do. Parts should be designed such that they can be disassembled again with basic tools, that is, manufacturing and assembly methods like welding that permanently seal parts of a design should be avoided. Additionally, parts should be designed such that as many sub components as possible can be replaced without removing other components. If entire assemblies or large portions of the powerplant need to be completely dismantled for a single part to be replaced or serviced, it will be very difficult for the operator to service a single part, even if removing and replacing the part itself once the rest of the powerplant is removed is trivial and quick.

3.4 Performance Specifications and Functionality

Ideally the potential designs and technical solutions developed for the combustor would be tested under conditions as similar as possible to the running conditions of a real counterpart or prototype, potentially even manufactured, and tested on a prototype. If that is not possible, as is the case here, computer simulations and software should be used. The solutions should be tested in simulation software that accurately and properly simulates the pressure, internal airflow, temperature, and any other relevant conditions dynamically, with a sufficiently high resolution to capture any important phenomenon at any point in the whole integrated systems cycle, even unforeseen problems or phenomenon.

In some cases, it may not be possible to accurately simulate a given problem, or the problem may be complex enough that simulating the system is significantly more expensive and time consuming than creating and iterating based on full scale or scaled prototypes in testing. In the problems discussed in this section, several such examples are explained in detail as they become apparent.

However, even in cases where the problem could be simulated in sufficient detail so that the simulation produces useful results, there may still be a need to simplify the simulations that are considered necessary, reduce the amount of simulations, or reduce the number of variables to be simulated at the same time. The more simulations are required and the more complex they are required to be increases the difficulty and cost of iteration. At some point then, the cost of doing of product development based on this form of "digital prototyping" approaches the cost of physical prototypes, in terms of the cost, time expenditure and difficulty. It is therefore desirable to take any steps possible in order to lower the cost of simulations and lower the time required in order to run each simulation, as long as the simulations remain accurate and relevant to the situation and circumstances they are supposed to simulate. This way more simulations can be run, the simulations can be run on hardware and software that is inexpensive and readily available, and more potential technical solutions can be evaluated in a given timeframe.

3.4.1 Fundamental Failure Modes

The problems identified for the combustor, or the causes of potential problems faced by the combustor can be divided into two groups, a thermal and a mechanical set of issues. The thermal problems are associated with the temperature, and variation of temperature within the combustor and its parts. The mechanical problems are associated with mechanical stresses, and variation of the mechanical stresses within the combustor. Each of these issues, thermal and mechanical problems, can therefore be divided into two further categories, problems caused by static and dynamic conditions for each. This yields a total of four categories of issues, static thermal, static mechanical, dynamic thermal and dynamic mechanical issues. These four categories collectively describe the primary causes of problems to be solved within the combustor.

3.4.1.1 Static Thermal

The moment in each cycle when the combustor experiences its maximum and minimum temperatures are of particular interest in determining the combustors peak thermal stresses. Specifying design criterions based on these points of interest for each set of parts is therefore important, as is developing technical solutions and part designs sufficient to handle these conditions. Because the increased temperature is directly caused by the combustion of fuel in the engine, these points also coincide with the extrema in pressure in the combustor. As mechanical properties and temperature are usually closely linked, there are also several concerns related to the combined issue of high temperature and high static pressure, which is further discussed later.

Melting

The first and most immediate concern related to static temperatures in the combustor is melting due to temperatures in greatly excess of the maximum service temperature. In addition to direct melting, concerns related to an excessive temperature can include material softening, annealing, oxidation as well as other unwanted chemical or physical reactions degrading the material properties.

Degradation of mechanical properties

More generally, degrading mechanical properties at elevated temperatures may be a concern. While certain components are here proposed to be constructed from ceramics with excellent refractory properties, other proposed materials, such as metals and metal alloys generally do not have this high temperature resistance Callister (2007). However, there are some. Callister (2007), on page 403, describe a group of materials referred to as the refractory metals, which contain metals and metallic alloys with favorable high temperature properties. This group contains metals such as niobium and tungsten, with melting points up to 3410°C. However, the melting point does not describe the maximum service temperature of the material. As opposed to ceramics, these materials exhibit the same properties as those of other metals, which is extensive degradation of their material properties and structural integrity when they approach these high temperatures (Callister, 2007). Largely because of this temperature response, they have significantly lower service temperatures than those of ceramics (Callister, 2007). Refractory metals are therefore not recommended for high temperature applications, due to the generally lower maximum service temperatures. Additionally, high temperatures above or approaching the recommended service temperature for a particular material, especially metallic alloys, can be a potential failure mode and should be avoided where the structural integrity or material properties need to be retained.

Annealing

A process that may cause technical issues when materials are utilized at elevated temperatures, is unwanted or unintentional annealing of metals and metal alloys. Annealing refers to a heat treatment process in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled (Callister, 2007). Ordinarily annealing is done to relieve stresses in a material, increase softness, ductility and toughness, or produce specific microstructures. In this case however, the concern is unwanted or unintentional annealing (Callister, 2007). This is especially concerning with the application of certain ferrous alloys, where the properties of a material can be greatly changed by the heat treatment of the material. However, this concern is usually considered at the design of a particular alloy (Callister, 2007). As such, the maximum service temperature specified by a material manufacturer will usually take into account the temperatures at which unwanted changes could occur to the internal structures of the material, by properties such as annealing. These unwanted effects can therefore be avoided by remaining below the recommended service temperatures.

Oxidation

There are also potential concerns related to the presence of unwanted chemical reactions at elevated temperatures. For instance, Oxidation and corrosion. Oxidation reactions are electrochemical reaction where electrons are transferred between one material and another. In some cases, this can lead to material dissolution, or loss of material in the corroded area, which is generally referred to as corrosion (Callister, 2007). This process is well known and common for metals and metal alloys. Oxidation occurs through the same reactions, but results in the formation of either film or scale like structures on the surface of materials (Callister, 2007). Callister (2007) specifies that oxidation reactions can be significantly accelerated with elevated temperatures, which is here a significant and recurring problem. Oxidation and corrosion can occur both on metals and metal alloys and ceramics and ceramic composites (Callister, 2007). While these concerns are sometimes addressed by limiting the specified maximum service temperature of a material, these reactions can also be accelerated by circumstances not solely related to temperature. Particularly relevant to mention here is that in this case, should the design later be modified to use an oxidizer source more corrosive than pure air, such as for example, pure O_2, in order to increase the combustion temperature, these concerns may require further consideration.

Creep

In many cases materials are placed into service at elevated temperatures and exposed to static mechanical stresses. Under such conditions, the material can deform plastically rather than through the normal stress strain relationships that may be expected. This deformation mechanic is usually referred to as creep, and may be important here. Callister (2007) defines creep as time dependent and permanent deformation of materials when parts are subject to a constant load or stress. Callister (2007) goes on to explain that creep is generally undesirable and a limiting factor in the lifetime of parts. For metals, creep is generally only a factor at temperatures in excess of 40% of the materials absolute melting temperature. Callister (2007) also explains that the creep characteristics of materials can be affected by three primary factors, the higher the melting temperature, the greater the elastic modulus of the material, and the larger the grain size, the better is the materials resilience to creep.

Concerns at low temperatures

Most of the effects discussed above deal solely with high temperatures. This is due to the physical properties of the combustor. Due to the proposed minimum temperature of the cooling loop, at no point will the combustor operate at excessively low temperatures. The minimum temperature proposed in the cooling loop, is relatively high, even for modern powerplants. As such, all the problems expected to be faced in the operation of the powerplant are related to temperatures that would normally be considered high, even at the minimum temperature throughout the cycle.

Immediate technical solutions for operating at elevated temperatures

The immediate technical solution to avoiding the negative effects and failure modes caused by excessive temperatures, is to use materials with higher service temperatures. This is however generally costly, and in some cases, such as for the internal combustor wall, no material with a sufficiently high maximum service temperature exists. The solution then, has to be a combination of multiple technical solutions, in order to make the design feasible. Alternatively, the temperature can be lowered. This is the proposed solution for the powerplant combustor in general, to lower the combustor housing temperature with active cooling and an insulating layer around the core of the combustor.

3.4.1.2 Static Mechanical

The moment in each cycle when the combustor experiences its maximum and minimum pressures are of particular interest in determining the combustors peak mechanical stresses. Specifying design criterions based on these points of interest is therefore important, as is developing technical solutions and part designs sufficient to handle these conditions. Because the increased pressure is directly caused by the combustion of fuel in the engine, these points also coincide with the temperature extrema in the engine, and the concerns related to the peak mechanical stresses therefore need to be considered with the high temperatures in mind.

Fracture Mechanics

The primary mechanical problem of interest in the pressurized combustor is one dealing with fracture mechanics. The problems that can be categorized under some form of fracturing include ductile and brittle fracture, which may be referred to as bursting and cracking respectively. Callister (2007) describes simple fracturing as the separation of a body into two or more pieces in response to an imposed static stress and at temperatures that are low relative to the melting temperature of the material. The applied stress may be tensile, compressive, shear or torsional. According Callister (2007) any fracture process involves two steps; crack formation and propagation in response to an applied stress.

The measured fracture strengths for most brittle materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies (Callister, 2007). This is thought to be due to the presence of microscopic flaws on the surface and within the interior of a material, that may serve to amplify or permit easier crack propagation than theoretically predicted. These flaws serve to concentrate stresses such that even though the homogenous average stress in the interior of a material may be within the limitations of the material, spots may exist where the stresses are considerably higher. As such, applying a factor of safety is recommend especially when managing brittle materials.

Ductile and Brittle fracture

Whether a material experiences ductile or brittle fracture, depends on the materials ability to experience plastic deformation. According to Callister (2007) ductile materials typically exhibit substantial plastic deformation with high energy absorption immediately before fracture. Brittle materials however experience little or no plastic deformation with low energy absorption accompanying a brittle fracture. Callister (2007) describes that ductile fracture is almost always preferred for two primary reasons; First, brittle fracture occurs suddenly and catastrophically without any warning as a consequence of the spontaneous and rapid crack propagation. On the other hand, for ductile fracture, the presence of plastic deformation gives some warning that a fracture is imminent and allows preventative measures to be taken. Under the action of an applied tensile stress, most metal alloys are ductile whereas ceramics are notably brittle (Callister, 2007).

3.4.1.3 Dynamic Thermal

The maximum and minimum temperatures are of particular interest when evaluating this particular design, and the transient conditions under which the temperature changes in between the two states can lead to a multitude of problems that need to be avoided or addressed as well. Thermal gradients within the material tends to be the cause for most of the problems associated with dynamic thermal conditions alone. These thermal gradients can be caused both by simple heat transfer, such as conduction through a plane wall with a hot and cold side, or through transient heat transfer, as shown in Figure 11. The latter case is of particular interest here.

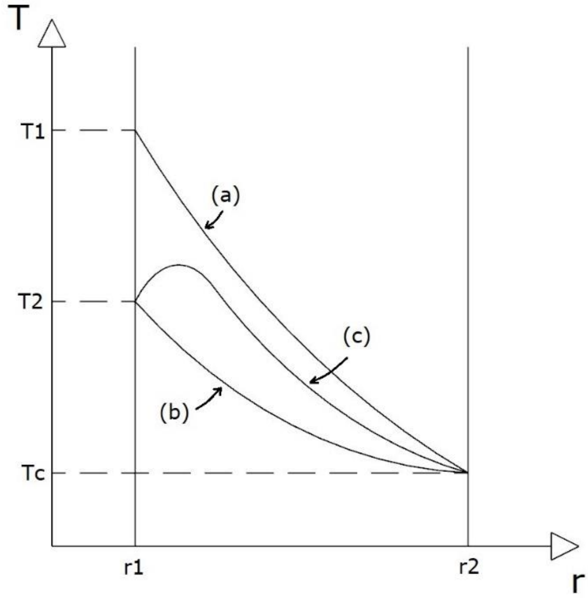

Figure 11: Theoretical transient thermal gradient response. The temperature changes from T1 to T2 on the hot side of a solid wall with thickness r2 - r1. a) The steady state temperature gradient between T1 and Tc, b) The steady state temperature between T2 and TC, c) The transient gradient between T2 and Tc.

Thermal Shock

Brittle materials such as ceramics are particularly susceptible to the non-uniform dimensional changes due to localized thermal expansion, often referred to as thermal shock (Callister, 2007). Ductile materials and polymers may alleviate some of the localized internal stresses due to thermal expansion with plastic deformation (Callister, 2007). However, due to their brittle nature, ceramics cannot deform to relieve these stresses, and are particularly susceptible to thermal shock (Callister, 2007). For ceramic bodies that are rapidly cooled, the thermal shock resistance depends on the temperature change and the mechanical and thermal properties of the material (Callister, 2007). Callister (2007) describe that ceramic materials that are subjected to temperature changes should have coefficients of thermal expansion that are relatively low, and in addition, they should be isotropic. The ceramic materials with the highest resistance to thermal shock are therefore ceramics with high fracture strengths and high thermal conductivities, as well as low moduli of elasticity and low coefficients of thermal expansion.

Callister (2007) goes on to describe that thermal shock may be prevented by altering the external conditions to the degree that cooling and heating rates are reduced and temperature gradients across a body are minimized. If possible, modifications of the properties of the materials to include the favorable characteristics mentioned above are also recommended.

3.4.1.4 Dynamic Mechanical

Lastly, there are multiple issues caused by fluctuating mechanical stresses within the part. Unlike with the thermal dynamic problems, these are mainly caused by the dynamic fluctuations of stresses within the part. The most common one of these problems, and most widely recognized, is that of a part being stressed, relaxed, and stressed again causing work hardening.

Dynamic stress categorization

Three general types of structural mechanical loading tend to be recognized in the literature, static loading, that is here referred to under the problem of peak mechanical loading, instantaneous, transient or momentary loading, and impact loading. The latter two are usually categorized as different types of dynamic structural loading. Of the latter two, only the former problem of instantaneous, transient or momentary loading is of interest here, as no momentary loading is taking place.

Momentary or transient loading is categorized as a non-stationary loading where the only energy relevant is the energy added to the system due to structural loadings such as forces applied to a structure meant to withstand those forces. As opposed to impact loading, where energy can also be added to the loaded part through the absorption of momentum and kinetic energy from an impact. The difference between these loading mechanics is subtle, but significant. In the case of momentary or transient loading the energy transfer or addition of energy to the system is dampened by the mass and flexibility of the loaded part. As a result, a part that experiences momentary or transient loading will generally be significantly over-dimensioned if it is dimensioned according to an equal static load.

This is in difference to impact loading, where the addition of the energy due to the impact results in the loaded part under impact loads being under-dimensioned if only the forces applied to the part are considered and the part is dimensioned according to an equal static load.

Both of these latter loading categories can be cyclic and lead to the problematic effects explained further on in this section, as cyclic loading refers to repetition of the loading over multiple stress cycles.

Fatigue

Callister (2007) describe fatigue as a form of failure that occurs in structures subjected to dynamic and fluctuating stresses. Under these circumstances, it is possible for failure to occur at stress levels considerably lower than the tensile or yield strength for a static load. Callister (2007) describe three important properties of materials in the study of material fatigue. Firstly, the fatigue limit describes the largest value of fluctuating stresses within a material that will not cause fatigue within a material even for a functionally infinite amount of cycles. For many steels, the fatigue limit is between 35% and 60% of the yield strength (Callister, 2007). Secondly, the fatigue strength describes the stress level at which failure will occur for some specified number of cycles (Callister, 2007). The fatigue strength is important for materials such as nonferrous alloys that do not have a known fatigue limit. Lastly, the fatigue life describes the number of cycles that is likely to cause failure at a pre specified stress level (Callister, 2007).

The fatigue limit provides a reasonable starting point for estimating a factor of safety required to prevent fatigue failure. If the material does not have a fatigue limit, the fatigue strength is recommended to be used, and the estimated number of cycles recommended to be noted in the performance specifications of the completed part.

Cyclic Crack Initiation and Propagation

Callister (2007) describes the process of fatigue failure as characterized by three distinct steps. Firstly, the crack initiation, wherein a small crack forms at some point of high stress concentration. Crack nucleation sites are similar to those described in Section 3.4.1.2, and include points such as surface scratches, sharp fillets, keyways, threads, dents, and so on. Additionally, cycling loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers and become crack initiation sites (Callister, 2007). Secondly, the crack propagation, during which this crack advances incrementally with each stress cycle (Callister, 2007). Finally, the final failure which occurs very rapidly once the advancing crack has reached a critical size (Callister, 2007).

Callister (2007) recommends certain design factors in order to mitigate the risk of fatigue failure of part designs. They emphasize notches and geometrical discontinuities as points that can act as stress raisers and fatigue crack initiation sites. They recommend that points such as grooves, holes, keyways, threads, and so on are avoided where possible. Callister (2007) goes on to describe that the sharpness of the discontinuity, in effect, the smaller the radius of curvature, the more severe the stress concentration may be. They go on to specifically recommend utilizing large rounded fillets with large radii of curvature as a specific way to remove sharp corners, as shown in Figure 12, in order to minimize the number of crack propagation sites.

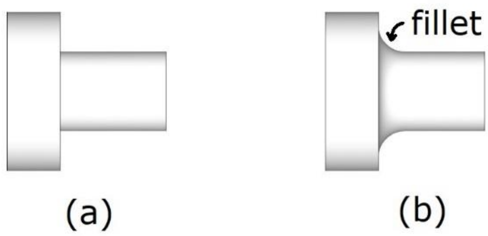

Figure 12: Part designs for fatigue mitigation. a) without large curvature fillets, b) with large curvature fillets.

Strain hardening

Callister (2007) describes strain hardening as the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes this effect is also referred to as work hardening, or cold working (Callister, 2007). Strain hardening occurs due to an increase in the density of dislocations in the metal crystal structure (Callister, 2007). As the metal is deformed repeatedly, the number of dislocations increase and each dislocation prevents more movement of any part of the structure (Callister, 2007). Strain hardening is both considered a problem related to fatigue failure, and used intentionally in order to improve the mechanical properties of metals during fabrication processes (Callister, 2007).

As strain hardening occurs due to plastic deformation of a material, one way to prevent unwanted strain deformation is to limit the stress on a material to at most the materials yield stress, thereby preventing plastic deformation as a whole. Elastic deformation cannot cause strain hardening.

3.4.2 Insulated Core

It is apparent that due to the excessive internal temperature of the combustor, a solution needs to be developed such that the wall temperature at the internal surface of the combustor can be reduced. The internal combustor wall is in direct contact with the combustion gases at the core of the combustor. Heat transfer at this surface occurs by convection, and radiation with the combustion gases. There are multiple ways in the literature to deal with similar situations directly.

One potential solution to avoiding the problems with elevated temperatures in the combustor is surface coating. Surface coatings are often used in high temperature applications to reduce the absorptivity of a surface, and add a high thermal resistance to heat transfer across a surface (Incropera et al., 2017). However, this solution alone is not sufficient. By applying a surface coating, it may be possible to reduce the temperature of whatever insulating or wall material is used beneath the coating, however the coating also has a maximum service temperature that needs to be accounted for. As such, surface coatings do not work in terms of reducing peak temperatures in the material, as they merely translate the issues, rather than address them. Surface coatings may however aid in preventing the concern of oxidation, if a material with a high risk of oxidation is utilized. However, as oxidation is not a parameter possible to test further in the context of this work, it will not be discussed further past this point.

As no other insulator can reasonably be applied, as it already is the insulator, or other stronger materials can be chosen, as these materials have some of the highest service temperatures of any available, active cooling is a necessity in preventing the concerns related to elevated temperatures in the insulated core. Of particular relevance to the insulated core are some of the problems discussed in Section 3.4.1.1, namely melting and oxidation. The problems of annealing and other forms of degrading mechanical properties, as well as creep, are not particularly relevant to ceramics like those proposed here. Creep may be beneficial here, as it may serve to offer some slight material flow in in the ceramic to mitigate some of the problems associated with thermal stress and fatigue (Callister, 2007).

The available materials that the insulating core can be made from, are all relatively brittle, and have high mechanical strength in compression, but not in tension. Problems such as thermal shock and cyclic stress fracture therefore need to be taken into consideration. (Callister, 2007) has recommended several means to prevent thermal stress fracture and crack formation and propagation as a way to mitigate failure. Avoiding small radii or sharp discontinuities in the design will therefore be necessary for this part.

Additionally, the problem should be addressed in the construction of the insulating core such that the brittle materials are under no risk of coming under tension, regardless of the temperatures of the parts surrounding it. This is a common problem in structural engineering with concrete construction, which is usually solved by pre-compressing if the material has to be in tension, or avoiding tensile applications completely with clever parts designs (Callister, 2007).

Pre-compression however needs to be dimensioned correctly depending on the temperature range of operation and the maximum stresses within the material. If for example the internal part pictured above has a higher thermal expansion coefficient than the external part, at elevated temperatures the tensile stresses within the outer part will increase, and the compressive stresses in the inner part will decrease. If the outer part has a higher thermal expansion coefficient than the inner part, at elevated temperatures the tensile stresses in the outer part will increase, and the compressive stresses in the inner part will decrease. The applicability of this solution is therefore limited by the thermal expansion coefficients of the materials, their magnitude related to each other, and the temperature range, as well as the materials mechanical properties.

In order to avoid the problem of thermal shock specifically, the temperature gradients within the material should be monitored and controlled to the greatest possible extent. The combustor should be heated gently to temperature before it is started if necessary, and cooled down slowly rather than shut off to cool rapidly. The temperature of the cooling loop may also be adapted to be high enough that it serves to heat the powerplant during the “cool” period of the cycle, and still cool during the “hot” period.

3.4.3 Cooling System

Another potential concern related to excessive temperatures in the combustor, is the potential for overstressing the cooling loop. Most active cooling systems have a maximum heat duty that they are able to accept, however, in this case, the heat duty of the cooling loop is not set in the initial design specifications. The cooling fluid is known, and its temperature is roughly estimated, however, this allows multiple solutions on how to prevent this potential problem. The cooling loop is specified to be using high temperature helium gas. As there is no phase change involved, boil off and related effects should not be a concern for this design, and do not need to be addressed.

The first potential solution to overstressing the cooling loop, is adapting the flowrate, and thereby also alter the heat duty of the cooling loop. While this could conceivably be done actively by a combustor controller, the solution proposed here is simply to increase the flowrate permanently such that the cooling loop has a sufficiently high heat duty and will not exceed this duty during normal operations.

The dynamic changes in temperature in the cooling system may also need to be addressed, but the solutions for this may require the inclusion of the design of the cooling system, which is outside the scope of the design of the combustor itself. One problem that may arise due to the dynamic changes in temperature is the changing heat duty of the cooling system resulting in overstressing the cooling system. Like earlier, a potential solution here can be found by looking to consumer electronics, and the construction of cooling systems for microchips and electronic circuits.

Many cooling systems for consumer electronics have to deal with the issue of irregular cooling demand, due to fluctuating temperatures and power draw of the electronics components they cool. This is an analogous problem to the one described for the combustor, where the fluctuations of temperature due to the cyclical combustion leads to an irregular cooling demand. This problem is usually addressed with the use an excessive heat capacity in the heat spreader and/or cooling loop. In the same way, the problem may be addressed here, by dimensioning the thermal capacity of the system in such a way that the heat duty of the cooling loop remains constant throughout the cycle.

As the cooling system is pressurized internally, peak and cyclic mechanic stresses may also need to be addressed in the dimensioning of the cooling loop. However, as the proposed cooling loop is to be constructed from available materials and parts which are usually limited to simple bent round tubing, or other simple geometry tubing, the dimensioning of these parts is trivial and can be done quickly and especially easily with the use of software as is described later.

3.4.4 Mounting Hardware and Heat Spreaders

The mounting hardware and heat spreaders are proposed to function both to interface the insulated core with the cooling system, and provide efficient thermal contact, as well as to compact the insulated core such that fracture modes may be prevented to the greatest possible extent. The thermal mass and a high thermal conductivity of the mounting hardware is also hoped to dampen the impact of localized temperature fluctuations on the cooling system.

The material properties required then, are a reasonably good thermal capacitance, a good thermal conductivity, and sufficiently high tensile strength. Materials such as aluminum alloys typically have all of these properties, and are additionally cheap and quick to machine and manufacture parts from.

Alloys such as aluminum alloys are characterized by the ductile failure mode, as well as a risk of potential surface oxidation, creep as well as an increased risk of fatigue failure due to cyclic stresses. As such the lifetime of a potential part needs to be taken under consideration, and design considerations like those proposed should be applied in order to prevent crack formation and propagation.

3.4.5 Combustor Housing

Finally, the combustor housing is at the outermost surface of the combustor. As the combustor is actively cooled, and because of the stacking order described in [section ref] the temperature of the combustor housing will likely approximate the temperature in the cooling system. Additionally, the problem of thermal fluctuations in the combustor housing are addressed implicitly. Because of the stacking order and the position of the combustor housing relative to the combustion, the combustor structure dampens thermal fluctuations, and the housing is as a result not expected to experience large thermal fluctuations.

Due to the problems of leakage and pressure homogenization across the combustor discussed further in Section 3.5, the combustor housing is here likely to experience the mechanical stresses associated with the pressure fluctuation in the combustor. As such, the concerns raised in Section 3.4.1.4 regarding cyclic mechanical stresses, as well as the ones for static mechanical stresses should be considered here, and some of the same considerations as were applied for the -blank- should be applied. Namely, the part should be constructed of materials likely to experience ductile fracture, that are also strong in tensile stress. As the materials proposed for this application mirror those used in conventional engines, this concern is satisfied. The part should also be designed such that the types of crack initiation sites discussed by Callister (2007) are avoided to the greatest possible extent. Finally, the part should be dimensioned such that both the static stresses do not exceed the elastic limits of the material, to prevent strain hardening, and the cyclic stresses do not exceed the fatigue limit or fatigue strength of the material, to prevent crack initiation and fatigue failure.

3.5 Insulation and sealing

The proposed structure of the combustor listed in the initial design specification in Section 2.1.1 and Section 3.1 is layered, in that in the center of the combustor, we have an insulated core, followed by a heat spreader and other mounting hardware, then a cooling system, and finally a housing. This is a complicated and costly structure for the engine cylinder as a whole. As a result, it would be wasteful and unreasonable to assume the entirety of the cylinder bore is constructed in a similar fashion when it doesn't need to be. This structure has holes and mating surfaces not only between the piston bore and the cylinder head, as is common in automotive powerplants, but intersections between each layer of the combustor as well as intersections between the piston head and the piston bore that does not require the advanced high temperature insulator. As such, this structure may face problems related to sealing, and insulating the sections of the combustor with the very high combustion temperatures from the sections that can't, or even the outside of the powerplant.

Cylinder bores on conventional engines do not require great consideration to be paid to sealing in between parts, as cylinder bores usually comprise a single part. Either an engine block with a bored cylinder bore, or a cylinder sleeve, both with a cylinder head on top. When constructed these methods have two parts interfaces in the whole system that are required to pressure proofed, if inlet and exhaust valves and injectors are discounted. These parts interfaces are the seal between the cylinder and the piston, and the seal between the cylinder head and the cylinder itself. With the addition of a high temperature combustor section on a conventionally designed cylinder, it adds at least one parts interface that also need to be sealed, in between the conventional cylinder bore, and the high temperature combustor section, potentially more.

Additionally, the layered structure of the combustor presents the problems with a potential lack of sealing in between the internal high temperature core, through to the outer combustor housing. Even though the housing itself may be sealed such that the total volume of the combustor itself is leaked, there may still be leaks of high temperature flue gases from the internal volume, through the insulator, heat spreader and in and around the cooling system.

Unfortunately, this is precisely the type of problem that was discussed in the introduction to Section 3.4, a typical example of a problem that is hard or near impossible to simulate directly, and the effects of which can be estimated to be either catastrophic or negligible. The effects could be catastrophic if large volumes of superheated combustion exhaust leaks past the thermal insulation, causing damage or destabilizing the components further out from the insulated core, but could also be completely negligible if the leakage is small, or the average temperature of the combustion vapor past the core is maintained low enough by convection cooling with the parts in this region. This problem is therefore noted, but would likely have to be reserved for testing and evaluation in prototyping or later studies.

Problem of pressure homogenization across all cavities and openings in combustor The lack of sealing or difficulty of sealing in between the layers of the high temperature combustor may also present certain issues with respect to pressure homogenization across the combustor. The leaks of flue gases from the internal volume of the core and into the combustor layers implies the possibility of pressure homogenization across the combustor, but again, this is a problem where solutions can be suggested, but are very difficult if not impossible to test for directly using simulations.

3.6 Concluding the in-depth problem analysis

It is clear from the analysis that there are many requirements to using the solution proposed in Section 3.1 effectively. These limitations and requirements span those that are due to pure operability concerns and are totally unrelated to the selected materials, to requirements purely due to the constraints related to the fragility of ceramics and ceramic composites. It is however clear that these materials have been used in many use cases previously, and as such, knowledge of their behavior in different sets of circumstances is abundant, and solutions that address their inherent shortcomings are well known, documented and easy to implement.

Some problems however are still required to be addressed. Section 3 gave an overview of potential problems with the implementation and their solutions, but not the interplay between those solutions when they are combined into a finished design. It also gave little clarity in the specific dimensions that the required product and design would need to have, as such, these will have to be determined through other methods than pure literary analysis, such as experimentally, or optimized through appropriate computer simulations.

In Section 4.2 the solutions and problems discussed in this section are addressed by developing a complete and coherent design that addresses the concerns elaborated in Section 3. The design is then optimized and tested simultaneously through computer simulations, such that its performance can be ascertained and its dimensions determined.

4 Designing and Optimizing the Solution

Once the problems and potential complications faced by the design have been investigated in detail, a design needs to be modeled by putting the lessons learned in the problem analysis to use. Once the design has been completed, it can be dimensioned and optimized for the current specified parameters and selected materials.

4.1 The Required Software

Both the design and the simulations for optimization can be done significantly easier through the use of properly selected, and established software packages and computer aided tools. These tools serve to automate some part of the process, by allowing parametrization for design and other simplifications for the design process that can greatly increase the efficiency by which the design and optimization process can be done. However, such tools are generally expensive, especially the ones with access to more complex simulation types, like dynamic or transient analysis types. It is therefore important to consider the cost both of the software itself, for example the licensing, the computation time where the user may have to wait to progress in the design and optimization process, and the cost in terms of time expenditure from the user due to the speed and efficiency of the software itself.

4.1.1 Autodesk Fusion 360

Fusion 360 is one of Autodesk newest CAD tools. Autodesk is a well-known company within CAD/CAM software that has previously released software packages such as AutoCAD and Inventor. Fusion 360 offers many advantages over its competitors, first and foremost is its high availability. Autodesk offers the software for free for any academic use, as well as for hobbyists and small businesses. This makes the CAD, CAM and CAE tools available in Fusion 360 accessible rapidly for almost anyone, in contrast with competitors such as Siemens NX and Solidworks, which tend to be costly and are largely unavailable for smaller companies that cannot afford their steep fees. Even for larger businesses that do not qualify for the terms under which Autodesk offers their software for free, Fusion360 is very inexpensive.

Fusion360 also offers many advantages in terms of the integration of what should be deemed different software packages within the same software, and an ergonomic and rapid user interface. The software offers CAD, CAM and CAE, and allows modeling, parts design, engineering, simulation, animation, and even physics simulating moving parts within the same software, all with relative ease. This makes the software package ideal for rapid digital prototyping, such as in this case.

CAD Software

Fusion 360 offers an extensive number of tools in the CAD portion of the software, including specialized ones for operations that may in other software be tricky or require the user to understand the limitations of the manufacturing methods required. One example of this is the integration of sheet metal tools, a custom toolset designed to mimic the operation usually used to manufacture sheet metal parts, which have rulesets to allow even untrained users to operate and design parts rapidly and easily.

Integrated Simulation Packages

Fusion 360 Simulation offers a number of different validation tools to allow users to evaluate the performance of designs generated in the CAD portion of the program. The program includes simulation tools that simulate the part under the given conditions in the cloud, as well as simulation tools for simulating parts locally on the computer running the software. Both are accessible with an academic or small business license, though the local simulations are of significantly higher interest.

Fusion 360 offers static stress analysis, modal frequency analysis, thermal stress analysis, and thermal analysis in the simulation package for use locally on the running computer. Of these, the static stress analysis, and thermal analysis modes are of particular interest. Both of these simulation types implemented in Fusion 360 utilize Finite Element Analysis.

The static stress analysis implemented in Fusion 360 has a series of assumptions implemented by default that may be important to consider. It assumes that the structure returns to its original form, that there are no changes in the loading direction or magnitude, that the material properties are constant, and the deformation and strain are small.

The thermal analysis implemented in Fusion 360 has a number of assumptions implemented by default as well. It assumes that the loads and constraints are time independent, and produces a steady state result. It requires a heat source and heat sink to be defined, and at least one temperature based thermal load is required to provide a reference temperature.

4.1.2 Additional Autodesk Software

Although the tools implemented by default in Fusion 360 are extensive, they may not cover all of the needs related to modern manufacturing and design. Of particular interest here, is the possibility of integrating Fusion 360 with programs such as Ansys Mechanical.

Ansys Mechanical is a well renowned simulation solution that can be used to facilitate, amongst other things, impact simulations and transient stress analysis. If necessary, integration with software packages such as Ansys Mechanical, can be done using Fusion 360. The results produced through static analysis methods, like those described and suggested in Section 3.4, can then be validated for dynamic loadings that closer approximate the real conditions the design is expected to experience.

4.2 The initial design and setup

Before more elaborate simulations can be done, and proper optimization of the components and sections can be done using those simulations, there is a significant amount of setup and preparation that needs to be done in the CAD module. Firstly, materials need to be created in the software so the proper criterions and limitations on the materials used can be applied and recognized in the design phase. Subsequently, an original CAD model needs to be made, keeping in mind the design constraints specified in Section 3. Finally, the simulations that are required for optimization need to be set up with the necessary limits, boundary conditions and other necessary parameters and then run. With the results of these simulations, the dimensions of the completed system can be determined, and its performance assessed.

4.2.1 Materials

Fusion 360 and Autodesk have established an extensive materials library containing many different types of materials, polymers, steels, and other metals, even some ceramics. The properties of each material are available in the material browser for inspection and even modification if required.

However, some materials of interest are understandably missing due to the limited scope of their applicability and their unusual nature, and will have to be added manually. The materials are custom generated for the project, using the visual aspects of existing materials as a starting point.

Material Selection

The initial study described in Section 2 was primarily an academic one. It showed very promising results from several materials, such as Hafnium and Tantalum Carbides. However, these materials also had their shortcomings that make them less desirable in a practical application where concerns other than simple thermal endurance have to be addressed. Namely, Hafnium Carbide is very susceptible to oxidation even at low temperatures. Additionally, these materials are still highly experimental, material properties for them are hard to find, and, most importantly, they are not regularly offered for sale through available suppliers for practical non-academic applications.

There are however materials that still offer promising results in the initial study in terms of their thermal resistance in high temperature applications, and offer good and favorable qualities elsewhere too. Silicon Carbide showed relatively good performance in the initial testing, though by no means the best, in particular due to its very high thermal conductivity leading to large wall thicknesses. It may however be more than good enough. Additionally, it offers resistance to oxidation at high temperature that the ceramics such as Hafnium Carbide does not. Additionally, the high thermal conductivity was recommended in Section 3 in order to prevent the problem of thermal fracture. It is also relatively easy to locate materials suppliers and manufacturers with extensive specifications sheets and performance ratings for the products they offer.

Uncertain Material Properties

However, the materials properties provided by the manufacturers may be based on assumptions about the use cases or the needs of their potential customers. As such, they may need to be reevaluated using the existing academic literature in order to see if such assumptions have been made, if the manufacturer or supplier does not specify the intended use case or assumptions made for certain properties.

The service temperature, is one such property that may be highly dependent on the use case. In the case of these materials, this is especially true. For one material, the service temperature was given as 970K from one manufacturer, whereas an academic publication, and another manufacturer showed the unloaded service temperature to be closer to 1350K. This is assumed to be the case elsewhere too, such that there exist both service temperatures under some load, and service temperatures unloaded. The latter is assumed to be relevant for this case, as the ceramic in the insulated core is not under any structural load by design, and becomes loaded only due to thermal expansion.

Custom Materials

Materials not in Fusion 360s material library have to be generated specifically for this project, by creating a custom material with properties found from various sources. As was discussed before, this may also be considered a benefit as it allows for closer investigation of the material properties to make sure that the ones listed are not biased by assumptions that are invalid in this application

Silicon Carbide is chosen for further evaluation in the simulations and optimization ahead. Several material suppliers and manufacturers were found that offer the material for sale in other applications, some also offer the material properties. The full material properties as they are implemented in Fusion 360s custom material editor, are included with sources in Appendix 1.

Standard Materials

Many materials, especially more common ones are however luckily included in Fusion 360s material library. This is beneficial due to the plug and play nature of the library and materials application in the CAD software, which lowers the amount of time necessary to spend on this particular task. Additionally, the concerns described earlier with biased assumptions due to the assumed use cases are not as prevalent here. Firstly, because these materials are in common use in many different applications in the world today, so assumptions about the use case are seldom made. Aluminum is commonly used both as a thermal conductor and structurally, and steels, Compacted Graphite Iron and other iron alloys are often used structurally. Two materials are chosen from the Fusion 360 Materials Library, Gray Cast Iron ASTM A48 for the housing, and 6061 Aluminum Alloy for the pressure collar and heat spreader. Gray Cast Iron is selected due to its common use in the manufacturing of powerplants, so as to take advantage of the preexisting knowledgebase, and 6061 aluminum alloy for its excellent thermal properties, machineability and tensile mechanical properties. The full material properties as they are implemented in Fusion 360s material library, are included in Appendix 1.

4.2.2 Generating the CAD Model

The CAD model itself has to be sketched and generated in the CAD software before simulations can be run. First, the initial design is sketched roughly in the CAD software in accordance with the basic assemblies described in Section 3.1 to generate a starting point for the CAD prototype. Solid operations, such as for example extruding, sweeping and lofting, can then be used to modify the CAD model to fit the requirements of the digital prototype described in the previous sections.

The sections relating to adaptability and repairability put several constraints on the design that should be considered. These may be natural to consider first, as they place fundamental limitations on how parts can be designed to fit together. There is a need to be able to repair and replace as many components as possible without significant time-consuming disassembly or modification. It is also necessary to be able to assemble the components together, the first time they are constructed. These requirements complement each other, as an assembly that is possible to disassemble without significant difficulty, modification or destruction is generally possible to assemble again as well, and the inverse may also be true in some cases. It is however a simple mistake to make in CAD software, as parts are generally modeled in their assembled state, and do not require initial assembly.

4.2.2.1 The Insulated Core

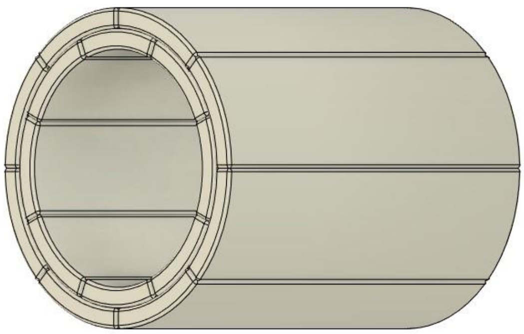

Figure 13: The Insulated Core

The insulated core is constructed from interlocking tiles. The tiles are cut with perfectly radial sides, in two layers, with the layers overlapping. This achieves multiple requirements outlined in Section 3.

The tiles need to be produced at least once. Assuming that all of the tiles are of approximately equal thickness, this allows the tiles to be made from the same thickness of precursor stock. Due to the two-dimensional geometry and flat ends of each tile, the part can be manufactured through the methods outlined in Section 3.3.2, namely Wire Electric Discharge Machining. As the parts are symmetric about a plane along the length of the tile, and the width of the tile, it allows for easier assembly as the part orientation remains more obvious to the end user, than if the part was asymmetric about either or both of these planes.

However, this symmetric part design presents issued related to the problem of sealing by creating straight paths from the center of the combustor out toward the heat spreader. Using two layers of overlapping tiles allows the tiles to seal better than they otherwise would with a single layer, by creating S or Z shaped paths that hot combustion gases have to travel down.

The part design also allows the tiles to support themselves while in the combustor, without the use of fastening hardware that both complicates the design process and may serve as crack initiation sites, as explained in detail originally in Section 3.4.1.4. Fastening hardware tends to involve many of the features specifically outlined by Callister (2007) as problematic in this concern. This structure is not ideal either, as exactly in the same way as older compression bridges, it is only supported under load and with all of the parts present. This may present an issue if one of the tiles in a layer is destroyed completely, the others would no longer be held in place. This is however a catastrophic issue that has a multitude of relatively simple other solutions that may be made, if the need should arise. Catastrophic destruction of individual tiles is not an apparent problem at this time, and not assumed likely to become an issue, as such will not be discussed further.

This mounting method allows for each tile to be supported strictly inertly, without being under significant structural loading except for a small compressive load applied through the use of a compression collar that is further described in detail with the rest of the mounting hardware and heat spreaders. This structural load also decreases as the temperature increases to the peak temperature during combustion, when the point of peak temperature and peak mechanical load coincide as previously explained in Section 3.4.1.2. This allows for a much greater service temperature of the material to be assumed, as was described in Section 4.2.1 with the difference between the loaded and unloaded service temperatures.

Lastly, all of the sharp edges of the tiles are chamfered with wide radii to further address the fracture problem described in Section 3.4.1.2 and Section 3.4.1.4 by lowering the number of crack initiation sites. The specific chamfer radius is not considered particularly important at this time, but the feature is added as a visual aid and to prevent stress propagation sites from showing up in the later simulations. It may be shown during prototyping that this additional step offers little or no benefit to the resistance of the part to the addressed concern, particularly due to the unloaded assembly method of the tiles used. If that is the case, this feature may be altered or omitted entirely.

4.2.2.2 Heat Spreader, Pressure Collar and Cooling Loop

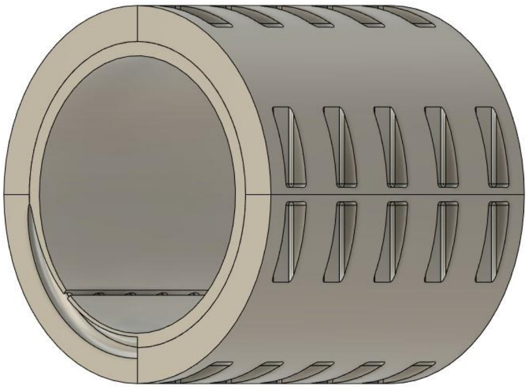

Figure 14: The Heat Spreader and Pressure Retention Collar

The mounting hardware and heat spreaders are divided into two major primary sets of parts. The inner one of these parts is the heat spreader itself, and the outer set of parts is a pressure retaining and stabilizing collar. Both of these parts are dimensioned to be made out of aluminum alloys that would save on weight and offer favorable material properties in both cases.

In the case of the inner heat spreading part, disassembly of it and the cooling circuit is assumed to be infrequent and the part is made such that the heat spreader and cooling loop may be removed simultaneously, without removing one part from the other. This allows for good thermal contact in between the cooling loop and the heat spreader to be maintained, through the use of a thermal bonding compound that can be left undisturbed.

A small cut feature is applied to the heat spreader to allow for the pressure collar mounted outside of the heat spreader and cooling loop to translate the compression from the collar to the insulated core. During installation, the cooling loop and collar may be allowed to move slightly in relation to each other due to the relief cut marked on Figure 15 in red. Additionally, this cut feature prevents the heat spreader from retaining mechanical stresses, by allowing it to move slightly to relieve them, even stresses caused by thermal expansion. This permits the materials used for it to be used at far higher temperatures than the service temperatures that would have to be observed if the part was structural.

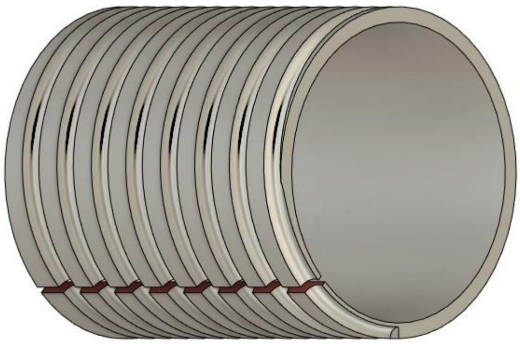

Figure 15: Heat Spreader with mechanical relief cut marked in red

The outer pressure collar is split into an indeterminate number of pieces, that can then be connected through the use of tensile fasteners to create compression around the central core. The specific tensile fasteners to be used here are not selected such that a larger degree of freedom in the selection can be made at a later time. Relief cuts are however added such that bolts may be added to compress each part together, and as a visual aid for further work on how this part is intended to be used.

Additional space for the cooling loop is allotted by avoiding features that go into the radial layer thickness allotted for the cooling loop. This permits the cooling loop to be rearranged to whatever orientation is necessary at the time when the cooling loop is designed in detail at a later date, provided the tube diameter does not increase. If the tube diameter is required to be changed, the parts could be re-dimensioned for this new part diameter, but if the tube thickness is smaller, this would not be required. This is to offer a great deal of flexibility for later work on this aspect of the design.

Unlike the heat spreader, the pressure collar does not require thermal conduction from and with the cooling loop. As such thermal interface compound is not required on this side, and good thermal contact may here be more desirable to reduce to prevent unwanted thermal conduction to parts that are unlikely to require cooling by this part of the cooling, such as the combustor housing itself. Internal and external lightening cuts may also be desirable here as a means to reduce the thermal contact area.

In order to facilitate sealing, it is recommended to utilize the pressurization of the combustor upon firing to the greatest possible extent. If the problem of sealing and pressure homogenization as described in Section 3.5 materializes, then it can potentially be used by allowing the relief ledge marked in red in Figure 16 to rest on a section of the housing. By utilizing this solution, the force of pressurization of the combustor will stretch the parts outward from the central axis, and help seal the combustor and prevent leaks.

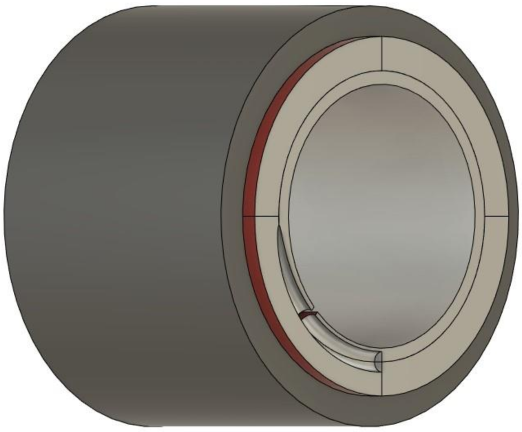

Figure 16: Relief ledge marked in red

4.2.2.3 The combustor housing

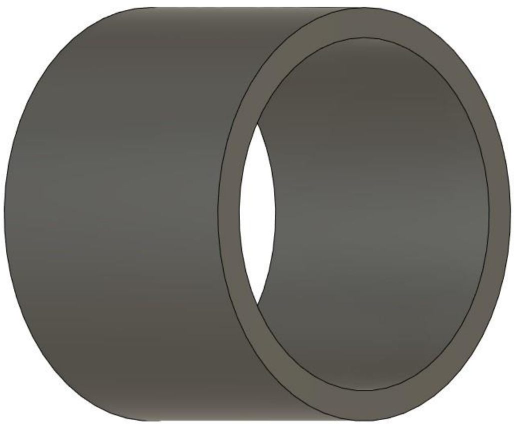

Figure 17: The Combustor Housing

Lastly, the combustor housing has a limited and basic design, with a lot of degrees of freedom allowed for future design integration. Figure 18 shows which sides and faces are not of particular or important design, and may be altered to fit with surrounding geometry during the project integration.

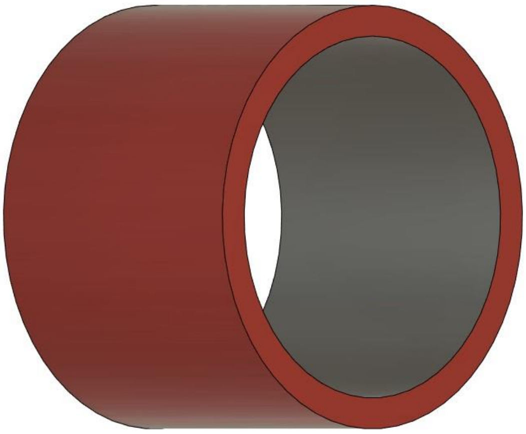

Figure 18: Cutaway of Combustor Housing. Un-important and modifiable faces depicted in red.

4.2.3 Concluding the Initial Design

Once the initial CAD design has been completed using parametric modeling, it can then be optimized using Fusion 360s integrated simulation packages. The parametric modeling employed by Fusion 360 makes this very simple, along with some rudimentary understanding of how the model is structured, and which problems need to be solved by dimensioning and optimizing the solution. Some problems however, remain to be solved even at this stage and will not be further discussed in this study. These problems include problems that are relatively easily solved, and that are thought to be better to solve when the system is integrated with the final complete powerplant design.

The primary problem of this kind is integration with the powerplant itself. Integration is accommodated by a basic structure of the cooling loop, such that there is a large degree of freedom available for engineers at a later date to discuss the best way to terminate and connect the cooling loop as dimensioned in this case to the rest of the integrated system. The large degree of freedom is accommodated by two primary factors; The use of a heat spreader, and the use of a basic coil structure for the cooling loop. The heat spreader and pressure collar allow for a lot of flexibility in moving the ends of the cooling loop without risking the accidental creation of hot or cold spots, as it distributes the heat efficiently and quickly through the material due to the large thermal conductivity of the aluminum alloy chosen.

Additionally, integration with the rest of the powerplant. For the ease of repairability and modifiability, it is recommended that the housing for this section of the powerplant is integrated with the powerplant through the use of non-permanent methods, such as bolts, rather than welds or other permanent attachment methods.

The final unoptimized design is therefore completed and can be passed to optimization in the next section, so part dimensions can be determined through simulations analogous to the conditions of the combustor when in use.

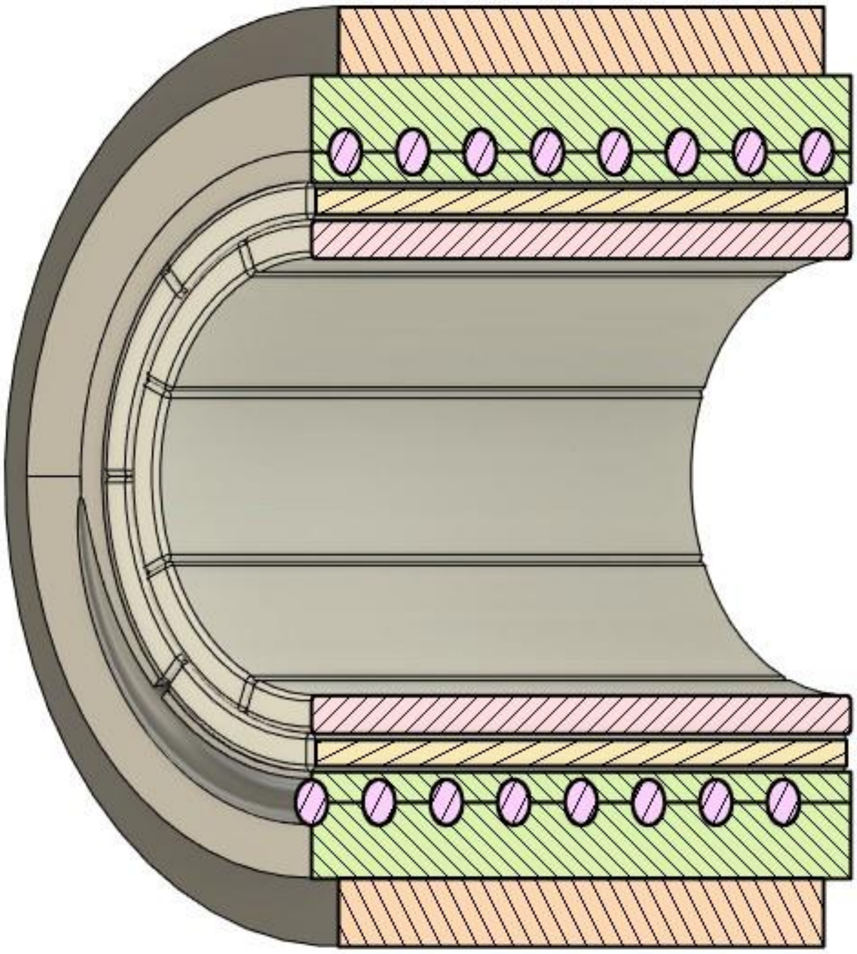

Figure 19: The Final Design. Unoptimized and cutaway to show internal geometry.

4.3 Dimensioning and Optimization

The parametric CAD approach that Fusion 360 offers lends itself well to using the simulation packages included in the same software to optimize the part dimensions. If a simulation produces a sub-optimal result, the relevant sketch or other operation in the CAD timeline can be accessed, its dimensions changed, and the simulations can be reloaded. The software will generally always recognize the limits and boundary conditions to have remained unchanged when the simulation is reloaded with the new dimensions. This permits very rapid optimization schemes as long as results can be read and understood directly from the simulation results.

Fusion 360 offers many tools for interpreting the results produced by simulations. In the case of thermal simulations, it allows direct graphical readout of thermal gradient, absolute temperature and heat flux, and color grades the result according to the scale chosen. In the case of stress simulation, the parameters of stress, displacement, safety factor according to yield stress, strain and contact pressure are possible to plot onto the design grid. For all simulation types Fusion 360 also allows readout of point probes, creation of point probes, pinpointing the minimum and maximum results of the simulation of any of the parameters listed earlier, and also creating slice planes into the model to show the internal conditions under the load specified in the mode of analysis.

4.3.1 Initial Dimensioning

There are certain aspects of the design that need to be dimensioned directly, but may not be tied to testable parameters, or in this specific case, parameters or performance that can be tested through software simulations.

The Length of The High Temperature Combustor

It is necessary to measure or otherwise determine the length of combustor. The combustion gases can be modeled using the ideal gas law and a polytropic process between the initial combustion temperature and the maximum service temperature of alloys in common use. The length of the combustor is determined such that it is sufficiently long that conventional materials used are not to any great extent exposed to combustion gases at the elevated temperatures. As the volume increases throughout the stroke, the temperature reduces in the combustion gases until they drop to temperatures where conventional materials and designs such as those described by Myagkov et al. (2014) can be utilized. Therefore, the length of the combustor is inextricably linked to the temperature throughout the process.

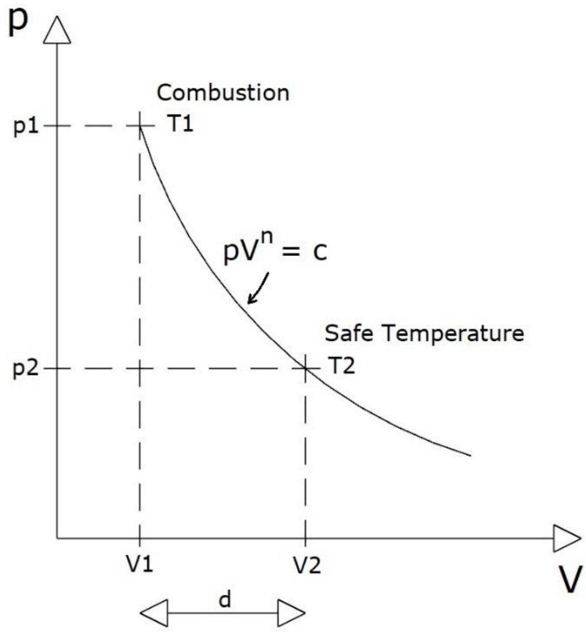

Figure 20: Pressure and volume diagram of a polytropic process. The diagram shows a polytropic process as indicated by the curved line, operating between two volumes, V1 and V2. The pressure and temperature change from p1 and T1 to p2 and T2. The length of a theoretical combustor is indicated as the change between the two volumes.

If the combustion gases are modeled as a homogenous ideal gas, undergoing a polytropic process, where the polytropic index **n** is defined such that $\boldsymbol{\gamma} \leq \boldsymbol{n} \leq \infty$. This special case of the polytropic index is consistent with isentropic and isochoric processes at the extrema, and in between it is consistent with processes where both heat and work flow out of the system as is the case here.

$p_1 V_1/T_1 = p_2 V_2/T_2$	The combined ideal gas law comparing two states.
$p_1 V_1^n = p_2 V_2^n$	The polytropic process relation comparing two states.

Using these two relations it is possible to form an expression for $V_2 = V_1(T_2/T_1)^{1/(1-n)}$. The worst case here is where $\boldsymbol{n} = \boldsymbol{\gamma}$, which results in the greatest final gas volume and therefore the longest high temperature combustor segment. It is also the case corresponding to an isentropic process, where no heat is removed. The other extrema is the case $\boldsymbol{n} = \infty$ where the process corresponds to an isochoric process, where no work is removed, and therefore the shortest high temperature combustor segment.

An increase in the polytropic index towards ∞^+ corresponds to an increase in the heat transfer out of the system. It is therefore apparent that the length of the high temperature combustor is variable and depends on the amount of heat that is removed through active cooling. For this system, at least some is required. Additional heat can be removed through active cooling as well, but this amount remains variable, and more suited to be determined in a cost benefit analysis once the relevant costs of cooling, and the cost per unit length of the finished combustor is established by the partner company, as such, no particular length of combustor is specified, and the combustor length in this work is considered to be arbitrary.

4.3.2 Thermal Optimization

For the thermal optimization scheme, a few assumptions have to be made. First and foremost, the method of heat transfer from the hot combustion gases in the center of the combustor into the insulated core has to be approximated by some method. For this, the method and calculation proposed by Woschni (1967) is used with its inclusion of radiation. Although this model is not without issue as has been discussed previously, it is still one of the most generally applicable models through which heat transfer can be calculated.

Simulation Selection and Load Case

There are two primary sets of requirements for the thermal performance of the combustor. Due to the relation between the peak thermal conditions and the static or steady state response of the system to the conditions applied, as was elaborated upon in Section 3.4.1.3, it is clear that if the system is dimensioned for steady state, it is over-dimensioned for the real circumstances at a cyclic rate of 100 rpm. As such, the steady state thermal simulation is chosen. The load case is chosen such that it mirrors the realistic conditions of the combustor as closely as possible. Convection heating is applied to the internal surface, and the cooling loop component is kept at a constant temperature. This sufficiently constrains the simulation.

For heat transfer by convection, Fusion360 requires the heat transfer coefficient **h** and the ambient temperature, in this case the temperature of the hot combustion gases, **T**, be input as heat loads in the simulation software. The heat transfer coefficient h is calculated using Woschni's heat transfer model using the original tuning constants, and results in a heat transfer coefficient of h = 184.97 w/m^{2}K. The relevant formulae and input constants in order to yield the heat transfer coefficient are included in Appendix 2. The ambient temperature is as specified in the problem description, T = 3850K.

The cooling loop is specified to be running at a constant temperature T = 473.15K. This temperature is chosen such that the aluminum components used, remain at temperatures sufficiently lower than their melting temperatures or maximum service temperatures, and the ceramic components are kept sufficiently hot such as to prevent the problems related to thermal fracture discussed in Section 3.4.1.3. Some of the other settings are discussed below, however the full list of settings applied, including load case parameters in the software is included in the printed report for the simulation in Appendix 3 for the unoptimized base case and Appendix 4 for the optimized case.

Parts Interactions and Contacts

Fusion 360 can generate and apply contacts between components in the design automatically, or they can be applied manually, and they can be modified in either case. In most cases the automatic contacts for thermal analysis are considered sufficient, and in this case the automatically applied contacts were found to mirror the real case sufficiently well. No modifications were made.

Mesh Design

The automatic mesh generation is considered sufficient, however it is inspected in between each simulation cycle, to prevent potential problems with artifacts or errors. No errors or artefacting were discovered.

Satisfying Performance Requirements

The area of interest in each iteration is the contact interface between the insulated core and the aluminum heat spreader, and the inner most surface of the insulate core. These areas represent the areas with the highest temperatures for the aluminum components, and ceramics respectively, and are therefore the areas with the highest risk of exceeding the maximum allowable temperatures for each material.

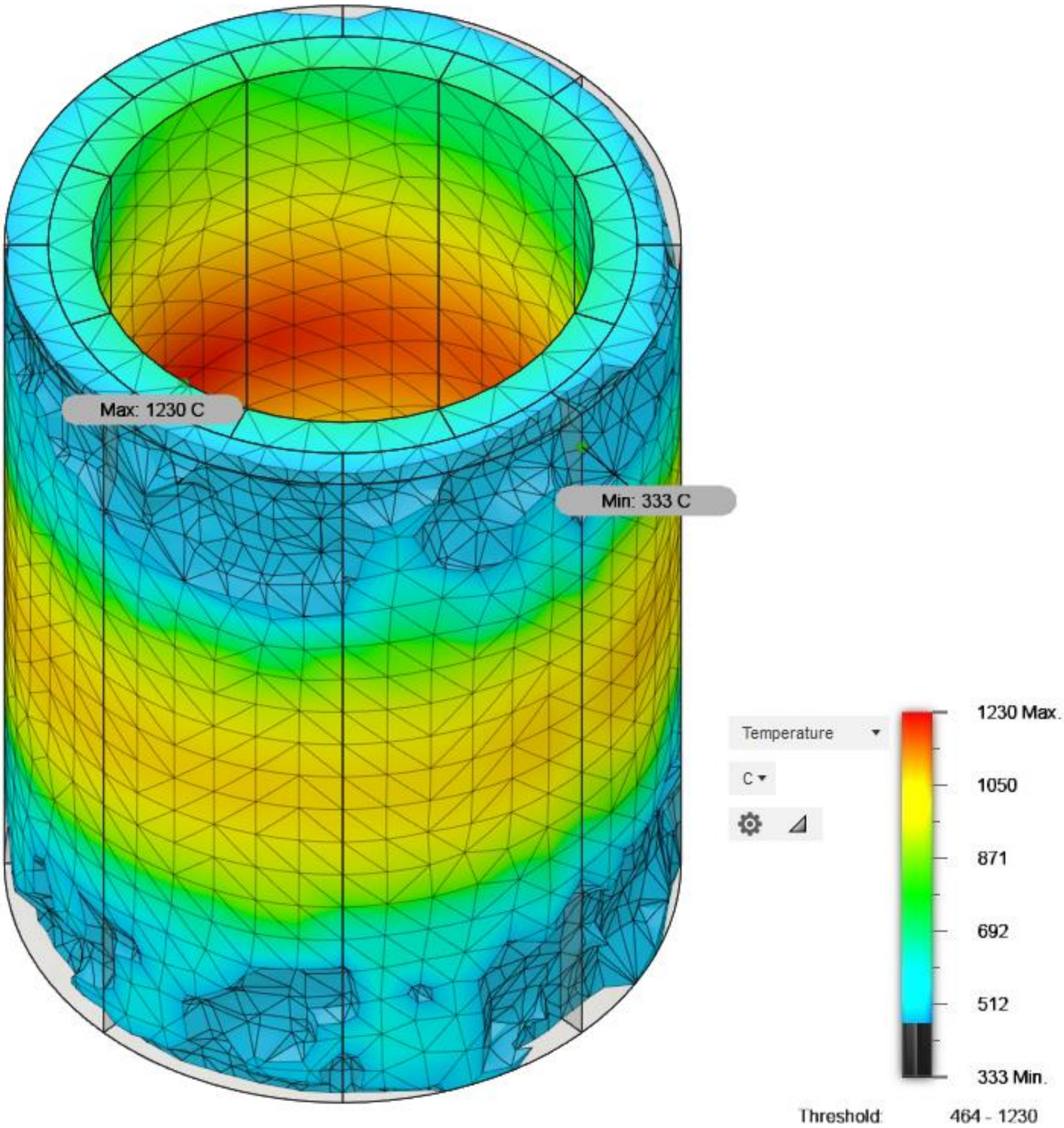

Figure 21: Unoptimized Insulated Core Design in Steady State Thermal Analysis. The displayed grid is modified such that any volume with temperatures lower than the minimum temperature or 464°C are not displayed. Minimum and Maximum Temperatures are displayed as Max and Min respectively.

From the first simulation it is apparent that while the internal temperature of the insulated core is well within the maximum service allowed, this is not the case for the temperature at the interface between the aluminum and the insulated core. The thickness of the insulated core is increased, and the simulation is repeated, until satisfactory results are obtained.

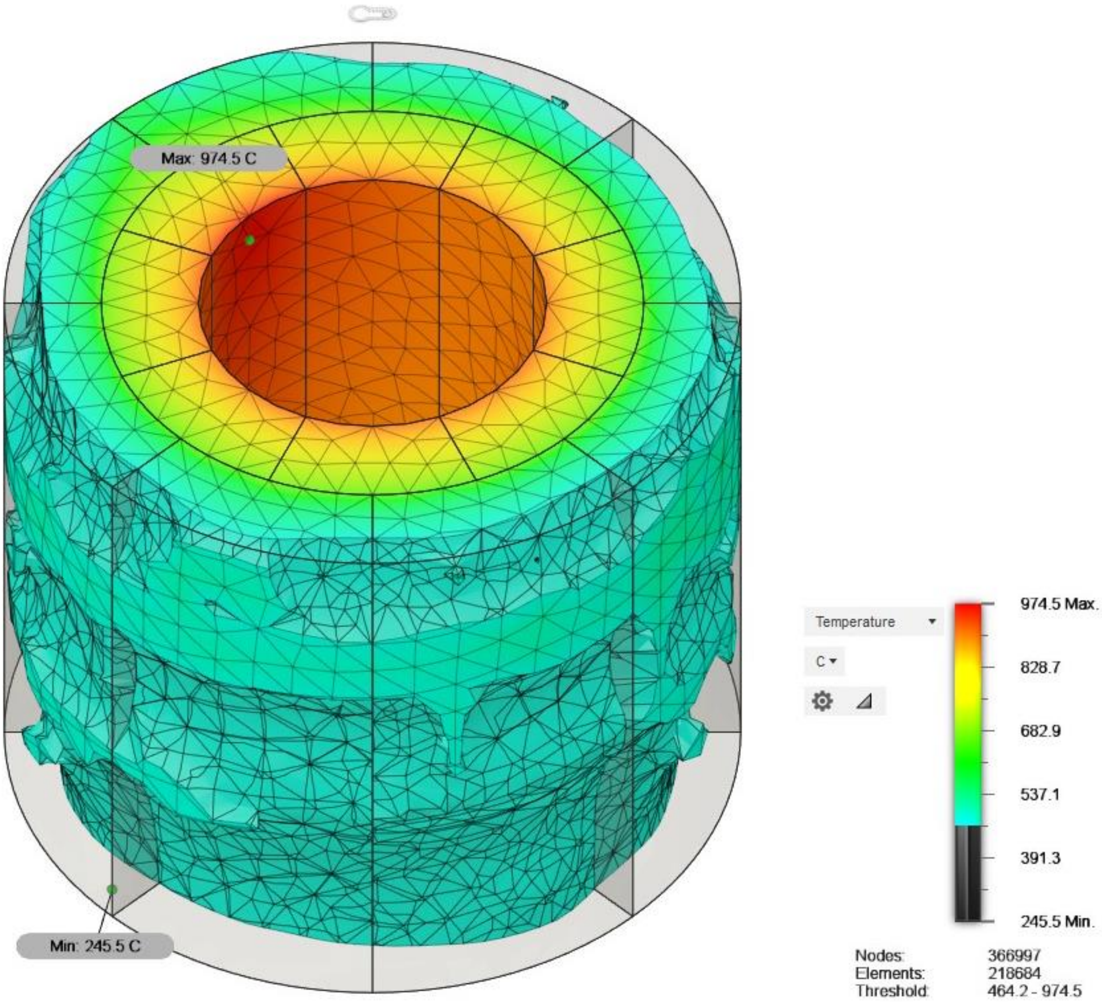

Figure 22: Optimized Insulated Core Design in Steady State Thermal Analysis. The displayed grid is modified such that any volume with temperatures lower than the minimum temperature or 464°C are not displayed. Minimum and Maximum Temperatures are displayed as Max and Min respectively.

In this case, the temperature on the external surface of the insulated core has been reduced sufficiently by dimensioning the insulated core. Only in some smaller areas does the temperature of the contact area exceed 80% of the melting temperature of the non-structural aluminum used as a thermal interface between the cooling system and the insulated core, shown in Figure 22 by the resultant rendering displaying only grid cells with a temperature greater than 464°C. The areas which show the highest temperature at the surface of the insulated core are underneath the areas where there is the greatest distance from the cooling loop coil through the aluminum heat spreader. The inner surface of the combustor does not exceed the maximum service temperature of non-structural ceramic composite used. As such, this result is considered satisfactory and within the limitations of the materials chosen.

4.3.3 Mechanical Optimization

As with the thermal optimization simulations, a few assumptions have to be made for the mechanical and stress-based optimizations. Primarily, the force applied to the combustor from the internal pressure due to combustion is assumed here to be constant. Additionally, some part has to remain fixed throughout the analysis. For this, the outer most edges of the pressure sealing collar were chosen, as they mirror the real mounting points suggested in the design of the combustor. However, these would not likely be truly fixed in a real system, so this may incur some error of excessive pressure at the fixed boundary.

Settings and Load Case

There are two primary sets of requirements for the mechanical performance of the combustor. Due to the existence of a momentary stress loading on the combustor in the transient pressurization during an engine cycle, the stress cycle cannot be described as an impact event. As such, all of the energy from the stress loading of the part is due to the pressure applied by combustion. The stress throughout the combustor under normal running conditions can only ever approach the steady state loaded conditions in the combustor, never exceed them. That is, any solution dimensioned for the steady state solution, will also here over-dimension the part for the conditions it experiences when installed. Therefore, the steady state stress simulation, with properly applied contacts, is chosen.

The load case in the mechanical simulation is chosen in a very similar manner as the thermal simulations. Pressure is applied to the inner surface of the insulated core, with the magnitude P = 385Bara. The outer most edges on the pressure sealing collar are fastened and used as constraints. These constraints mirror the relief cut for pressurized sealing suggested in Section 4.2.2.2. Another potential choice here would be to consider the entire external surface of the pressure collar a constraint, however, the load case chosen here imparts more stress on the parts, as constraining the entire external surface would put every part in the stack under compressive stress.

Some of the other settings are discussed below, however the full list of settings applied, including load case parameters in the software is included in the printed report for the simulation in Appendix 5 for the unoptimized base case and Appendix 6 for the optimized case.

Parts Interactions and Contacts

In the mechanical stress simulation interface, contacts need to be applied. In this case, automatic contacts are not considered to be sufficient, as they generate non-physical behavior of the interacting parts in the assembly. As such, the contacts are generated automatically through software, and then modified appropriately such that they mirror the realistic behavior of the parts. The automatic contacts were not found to mirror the realistic implementation of the design and were manually modified.

Mesh Design

The automatic mesh generation is considered sufficient, however it is inspected in between each simulation cycle, to prevent potential problems with artifacts or errors. No errors or artefacting were discovered.

Satisfying Performance Requirements

In this case, there is no proper or constrained area of interest in the combustor. All the internal volume of every part except the combustor housing is required to be simulated. Because of the construction of the part however, the only area that experiences any significant loading is the outer aluminum collar. The other parts are constructed specifically to avoid tensile loading, and as such will only experience compressive loading which is beneficial especially for the ceramic components.

In the process of dimensioning the parts, in the interest of speed and usability of the simulations, parts such as the housing, which is not considered structural, and the cooling loop are removed. Additionally, features such as the relief cuts for tightening bolts is removed. The relief cut in the heat spreader and pressure collar are also removed for ease of simulation.

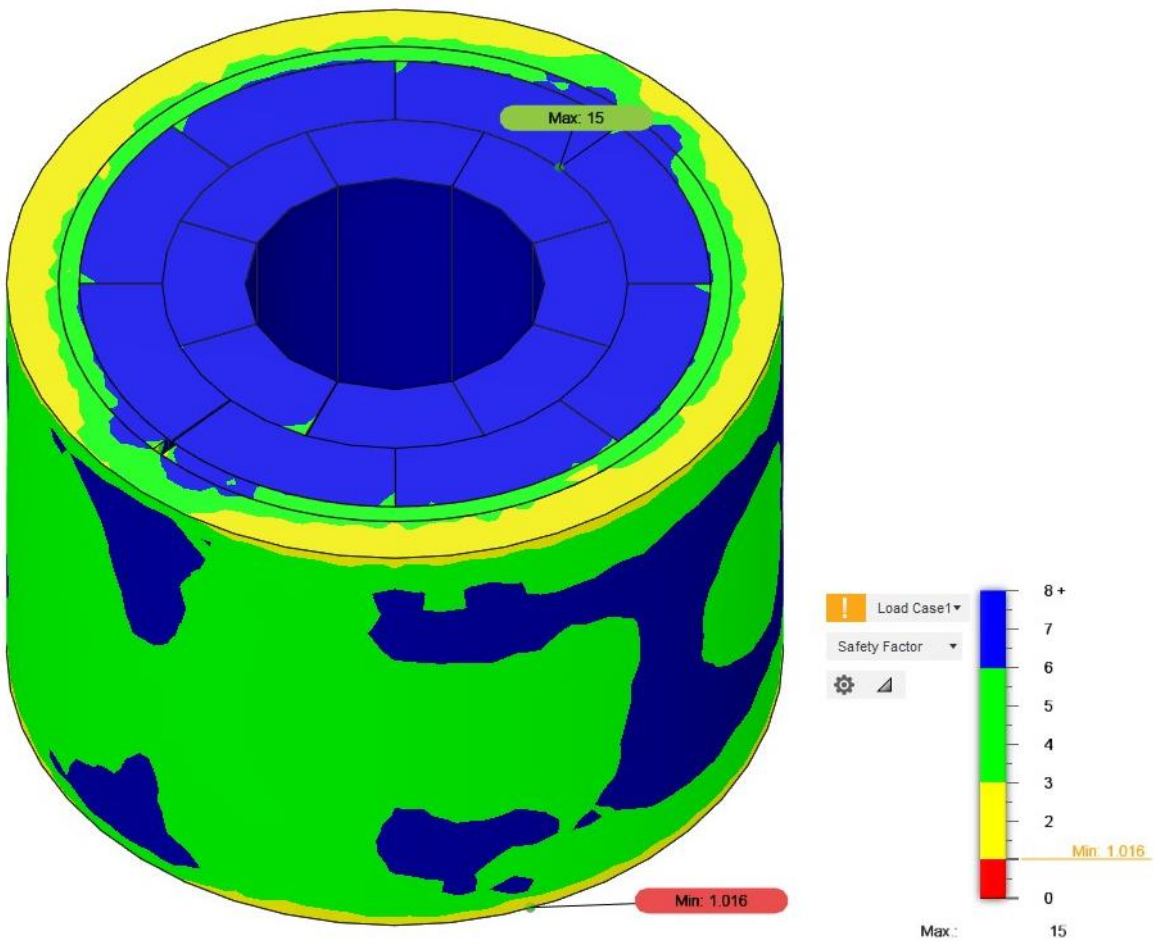

Figure 23: Unoptimized Combustor Design in Static Stress Analysis. Minimum and Maximum safety factors are included in the diagram as Min and Max respectively.

From the first simulation, it is readily apparent that the structure shown is greatly over-dimensioned. Some safety factor is of course usually recommended, however, the greatest safety factor in this particular simulation iteration is a factor of 15, and the minimum is 1.016, at an isolated spot that is likely an artifact from the automatic meshing or constraints rather than a realistic area of concern. As such the true minimum is likely much larger, and the part can safely be altered such that it is dimensioned more appropriately.

The cooling loop was however removed for ease and speed of simulation. While the cooling loop is not structural, it does represent space that is required to be retained. The negative space for the cooling loop to have room, needs to be there, regardless if this over-dimensions the part. As such, it is retained, and the simulation is repeated with what is assumed to be the minimum thickness of the material retained on the outside of the pressure collar, such that the pressure collar is of identical thickness to the heat spreader.

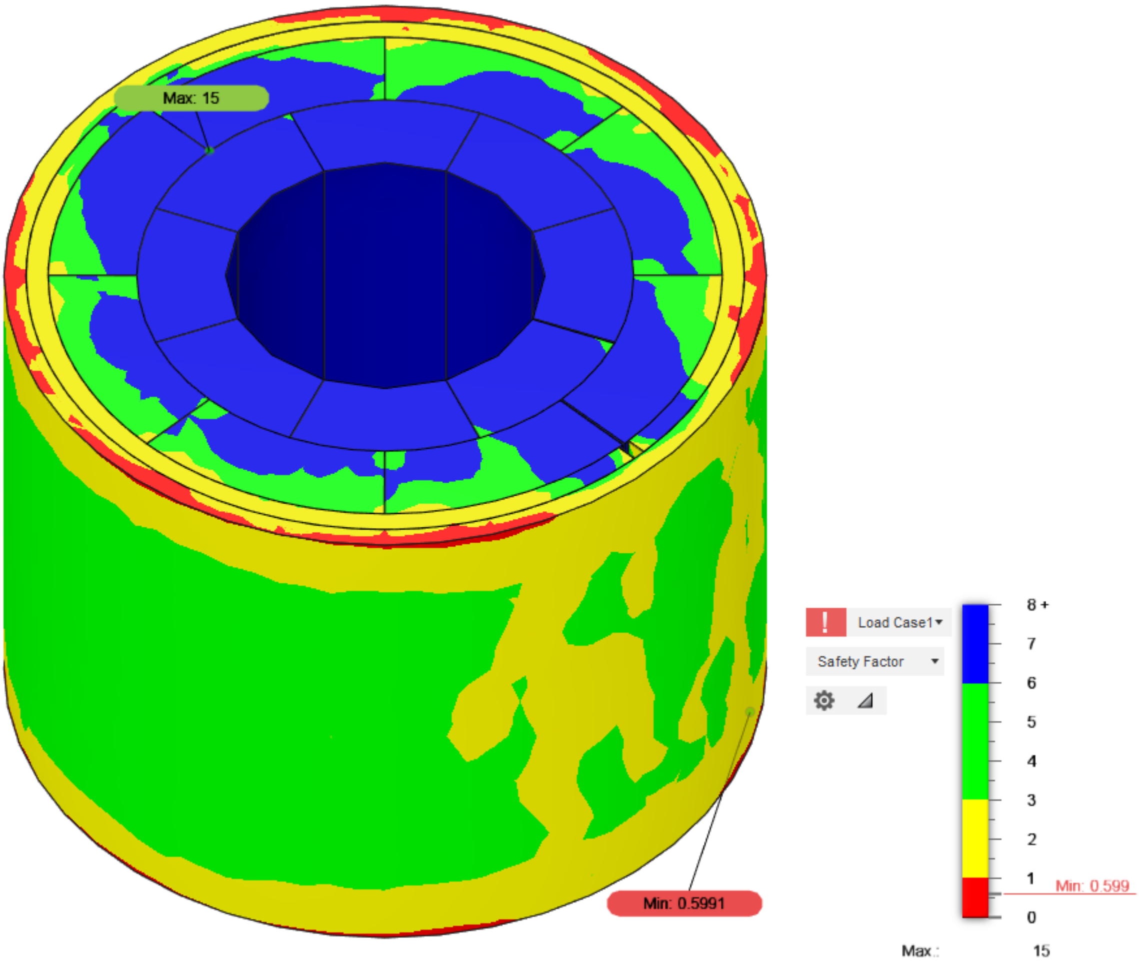

Figure 24: Optimized Combustor Design in Static Stress Analysis. Minimum and Maximum safety factors are included in the diagram as Min and Max respectively.

As is evident from the simulation here as well, the part is still over-dimensioned, with a safety factor of between 1 to 3 and in excess of 8 on most of the part, with the exception of the areas marked red on Figure 24 where the safety factor is 0.6, which again is likely an artifact due to the constraints applied, and is very unlikely to be a realistic area of concern. As previously explained however, the part cannot be reduced further, and as such, this is considered sufficiently optimized for the mechanical stresses the part will experience.

4.4 Evaluation of the Final Combined Solution

The solution developed here has been developed with the technical solutions and problems described in Section 3 in mind. It has been dimensioned for static loads equivalent to the transient loads the system is expected to experience when implemented in practice, with safety factors on all aspects as was recommend. Of particular note is the relatively low temperature of 974.5°C on the internal surface of the combustor, and the high average safety factor shown in the mechanical analysis. These results are indicative that a solution of the form proposed here may be possible to implement and further work in the form of prototyping or testing in more sophisticated software should be performed, if such testing becomes available to the partner company.

Further testing of these designs may be especially important in order to capture effects such as internal temperature transients, or behaviors of the materials chosen that have not been anticipated in this study. Even though the parts here are slightly over-dimensioned with safety factors to account for transient effects that as proposed in Section 3, and these transient effects are not expected to exceed the stresses shown in the design during the static analysis, other unexpected concerns may manifest themselves, especially if a physical prototype is constructed.

Conclusion

This study showed a path to create a coherent design solution, and optimize, taking into account dynamic and static, mechanical and thermal stresses, and the problems such conditions may cause for the design proposed. The analysis using static stress analysis and steady state thermal analysis in CAD Software, to overestimate the dynamic and transient loadings the design is expected to endure, showed that Silicon Carbide may be used successfully in a purpose designed combustor such that the very high temperature combustion proposed may be feasible. Silicon Carbide showed the possibility of reducing the temperature in the combustor from the combustion temperature of 3850K to less than 740K at the outer surface with active cooling, such that even aluminum alloys with their low maximum service temperatures may be utilized for pressure retention and thermal conduction with a cooling system.

Future Work

Many recommendations have been made throughout the work for future work to be done on the design and optimization, and also on related topics, where a lacking literature was apparent. These recommendations have been collected and summarized here, and divided into three categories.

Category I: Recommendations for future theoretical related work

Even at the stage of the preliminary study, multiple shortfalls were found in the literature that significantly increases the uncertainty of the solution and results produced.

Studies describing and testing the potential for the use of ceramic materials as insulators in closed combustors is lacking, leading to some of the most appropriate studies being focused on the leading edges of aircraft and spacecraft. More work is required to assess the properties of these materials in this particular application, or more analogous applications, in the form of experimental studies.

But the implementation of these materials is not the sole concern. Testing and assessment of the properties of the materials tested in the preliminary study is also lacking, and several materials had to be excluded due to unknown properties. Additionally, where properties are largely available, the validity of the properties in many cases had to be interpolated and extrapolated from the available data, as the source material is lacking. A more complete understanding of the properties of the materials in general is also considered relevant for future work.

The methods of high temperature heat transfer are also relatively unknown, especially heat transfer by radiation, which at the time of writing did not have databases or relevant studies that fully covered the temperature range required for this study. The models for heat transfer by convection do not have a strict temperature range. and as such the temperature cannot be so easily exceeded as with the validity range for radiation. It is however uncertain how well this model determines the heat transfer by convection at very high temperatures. This is especially apparent given the form of Woschni's heat transfer model, which is tuned to the particulars of heat transfer from combustion through convection in combustion motors at the time of its development. Later models have expanded on Woschni's models, but they do so generally through modification of the tuning constants to better approach the performance and measurements from current combustion engines. This may seem a benefit at first, but it detracts from the universal applicability of the model as originally developed by Woschni and tuned to a general bomb-type combustor device. It is therefore even more uncertain how accurate the results are when applied to a non-traditional powerplant such as this one. More work is therefore recommended as to the development of heat transfer models for high temperature combustion, or confirmation of the validity of the models for high temperature combustion.

Category II: Recommendations for future work on improved designs

More specifically tailored to the work conducted in this study, there are shortcomings that result from the narrowly tailored approach utilized here. The main shortcomings directly related to this are comparisons of different materials, the lack of transient analysis both for thermal and mechanical problems and dimensioning.

It is recommended that other materials are investigated as well, if need be using the approach outlined in this study, and the design as well. It may be possible to utilize materials with lower cost, with greater ease of manufacturing, or other benefits entirely that were not considered here. Additionally, it is recommended that this study be updated when and if the dimensions or operational parameters of the powerplant may change.

This study focused on a low cost rapid digital prototyping approach which made certain simplifications in an aim to lower cost and time spent doing simulations in the software packages available. If necessary or possible, it is recommended that future work remedies potential problems caused by these simplifications such as validating the assumptions and simplifications related to dimensioning a dynamic and transient problem through static simulations.

Category III: Recommendations for future work on the design proposed here

Lastly, this category of future work deals with shortcomings in this study that are strictly missing. For instance, the fastening and tension system for applying an inward pressure from the pressure collar onto the combustors insulated core, needs to be solved. Additionally, the cooling system needs to be designed, dimensioned and optimized. Lastly the combustor designed here needs to be integrated with the rest of the powerplant.

The simulations and further optimization may also need to be altered and redone when the design of the remainder of the powerplant is known, and it is known whether other strictly necessary aspects of the powerplant may require changes to the design developed here.

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Appendices

Appendix 1: Material Properties as Used in the Simulations

Appendix 2: Calculation of Heat Transfer Coefficient for Thermal Simulations using Woschni's Heat Transfer Model

Appendix 3: Unoptimized Thermal Stress Analysis Report.

Appendix 4: Optimized Thermal Stress Analysis Report

Appendix 5: Unoptimized Mechanical Stress Analysis Report

Appendix 6: Optimized Mechanical Stress Analysis Report

Appendix 1: Material Properties as Used in the Simulations

The following appendix shows the properties of materials implemented in Fusion 360 in relation with the simulations performed in Section 604.3.

Custom Materials Implemented through Fusion 360's Material Editor

In Fusion360s material editor, the following properties are entered. The material setting basic is used, which applies some limitations on the materials and what studies may be performed, but those limitations are not relevant here.

Properties of Silicon Carbide (SiC)
Implemented as a custom material in Fusion 360

Properties	Value	Units	Source
Thermal Conductivity	120.0	W/mK	[3]
Specific Heat	0.58	J/(g·°C)	[2] - Averaged
Thermal Expansion Coefficient	9.45	µm/(m·°C)	[2] - Averaged
Young's Modulus	300	GPa	[1],[2],[3] - Averaged
Poisson's Ratio	0.35		[2] - Lower end chosen due to high discrepancy between the manufacturers
Shear Modulus	41	MPa	[2] - Averaged
Density	3.02	g/cm^3	[1],[2] - Averaged
Damping Coefficient	0.0		- No manufacturer had relevant data
Yield Strength	708.5	MPa	[2] - Averaged
Tensile Strength	932.5	MPa	[2] - Averaged

Of the manufacturers found, Azo Manufacturing had the most complete material properties, however, in certain cases, the material properties required were not available, or drastically different than the ones from other manufacturers or academic sources, in which case, the others were used.

Sources for Custom Materials;

[1] Skyline Components (unknown), *Silicon Carbide (SIC)*, Available from:
http://skylinecomponents.com/SiC.html
(Data collected: 17.06.20)

[2] Azo Materials (Feb 5 2001), *Silicon Carbide (SiC) Properties and Applications*,
Available from: https://www.azom.com/properties.aspx?ArticleID=42
(Data collected: 17.06.20)

[3] Accuratus (unknown), *Silicon Carbide SiC Ceramic Properties*, Available from:
https://accuratus.com/silicar.html
(Data collected: 17.06.20)

Materials Implemented from Fusion 360's Material Library

The materials listed on this page are included in the Fusion 360 materials library, and the properties are taken and used unaltered.

Properties of Gray Cast Iron ASTM A48

Properties	Value	Units
Thermal Conductivity	48.04	W/mK
Specific Heat	0.450	J/(g·°C)
Thermal Expansion Coefficient	12.997	μm/(m·°C)
Young's Modulus	81.496	GPa
Poisson's Ratio	0.23	
Shear Modulus	33025.7	MPa
Density	7.395	g/cm^3
Damping Coefficient	0.00	
Yield Strength	151.684	MPa
Tensile Strength	179.263	MPa

Properties of 6061 Aluminum Alloy

Properties	Value	Units
Thermal Conductivity	167.0	W/mK
Specific Heat	0.897	J/(g·°C)
Thermal Expansion Coefficient	23.600	μm/(m·°C)
Young's Modulus	68.900	GPa
Poisson's Ratio	0.33	
Shear Modulus	25864	MPa
Density	2.700	g/cm^3
Damping Coefficient	0.00	
Yield Strength	275.00	MPa
Tensile Strength	310.00	MPa

Appendix 2: Calculation of Heat Transfer Coefficient for Thermal Simulations using Woschni's Heat Transfer Model

This appendix shows the calculation of the heat transfer coefficient used in the thermal simulation setup in Section 4.3, using the heat transfer model proposed by Woschni (1967). Applying the values of the variables specified in the Table I to the equations specified below, yields the heat transfer coefficient $h_{convection}$ = 184.9745 w/m^2K.

$$v = c_1 \cdot v_{piston} + c_2 \cdot \frac{V_{displacement} \cdot T_{initial}}{p_{initial} \cdot V_{initial}} \cdot (p_{combustion} - p_{initial})$$

Woschni's heat transfer formula for the gas velocity (Woschni, 1967).

$$h_{Convection} = c_0 \cdot b^{-0.2} \cdot p^{0.8} \cdot T^{-0.53} \cdot v^{0.8}$$

Woschni's heat transfer formula for the convection coefficient using the gas velocity calculated from formula one (Woschni, 1967).

Table I

Variable	**Explanation**	**Calculation (if applicable)**	**Value**	**Unit**
c0	Tuning constant		2.28	
c1	Tuning constant		2.28	
c2	Tuning constant		3.24*10^-3	
s	Stroke length		2.87	[m]
n	Cycles per minute		100	[rpm]
b	Bore diameter		0.287	[m]
v_{piston}	Piston velocity	s*n/60	4.7833	[m/s]
$V_{initial}$	Initial volume pre combustion		0.185	[m^3]
$V_{displacement}$	Total displacement volume	pi*s*(b^2)/4 + Vinitial	0.3707	[m^3]
$T_{initial}$	Initial temperature pre combustion		635	[K]
$T_{combustion}$	Temperature immediately post combustion		3850	[K]
$p_{initial}$	Initial pressure pre combustion		25	[Bara]
$p_{combustion}$	Pressure immediately post combustion		385	[Bara]

Appendix 3: Unoptimized Thermal Stress Analysis Report

This file has been transcribed from the original HTML format.

Study Report

Analyzed File	Unoptimized thermal v6
Version	Autodesk Fusion 360 (2.0.8412)

Study Properties

Study Type	Thermal

Settings

Contact Tolerance	0.1 mm
Global Initial Temperature	20 C

Damping

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Heat Flux

Materials

Component	Material	Safety Factor
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Heat Spreader	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (1)	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (1) (1)	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (2)	Aluminum 6061	Yield Strength

Silicon Carbide

Density	3.02E-06 kg / mm^3
Young's Modulus	300000 MPa
Poisson's Ratio	0.35
Yield Strength	708.5 MPa
Ultimate Tensile Strength	932.5 MPa
Thermal Conductivity	0.120 W / (mm C)
Thermal Expansion Coefficient	9.45E-06 / C
Specific Heat	580 J / (kg C)

Aluminum 6061

Density	2.7E-06 kg / mm^3
Young's Modulus	68900 MPa
Poisson's Ratio	0.33
Yield Strength	275 MPa
Ultimate Tensile Strength	310 MPa
Thermal Conductivity	0.167 W / (mm C)
Thermal Expansion Coefficient	2.36E-05 / C
Specific Heat	897 J / (kg C)

Contacts

All contacts bonded.

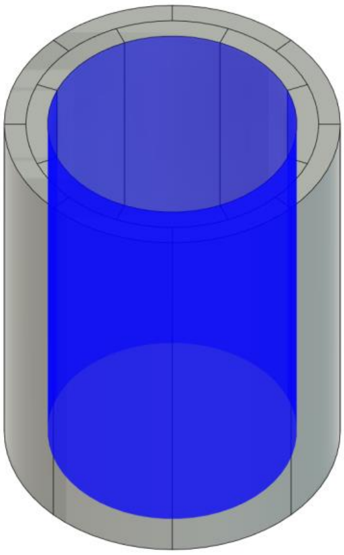
Mesh

Type	Nodes	Elements
Solids	304784	181279

Loads

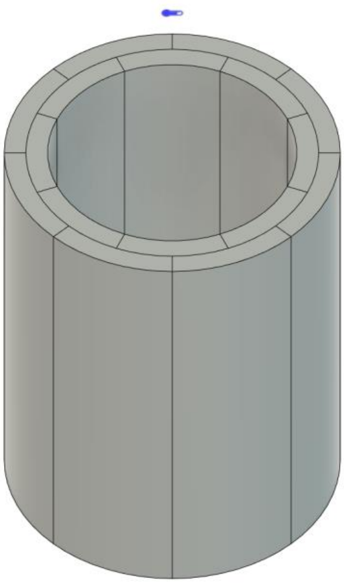
Convection

Type	Convection
Convection Value	185 W / (m^2 K)
Ambient Temperature	3850 C



Applied Temperature 1

Type	Applied Temperature
Value	200 C



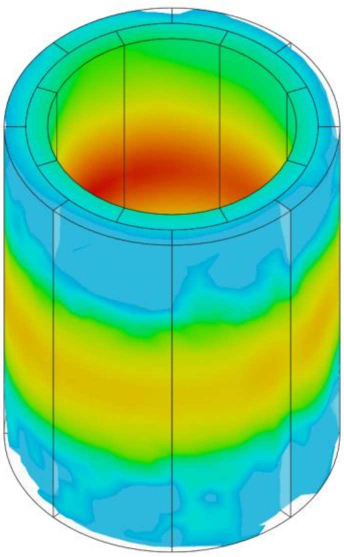
Results

Result summary

Name	Minimum	Maximum
Temperature		
Temperature	191.6 C	1230 C
Heat Flux		
Total	1.228E-18 W / mm^2	4.817 W / mm^2
X	-1.811 W / mm^2	3.145 W / mm^2
Y	-4.5 W / mm^2	1.971 W / mm^2
Z	-2.87 W / mm^2	2.399 W / mm^2
Thermal Gradient		
Total	2.194E-17 C / mm	28.84 C / mm
X	-18.83 C / mm	10.84 C / mm
Y	-11.8 C / mm	26.95 C / mm
Z	-14.37 C / mm	17.19 C / mm
Applied Heat Flow		
Applied Heat Flow	-2.469E-08 W / mm^2	2.352E-04 W / mm^2

Temperature

[C] 333 1230, Threshold: 464 - 1230



Appendix 4: Optimized Thermal Stress Analysis Report

This file has been transcribed from the original HTML format.

Study Report

Analyzed File	Optimized Thermal v6
Version	Autodesk Fusion 360 (2.0.8412)

Study Properties

Study Type	Thermal

Settings

Contact Tolerance	0.1 mm
Global Initial Temperature	20 C

Damping

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Heat Flux

Materials

Component	Material	Safety Factor
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Heat Spreader	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (1)	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (1) (1)	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar (1) (2)	Aluminum 6061	Yield Strength

Silicon Carbide

Density	3.02E-06 kg / mm^3
Young's Modulus	300000 MPa
Poisson's Ratio	0.35
Yield Strength	708.5 MPa
Ultimate Tensile Strength	932.5 MPa
Thermal Conductivity	0.120 W / (mm C)
Thermal Expansion Coefficient	9.45E-06 / C
Specific Heat	580 J / (kg C)

Aluminum 6061

Density	2.7E-06 kg / mm^3
Young's Modulus	68900 MPa
Poisson's Ratio	0.33
Yield Strength	275 MPa
Ultimate Tensile Strength	310 MPa
Thermal Conductivity	0.167 W / (mm C)
Thermal Expansion Coefficient	2.36E-05 / C
Specific Heat	897 J / (kg C)

Contacts

All contacts bonded.

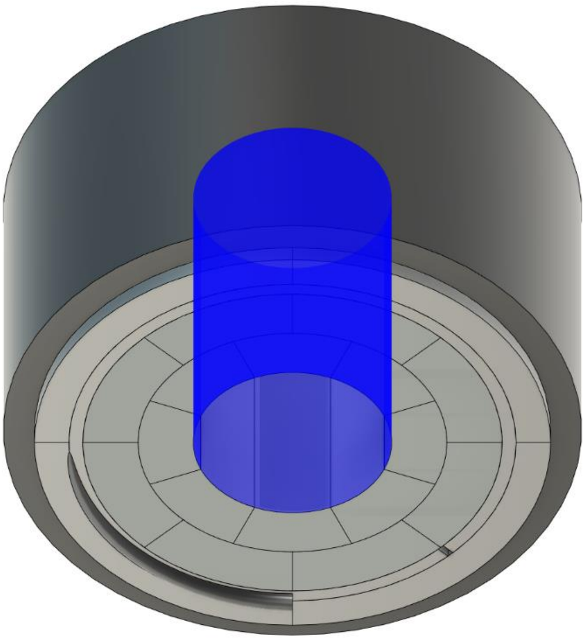
Mesh

Type	Nodes	Elements
Solids	366997	218684

Loads

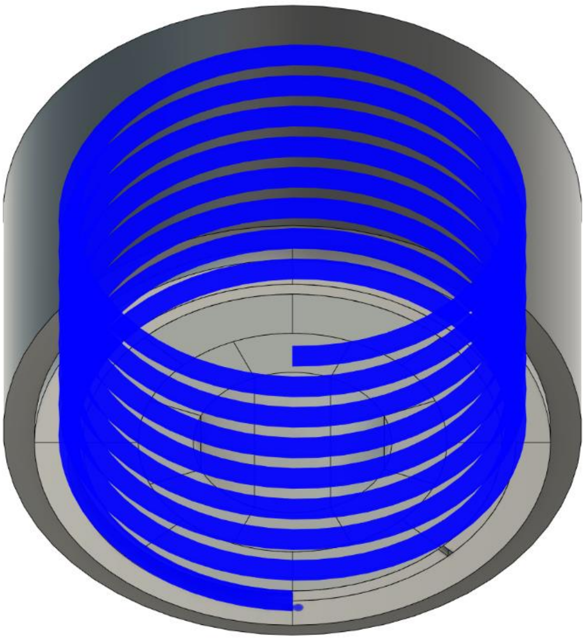
Convection

Type	Convection
Convection Value	185 W / (m^2 K)
Ambient Temperature	3850 C



Applied Temperature 1

Type	Applied Temperature
Value	200 C



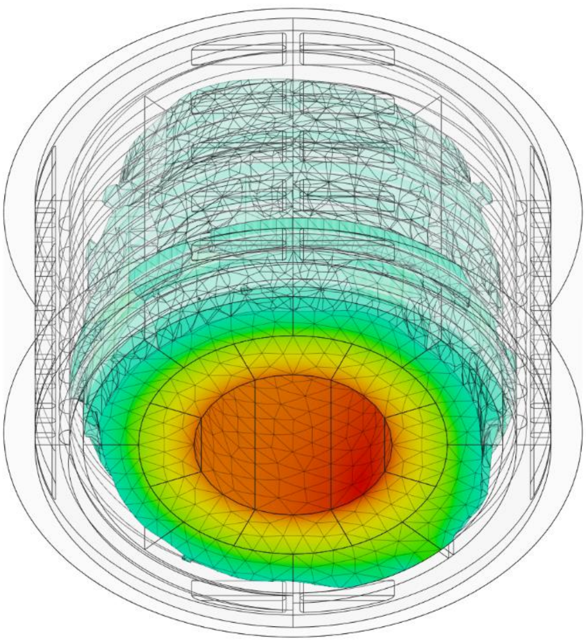
Results

Result summary

Name	Minimum	Maximum
Temperature		
Temperature	186 C	974.5 C
Heat Flux		
Total	1.354E-18 W / mm^2	2.185 W / mm^2
X	-1.342 W / mm^2	1.518 W / mm^2
Y	-1.207 W / mm^2	2.168 W / mm^2
Z	-1.085 W / mm^2	1.845 W / mm^2
Thermal Gradient		
Total	2.418E-17 C / mm	13.08 C / mm
X	-9.092 C / mm	8.038 C / mm
Y	-12.98 C / mm	7.228 C / mm
Z	-11.05 C / mm	6.499 C / mm
Applied Heat Flow		
Applied Heat Flow	-1.03E-07 W / mm^2	3.947E-04 W / mm^2

Temperature

[C] 186 974.5, Threshold: 464.2 - 974.5



Appendix 5: Unoptimized Mechanical Stress Analysis Report

This file has been transcribed from the original HTML format.

Study Report

Analyzed File	Optimized Thermal, Unoptimized Mechanical v2
Version	Autodesk Fusion 360 (2.0.8412)

Study Properties

Study Type	Static Stress

Settings

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Damping

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Heat Spreader	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar	Aluminum 6061	Yield Strength

Silicon Carbide

Density	3.02E-06 kg / mm^3
Young's Modulus	300000 MPa
Poisson's Ratio	0.35
Yield Strength	708.5 MPa
Ultimate Tensile Strength	932.5 MPa
Thermal Conductivity	0.120 W / (mm C)
Thermal Expansion Coefficient	9.45E-06 / C
Specific Heat	580 J / (kg C)

Aluminum 6061

Density	2.7E-06 kg / mm^3
Young's Modulus	68900 MPa
Poisson's Ratio	0.33
Yield Strength	275 MPa
Ultimate Tensile Strength	310 MPa
Thermal Conductivity	0.167 W / (mm C)
Thermal Expansion Coefficient	2.36E-05 / C
Specific Heat	897 J / (kg C)

Contacts

Bonded

Name
[S] Bonded61 [Insulated Core Outer tile:8||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded62 [Insulated Core Outer tile:8||Insulated Core Inner tile:8]
[S] Bonded65 [Insulated Core Outer tile:7||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded66 [Insulated Core Outer tile:7||Insulated Core Inner tile:7]
[S] Bonded69 [Insulated Core Outer tile:6||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded70 [Insulated Core Outer tile:6||Insulated Core Inner tile:6]
[S] Bonded73 [Insulated Core Outer tile:5||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded74 [Insulated Core Outer tile:5||Insulated Core Inner tile:5]
[S] Bonded77 [Insulated Core Outer tile:4||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded78 [Insulated Core Outer tile:4||Insulated Core Inner tile:4]
[S] Bonded81 [Insulated Core Outer tile:3||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded82 [Insulated Core Outer tile:3||Insulated Core Inner tile:3]
[S] Bonded85 [Insulated Core Outer tile:2||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded86 [Insulated Core Outer tile:2||Insulated Core Inner tile:2]
[S] Bonded89 [Insulated Core Outer tile:1||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded91 [Insulated Core Outer tile:1||Insulated Core Inner tile:1]

Separation

Name
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[S] Separation54 [Insulated Core Inner tile:6||Insulated Core Inner tile:7]
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[S] Separation58 [Insulated Core Inner tile:2||Insulated Core Inner tile:3]
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[S] Separation84 [Insulated Core Outer tile:2||Insulated Core Outer tile:3]
[S] Separation88 [Insulated Core Outer tile:1||Insulated Core Outer tile:2]
[S] Separation92 [Insulated Core Outer tile:1||Insulated Core Outer tile:8]

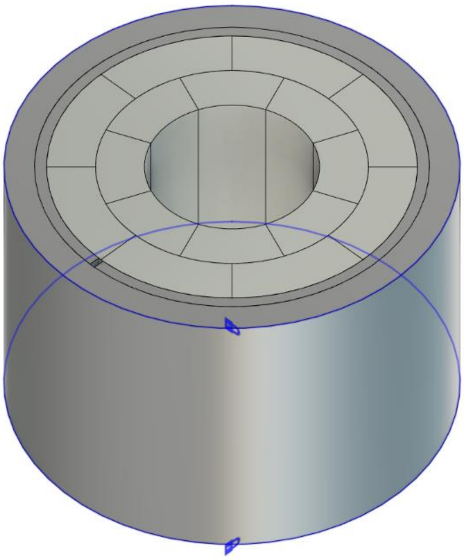
Mesh

Type	Nodes	Elements
Solids	48450	26171

Loads

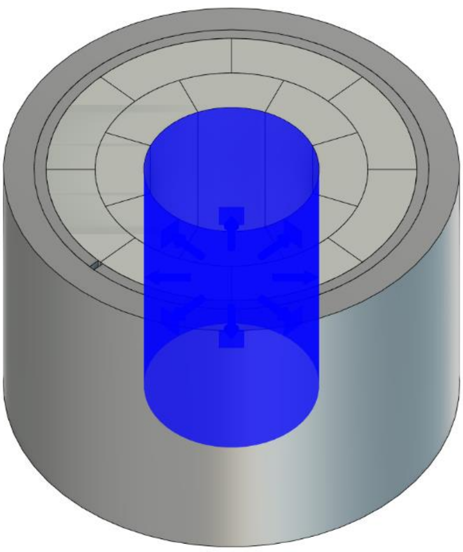
Fixed Constraints

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes



Pressure1

Type	Pressure
Magnitude	385 bar



Results

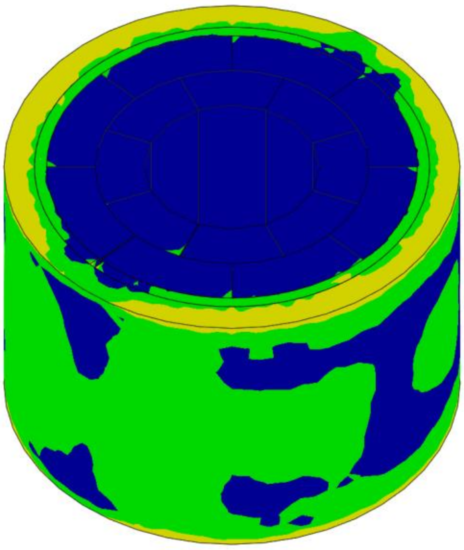
Result summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	1.016	15
Stress		
Von Mises	0.9842 MPa	297.1 MPa
1st Principal	-69.98 MPa	233.4 MPa
3rd Principal	-342.7 MPa	52.08 MPa
Normal XX	-283.2 MPa	210.4 MPa
Normal YY	-226 MPa	173.9 MPa
Normal ZZ	-88.77 MPa	133.2 MPa
Shear XY	-104.1 MPa	135.7 MPa
Shear YZ	-62.2 MPa	60.06 MPa
Shear ZX	-75.85 MPa	101.1 MPa
Displacement		
Total	0 mm	0.9412 mm
X	-0.6103 mm	0.8507 mm
Y	-0.8635 mm	0.6372 mm
Z	-0.1519 mm	0.1543 mm
Reaction Force		
Total	0 N	78424 N
X	-73748 N	62887 N
Y	-66444 N	69554 N
Z	-23348 N	21278 N
Strain		
Equivalent	1.628E-05	0.005721
1st Principal	-1.248E-05	0.003585
3rd Principal	-0.005998	2.131E-05
Normal XX	-0.002821	9.619E-04
Normal YY	-0.002484	9.454E-04
Normal ZZ	-0.001069	0.001288
Shear XY	-0.002457	0.003122
Shear YZ	-0.002401	0.002319
Shear ZX	-0.002928	0.003901
Contact Pressure		
Total	0 MPa	225.6 MPa
X	-193.7 MPa	163.4 MPa
Y	-159.4 MPa	130.2 MPa
Z	-42.58 MPa	42.16 MPa

Safety Factor

Safety factor (Per Body)

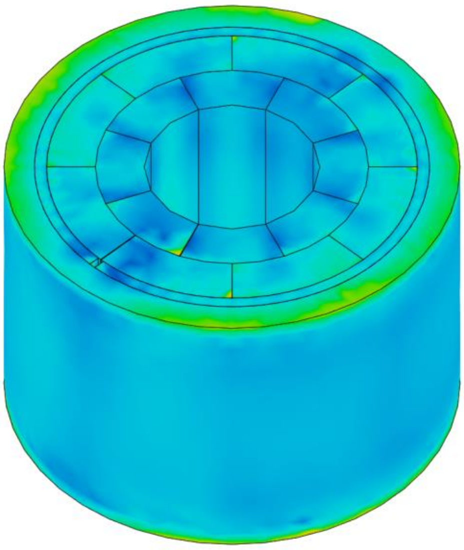
0 8



Stress

Von Mises

[MPa] 1 297.1



1st Principal

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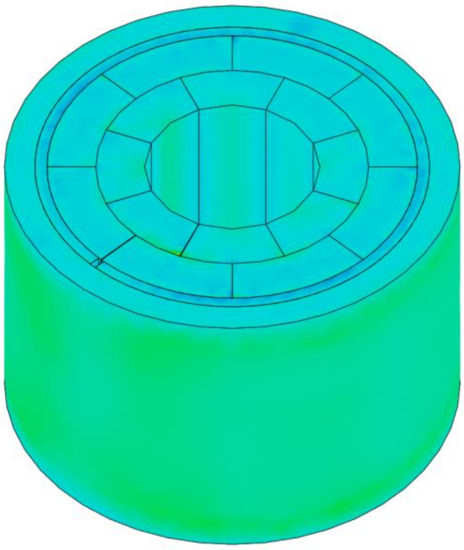

3rd Principal

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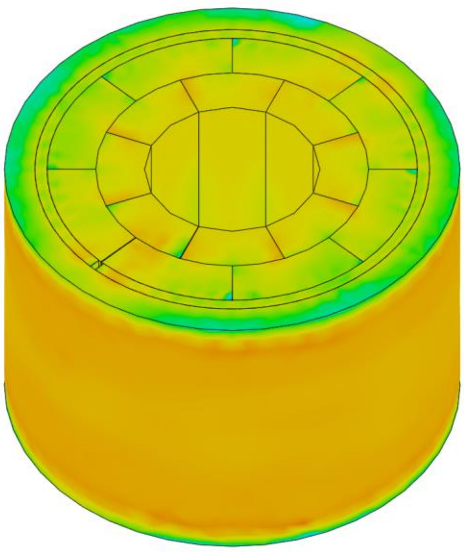
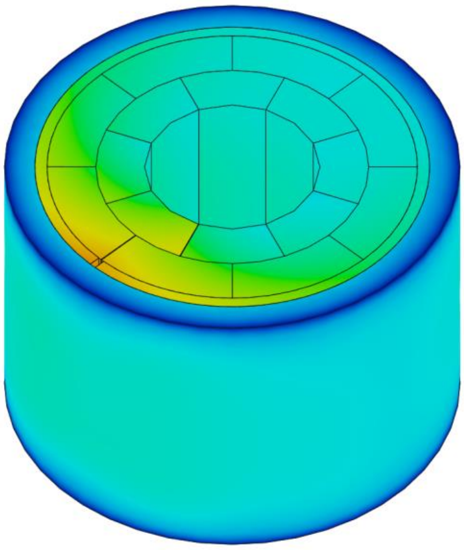


Displacement

Total

[mm] 0 – 0.9412



Appendix 6: Optimized Mechanical Stress Analysis Report

This file has been transcribed from the original HTML format.

Study Report

Analyzed File	Optimized Thermal, Optimized Mechanical v9
Version	Autodesk Fusion 360 (2.0.8412)

Study Properties

Study Type	Static Stress

Settings

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Damping

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Outer tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:1	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:2	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:3	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:4	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:5	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:6	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:7	Silicon Carbide	Yield Strength
combustor v16:1/Insulated Core:1/Insulated Core Inner tile:8	Silicon Carbide	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Heat Spreader	Aluminum 6061	Yield Strength
combustor v16:1/Heat Spreaders and Mounting:1/Compression Collar	Aluminum 6061	Yield Strength

Silicon Carbide

Density	3.02E-06 kg / mm^3
Young's Modulus	300000 MPa
Poisson's Ratio	0.35
Yield Strength	708.5 MPa
Ultimate Tensile Strength	932.5 MPa
Thermal Conductivity	0.120 W / (mm C)
Thermal Expansion Coefficient	9.45E-06 / C
Specific Heat	580 J / (kg C)

Aluminum 6061

Density	2.7E-06 kg / mm^3
Young's Modulus	68900 MPa
Poisson's Ratio	0.33
Yield Strength	275 MPa
Ultimate Tensile Strength	310 MPa
Thermal Conductivity	0.167 W / (mm C)
Thermal Expansion Coefficient	2.36E-05 / C
Specific Heat	897 J / (kg C)

Contacts

Bonded

Name
[S] Bonded61 [Insulated Core Outer tile:8||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded62 [Insulated Core Outer tile:8||Insulated Core Inner tile:8]
[S] Bonded65 [Insulated Core Outer tile:7||Heat Spreaders and Mounting:1(Heat Spreader)]
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[S] Bonded85 [Insulated Core Outer tile:2||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded86 [Insulated Core Outer tile:2||Insulated Core Inner tile:2]
[S] Bonded89 [Insulated Core Outer tile:1||Heat Spreaders and Mounting:1(Heat Spreader)]
[S] Bonded91 [Insulated Core Outer tile:1||Insulated Core Inner tile:1]

Separation

Name
[S] Separation53 [Insulated Core Inner tile:7||Insulated Core Inner tile:8]
[S] Separation54 [Insulated Core Inner tile:6||Insulated Core Inner tile:7]
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[S] Separation76 [Insulated Core Outer tile:4||Insulated Core Outer tile:5]
[S] Separation80 [Insulated Core Outer tile:3||Insulated Core Outer tile:4]
[S] Separation84 [Insulated Core Outer tile:2||Insulated Core Outer tile:3]
[S] Separation88 [Insulated Core Outer tile:1||Insulated Core Outer tile:2]
[S] Separation92 [Insulated Core Outer tile:1||Insulated Core Outer tile:8]

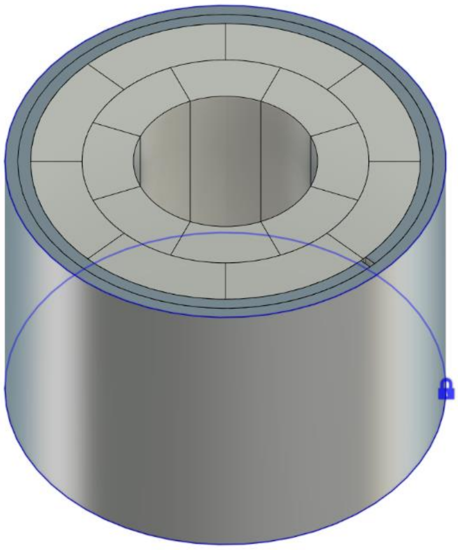
Mesh

Type	Nodes	Elements
Solids	54400	29395

Loads

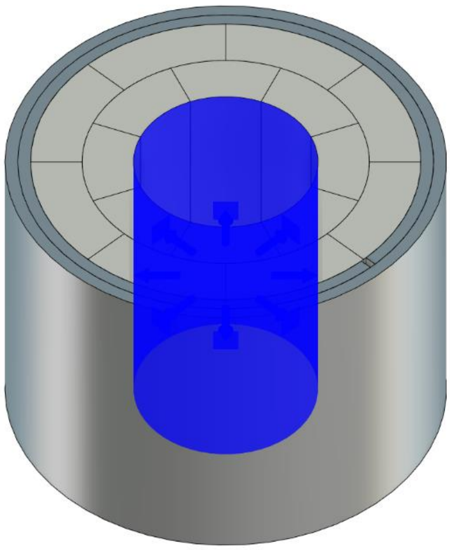
Fixed Constraints

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes



Pressure1

Type	Pressure
Magnitude	385 bar



Results

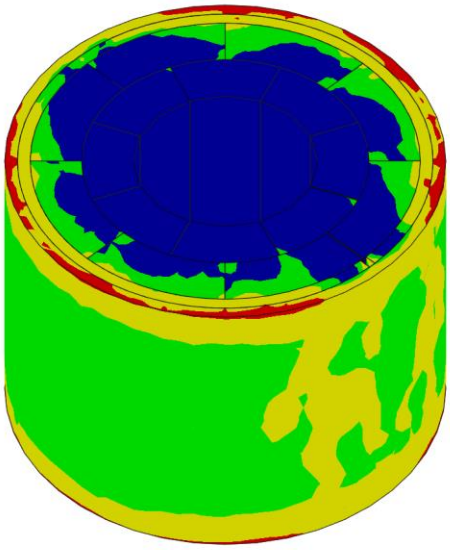
Result summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	0.5991	15
Stress		
Von Mises	1.955 MPa	459.1 MPa
1st Principal	-136.5 MPa	271.8 MPa
3rd Principal	-507.7 MPa	102.2 MPa
Normal XX	-500.2 MPa	262.8 MPa
Normal YY	-481 MPa	215.1 MPa
Normal ZZ	-297.4 MPa	210.1 MPa
Shear XY	-148.2 MPa	143.9 MPa
Shear YZ	-98.15 MPa	115.2 MPa
Shear ZX	-120.9 MPa	113.3 MPa
Displacement		
Total	0 mm	1.476 mm
X	-1.02 mm	1.299 mm
Y	-1.341 mm	0.9619 mm
Z	-0.2679 mm	0.265 mm
Reaction Force		
Total	0 N	111338 N
X	-103911 N	93298 N
Y	-96598 N	108541 N
Z	-17096 N	14278 N
Strain		
Equivalent	1.845E-05	0.008035
1st Principal	3.684E-06	0.005442
3rd Principal	-0.008805	8.928E-06
Normal XX	-0.006553	0.002567
Normal YY	-0.006306	0.00256
Normal ZZ	-0.00424	0.003559
Shear XY	-0.005723	0.005554
Shear YZ	-0.003789	0.004449
Shear ZX	-0.004668	0.004376
Contact Pressure		
Total	0 MPa	458.6 MPa
X	-458.5 MPa	423.7 MPa
Y	-415.2 MPa	436.8 MPa
Z	-56.75 MPa	77.8 MPa

Safety Factor

Safety factor (Per Body)

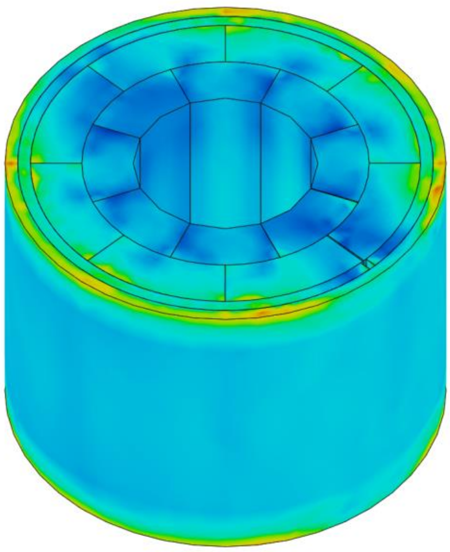
0 8



Stress

Von Mises

[MPa] 2 459.1



1st Principal
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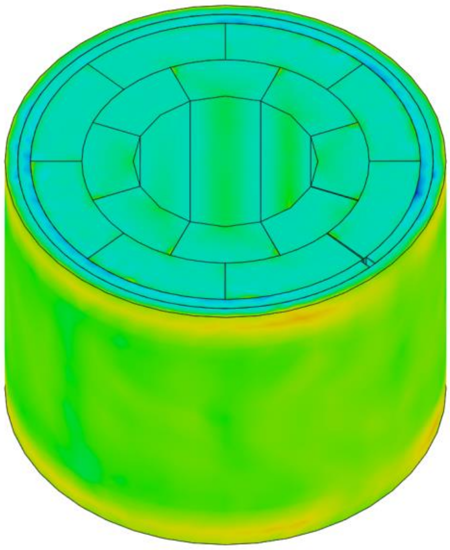

3rd Principal
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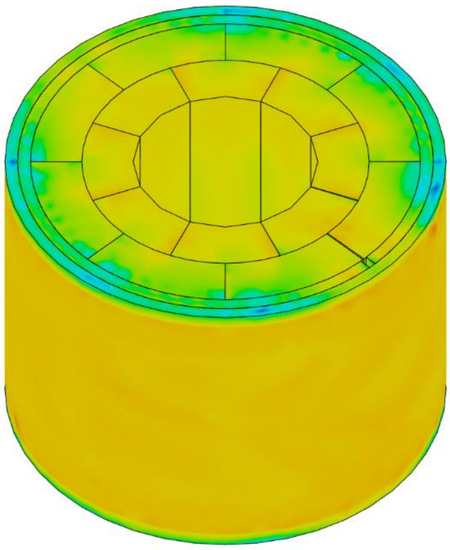
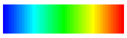
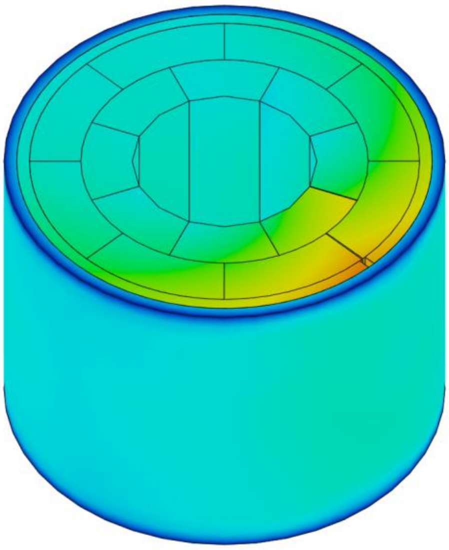


Displacement

Total

[mm] 0  1.476



NTNU

Norwegian University of
Science and Technology