Dish Stirling System

FINAL YEAR PROJECT THESIS

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BE Mechanical Engineering

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Declaration

I certify that this research work titled

"**Dish Stirling System**"

is our own work. The work has not been presented elsewhere for assessment. The material that we used from other sources has been properly acknowledged.

Signature of Students

Signature of Supervisor

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

Signature of Students

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Copyright Statement

Acknowledgements

We are thankful to Allah almighty to have guided us throughout this work at every step and for every new thought which He setup in our minds to improve it. Indeed we could have done nothing without His priceless help and guidance. Whosoever helped us throughout the course of our thesis, whether our parents or any other individual was Allah’s will, so indeed none be worthy of praise but Allah.

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“Dedicated to our exceptional parents and adored siblings whose tremendous support and cooperation led us to this wonderful accomplishment”

Project Aim

“To successfully develop a prototype Stirling engine that can be run on solar energy for use in disaster struck areas.”

Abstract

In order to satisfy the rising energy demands of global consumption, a new cleaner and renewable power source needs to be explored, conceptualized, and developed. Solar energy is a free and clean energy resource which can be used to generate power without damage to humans or the local ecosystems. To efficiently capture this solar energy as a feasible power source, a Stirling engine will be developed and will use sunlight as a source via a solar concentrator. This project intends to utilize methods of gathering solar energy that have not yet been commercially implemented, and modifications to traditional Stirling engines will be made in order to maximize the efficiency of solar Stirling engines. These modified solar Stirling engines can produce power for a wide variety of applications. The nature of the engine allows for both the scalability to create a solar farm as well as use for producing power in remote areas and disaster relief.

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Introduction

Problem Statement

The political, economic, environmental concerns over traditional fossil fuel power generation have led to an overwhelming amount of innovation and research into cleaner renewable sources. It is in the nation’s best interest to invest heavily in renewable energy so that we could reap the benefits to the economy, environment, politics, and human health.

Motivation

Of the existing sources of renewable energy, the most promising is the sun. It is the most abundant source of energy on the planet and it is a phenomenal source of light and heat. Scientific American magazine states, “The energy in sunlight striking the Earth for 40 minutes is the equivalent to global energy consumption for one year.” (Systems, Technology, 2009). Therefore, it behooves engineers to design way of capturing this incredible natural resource for use in power generation as an alternative to other methods such as fossil fuels.

Justification

The United Nations has a difficult time quantifying the exact number of lives that are lost in nature disaster. Perhaps more surprising is not the amount of death that occur from natural disasters, but the deaths that occur after disaster hits. The lack of clean water, food, and electricity can sometime cause more deaths than the actual disastrous event. Creating a technology that provides power to such disastrous areas can provide much needed clean water, and desperately needed electricity for life saving operations such as medical equipment, communications, and food preparation. Remote power can provide a real survival opportunity for disaster victims who have been left without a home, food, water, or power.

Ideal Locations for Solar Energy Power Generation

The irony of the tragedies experienced by the citizens of these locations that are in the path of disaster is that they are also the most ideal source for solar energy power. The same conditions that create a breeding ground for natural disasters also provide a unique ability to generate solar power. The world map shown below demonstrates the availability of solar power at different locations on the globe. What we have discovered is that the places that would most benefit from a solar Stirling engine system are the same places that the system would be the most efficient (Beta, 2008).

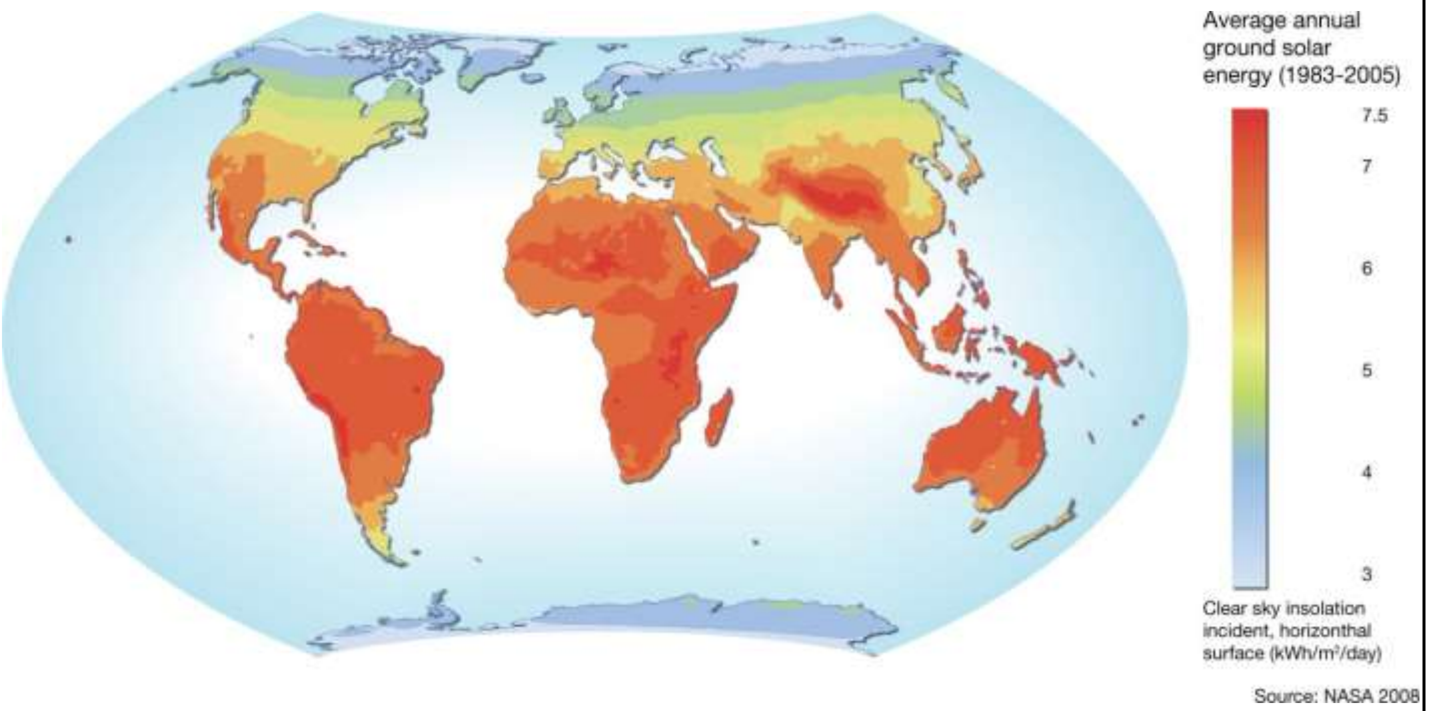


Figure 1: average annual ground solar energy(Source: NASA 2008)

ANNUAL AND SEASONAL DISTRIBUTION OF SUNSHINE IN PAKISTAN 1931-1990

Pakistan receives a considerable amount of sunshine throughout the year and has opportunity to control the shortage of power energy using advance technology for the utilization of solar energy.

- January has a lowest sunshine with 6.1hr/day with short winter days.
- June has the highest sunshine of above 9hr/day having long summer days.
- The annual sunshine of Pakistan increases from January to June then decreases in August with little increases in September and then again decreases till December. This variation of the sunshine in Pakistan is generally, because of its latitudinal and altitudinal extent and annual march of the sun.
- The plain areas of the country have long sunshine period and decreases as we move towards north of the country.
- The coastal belt usually, records high sunshine periods as compared to the rest of the country and is more suitable for solar energy plants.
- The sunshine duration of the country generally, increases from northwest to southeast. This variation normally, is due to temperature and cloudiness variation, altitudinal, and latitudinal extent of the country and the annual march of the sun.

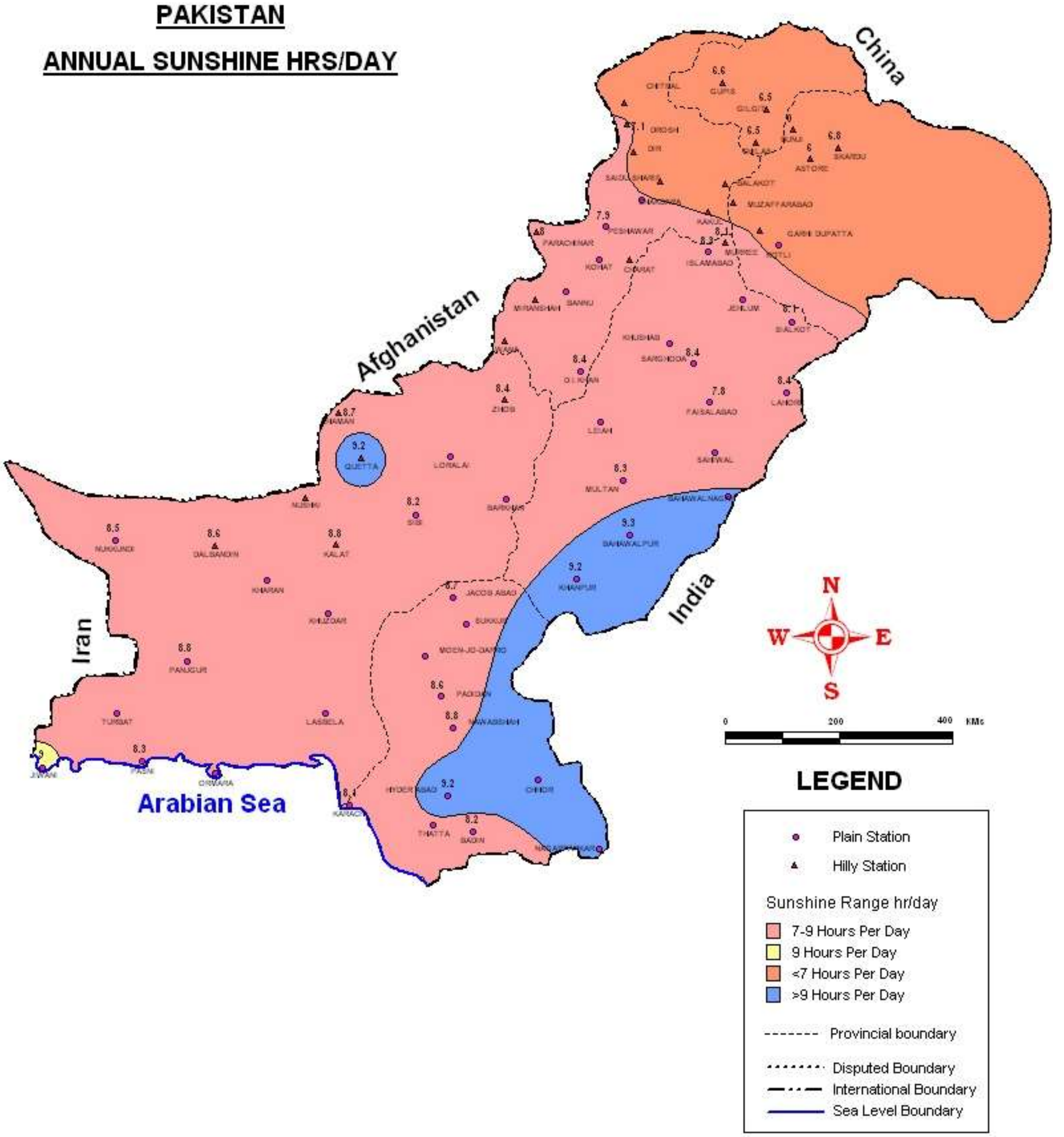
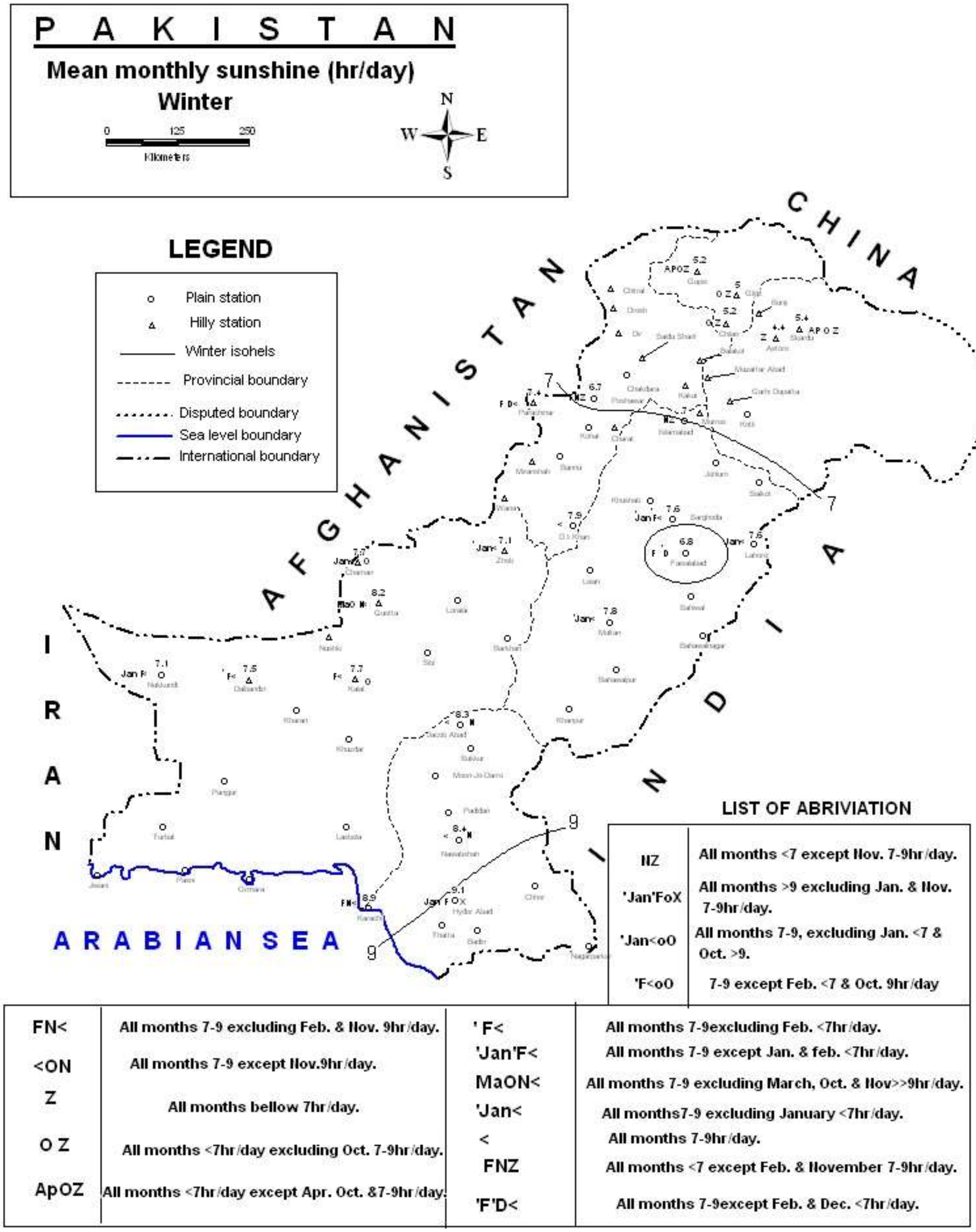


Figure 2:Pakistan annual sunshine Hrs/day (Source Water resources and wetlands:Saifullah Khan)



LIST OF ABRIVIATION

NZ	All months <7 except Nov. 7-9hr/day.
'Jan'FoX	All months >9 excluding Jan. & Nov. 7-9hr/day.
'Jan<oO	All months 7-9, excluding Jan. <7 & Oct. >9.
'F<oO	7-9 except Feb. <7 & Oct. 9hr/day

FN<	All months 7-9 excluding Feb. & Nov. 9hr/day.
<ON	All months 7-9 except Nov.9hr/day.
Z	All months bellow 7hr/day.
o Z	All months <7hr/day excluding Oct. 7-9hr/day.
ApOZ	All months <7hr/day except Apr. Oct. &7-9hr/day.

' F<	All months 7-9excluding Feb. <7hr/day.
'Jan'F<	All months 7-9 except Jan. & feb. <7hr/day.
MaON<	All months 7-9 excluding March, Oct. & Nov>>9hr/day.
'Jan<	All months7-9 excluding January <7hr/day.
<	All months 7-9hr/day.
FNZ	All months <7 except Feb. & November 7-9hr/day.
'F'D<	All months 7-9except Feb. & Dec. <7hr/day.

Figure 3:Pakistan mean monthly sunshine(Source: Water resources and wetlands:Saifullah Khan)

Literature Survey

Stirling engines are external combustion engines which can function by using a wide variety of fuel sources such as a combustible gas, nuclear head, or solar energy. The heat supplied to the engine causes the working fluid to expand; thereby, moving a displacer piston. This piston then displaces the working fluid from the hot end into the cold end of the engine where the working fluid is compressed and the piston retracts. The displacer piston then moves the fluid into the hot end where it will once be expanded and then displaced into the cold end where it will compress and this cycle will continue as long the temperature difference exists. The Stirling cycle is a reversible cycle which closely follows the Carnot principal, making it a highly efficient cycle. Stirling engines are the simplest form of heat engine and are arguably the most efficient engine (Berchowitz, 1984).

History

The first patent containing a Stirling engine was written in 1816 by the Rev'd Dr. Robert Stirling. He patented an ‘economizer’ which is synonymous with today’s regenerator, used to increase the efficiency of the engine. The Stirling engine did not gain wide popularity compared to the steam engine due to the limits that currently available materials offered. Stirling engines went relatively unnoticed and not improved on until the late 1930 when Philips selected Stirling engines to power radios for remote areas. The decision to use Stirling was based on its low audible and E&M noise and ability to run on any heat source from heating oil to wood (Berchowitz, 1984).

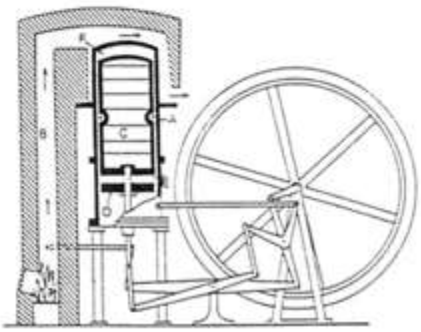


Figure 4:the oringinal Robert Stirling Engine(Source:Author: Jiří Škorpík)

In 1972 Ford Motor Company teamed up with Philips to develop an automotive Stirling engine, and gauge its potential for automobiles. What was produced was a four cylinder, 170 Horse Power Stirling engines which used a swash plate to transfer the power from the Stirling engines into torque that could be connected to a traditional transmission [7]. The engine ended up having little potential for use in automobiles due to the nature of external combustion engines inability to produce immediate power.

There is however concepts to revive the automobile Stirling engine for use in hybrid electric vehicles because of its higher power to weight ratio and overall efficiency (Nightingale, 1986)

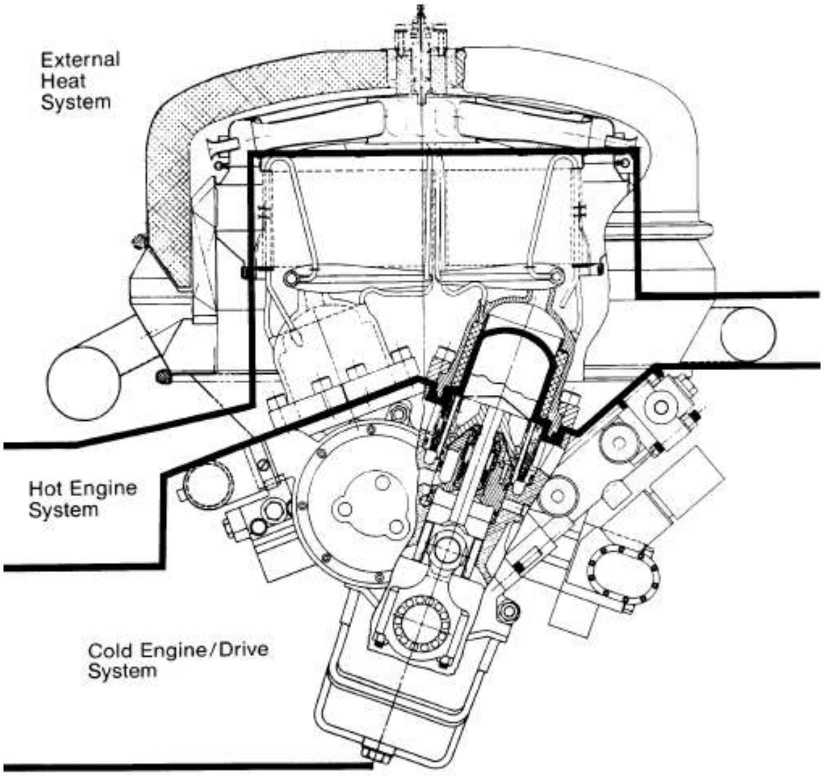


Figure 5: Automotive Stirling Engine(Source: Ford Motor Company Nightingale,1986)

Automotive Stirling Engine

Beginning in the 1970‟s NASA‟s Glenn Research Center began investigations and development of high efficiency Stirling engines to be used in space applications. The decision to use Stirling engines was centered on their relative reliability compared to other mechanical engines, simplicity, low noise (audible, E&M), essentially nonexistent vibration (when convertors were paired), and most importantly high power to weight ratio. The Brayton Rotating Unit (BRU) Project aim at obtaining higher efficiency power conversion system for isotope, reactor, and solar receiver hear sources (Lee Mason, 2007).

Figure 6:Brayton Rotating Unit (BRU)(Source NASA Glenn research Project,Lee Mason 2007)

Brayton Rotating Unit (BRU)

NASA is now taking a serious interest in Stirling engines for their potential use on other planetary bodies. One of the most prominent possibilities is the use of a Stirling-based Fission Surface Power System which can generate power of about 50kWe per unit. This form of power generation is a viable solution to the monumental problem of attempting a manned mission to the Lunar and Martian Surfaces for extended periods of time. This type of system could be used to provide power for rovers, remote science experiments, or as a utility power source for an outpost in any of our celestial orbiting bodies (Lee Mason, 2007).

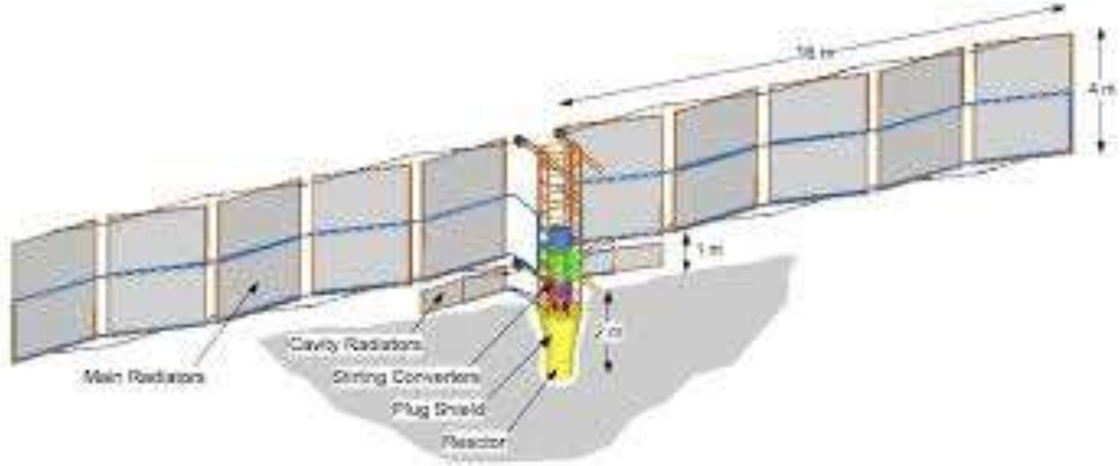


Figure 7:Stirling based Fission Surface Power System(Source:NASA.gov)

Stirling Engine Configurations

Stirling engines are commonly found in three different configurations; alpha, beta, and gamma. There is also a variation of each one named free-piston but due to its complexity and high cost, it will not be discussed in details for this project. Each of the three main configurations has unique advantages and disadvantages due their variation in geometry and arrangement.

Alpha Stirling Engine

An Alpha Stirling engine is composed of two power pistons which are housed in two separate cylinders where one cylinder is exposed to heat while the second is subjected to cold and heat dissipation. Alpha Stirling engines will sometimes utilize a regenerator as part of its configuration. The regenerator function is to store heat as it moves from the hot end to the cold one and re-supplying the fluid with heat as it returns to the hot end.

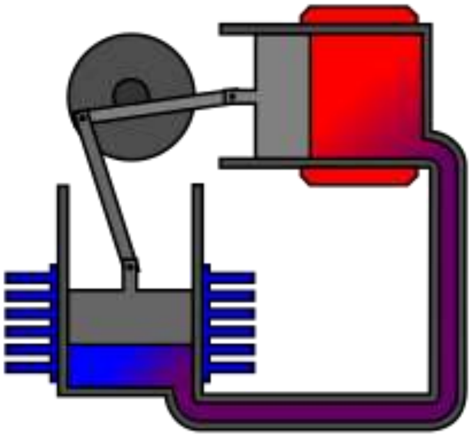


Figure 8:Alpha Configuration (Source:engineering.uiowa.edu)

1. Most of the working gas is in contact with the hot cylinder walls, it has been heated and expansion has pushed the hot piston to the bottom of its travel in the cylinder. The expansion continues in the cold cylinder, which is 90° behind the hot piston in its cycle, extracting more work from the hot gas.

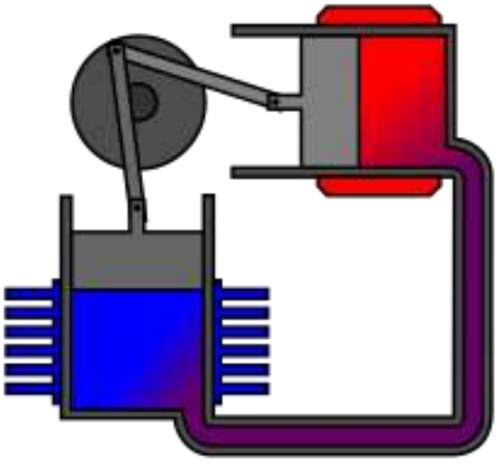
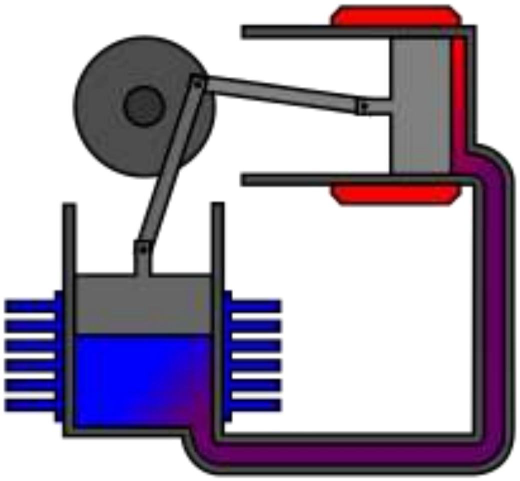


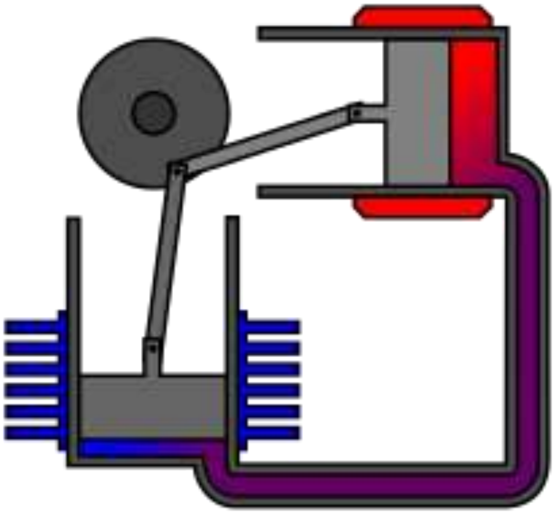
Figure 9:Alpha Configuration (Source:engineering.uiowa.edu)

2. The gas is now at its maximum volume. The hot cylinder piston begins to move most of the gas into the cold cylinder, where it cools and the pressure drops.



3. Almost all the gas is now in the cold cylinder and cooling continues. The cold piston, powered by flywheel momentum (or other piston pairs on the same shaft) compresses the remaining part of the gas.

Figure 10:Alpha Configuration (Source:engineering.uiowa.edu)

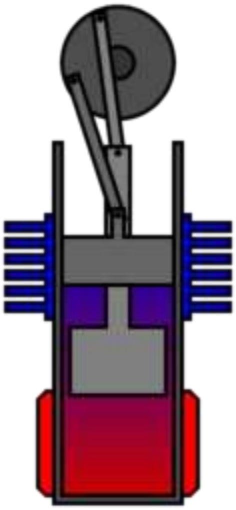


4. The gas reaches its minimum volume, and it will now expand in the hot cylinder where it will be heated once more, driving the hot piston in its power stroke.

Figure 11:Alpha Configuration (Source:engineering.uiowa.edu)

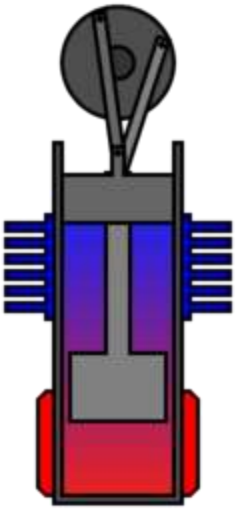
Beta Stirling Engine

A Beta Stirling Engine configuration uses one cylinder which houses both the power and displacement piston. The displacer piston purpose is to shuffle the air between the hot end and the cold end while not extracting any power from the expanding gas.



1. Power piston (dark grey) has compressed the gas, the displacer piston (light grey) has moved so that most of the gas is adjacent to the hot heat exchanger.

Figure 12: Beta Configuration (Source:engineering.uiowa.edu)



2. The heated gas increases in pressure and pushes the power piston to the farthest limit of the power stroke.

Figure 13:Beta Configuration (Source:engineering.uiowa.edu)

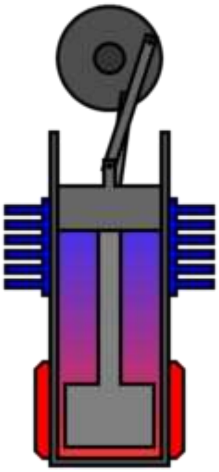


Figure 14:Beta Configuration (Source:engineering.uiowa.edu)

3. The displacer piston now moves, shunting the gas to the cold end of the cylinder.

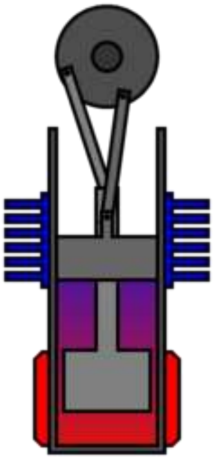


Figure 15:Beta Configuration (Source:engineering.uiowa.edu)

4. The cooled gas is now compressed by the flywheel momentum. This takes less energy, since its pressure drops when it is cooled.

Gamma Stirling engine

Lastly, a Gamma Stirling engine is similar to a Beta configuration expect save for the power piston which is housed in a separate cylinder but still connected to the same flywheel as the displacer piston.

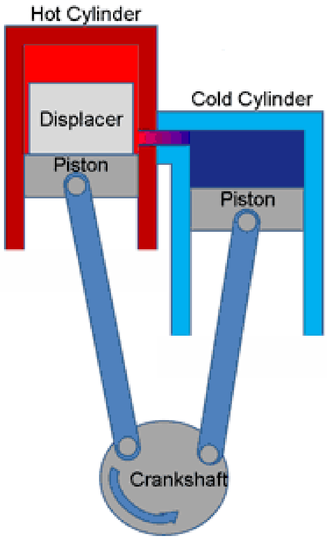


Figure 16:Gamma Configuration (Source:engineering.uiowa.edu)

The Pressure-Volume diagram and the cycle efficiency:

The volume variations:

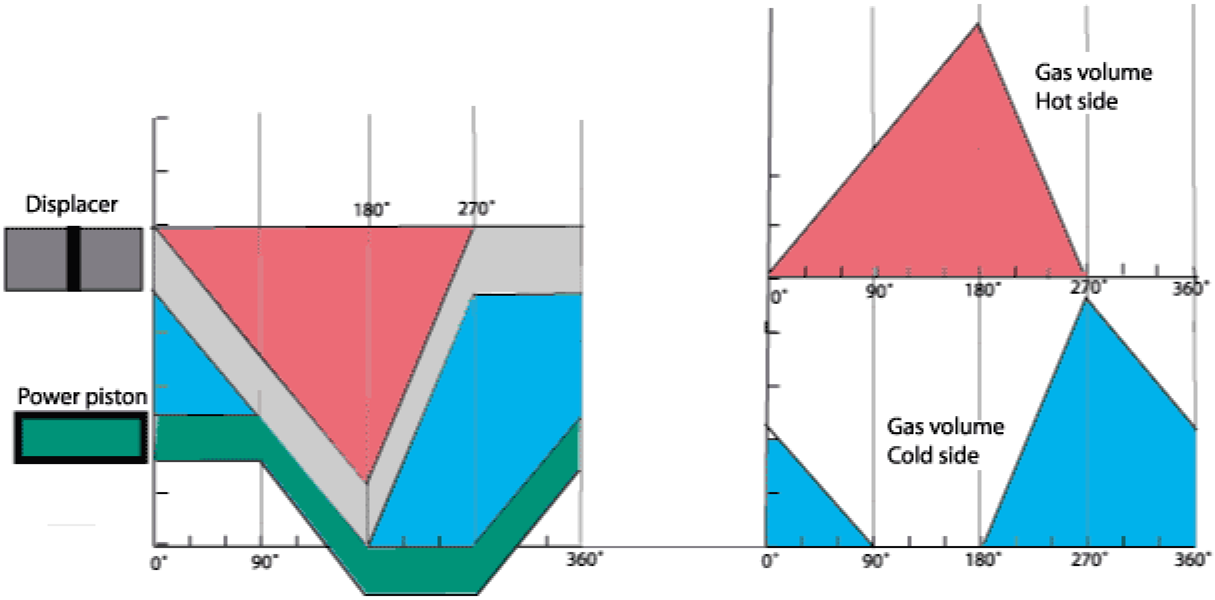


Figure 17: volume variations (Source:Pierre Gras, Author Moteur Stirling)

On the diagram above, one can see:

- The variation of hot volume, on the upper part, during the cycle (red zone).

- The variation of cold volume, at the bottom, between displacer and operating piston, during the cycle (blue zone).

The PV diagram :

The principle of operation, above exposed, can be represented on a diagram called “Pressure-Volume diagram” or PV diagram.

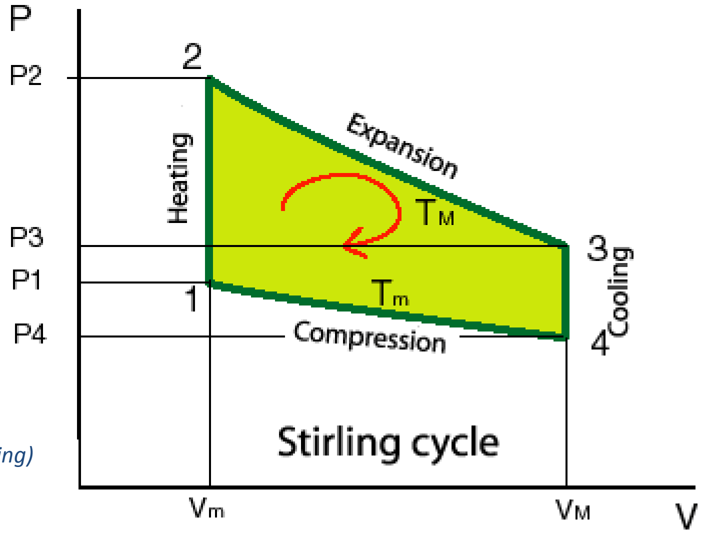


Figure 18:PV Diagram(Source:Pierre Gras, Author Moteur Stirling)

At every moment, the force which is exerted on the piston is F = S x P where S is the surface of the piston and P the instantaneous pressure.

The elementary work provided during a short time “dt” is equal to the instantaneous force multiplied by displacement “dy “of the piston during this period “dt”.

dW = F x dy

or

dW = S x P x dy

or, if it is noticed that S x dy = dV , the variation in volume during the period of time "dt"

dW = P x dV

On the PV diagram, this last expression is the elementary surface located under each curve.

The work is positive under the curve of expansion because dV>0. Work is negative under the curve of compression because dV<0.

The resulting work during a cycle is represented by surface under the curve of expansion decreased by surface under the curve of compression. Therefore, it is the surface between the curves.

The cycle efficiency :

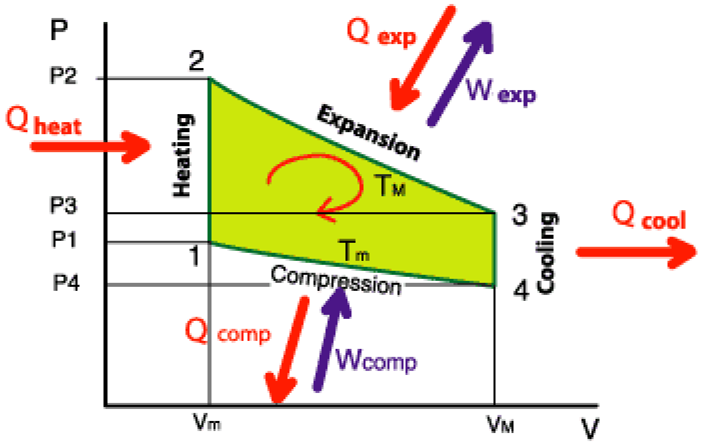


Figure 19:Cycle efficiency(Source:Pierre Gras, Author Moteur Stirling)

The efficiency of the engine is equal to the ratio between the recovered mechanical energy W_{net} and the heat Q_{total} that is required to provide. The latter is provided during the isochoric heating and during the isothermal expansion.

With the diagram, we can write:

$W_{net} = W_{exp} + W_{comp}$

Where, see above, W_{comp} will be negative after its calculation.

$Q_{total} = Q_{heat} + Q_{exp}$

Solar Radiation

The sun can be considered a spherical radiation source that is 1.39 x m in diameter and at a distance of about 1.50 x10^{611} m from the Earth (Frank P. Incropera, 2002). Due to Earth‟s Ozone Layer, the radiation felt by body outside our atmosphere would be different than the radiation felt on Earth surfaces as shown in Figure.

Solar Concentrator

A wide variety of solar concentrators are currently commercially available in order to concentrate solar rays for the purpose of power generation. There are many forms of solar concentrators, but the most common forms are those which utilize curved, parabolic mirrors and those which use Fresnel lenses.

Parabolic Troughs are the most widely used type of solar concentrator. It consists of a linear parabolic reflector which can concentrate sunlight onto a tube, commonly filled with a working fluid such as molten salt, and positioned along the focal length in order to generate heat for power generation. This type of solar concentrator can be found in Solar Energy Generating Systems (SEGS) plants in California, Acciona‟s Nevada Solar One, and Plataforma Solar de Almerias in Spain (Laboratories, 2009).

Figure 20:Parabolic trough in Sandia(Source ACWA Power Ouarzazate)

Figure 21Fresnel Reflectors Ausra (Source:ACWA Power Ouarzazate)

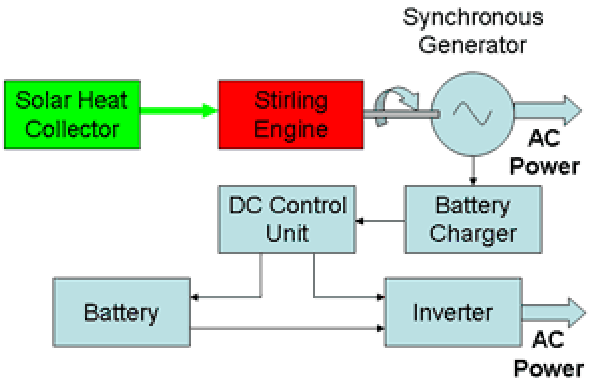
Concentrating Linear Fresnel lenses are defined as many thin mirror strips in the place of parabolic mirrors to focus sunlight and heat on a given point. The advantage to this method over parabolic mirrors is that flat mirrors are much cheaper than parabolic mirrors and that more reflectors can be used in the same amount of space which provides more sunlight energy at the focus. This type of solar concentrator shown in Figure 16 was constructed a company called Ausra (Ausra, 2009).

Solar Stirling Engine

Due to Stirling engine's unique ability to produce power in the presence of any heat source, a wide variety of fuels can be utilized for the purpose of power generation which includes Solar. Using sunlight as a viable heat source for Stirling engines yields a method of producing power without harmful emissions and without using manufacturing methods which deplete the Earths of its precise natural resources.

Solar energy has been utilized before for power production in heat engines, however, most of the previous applications were for steam turbines that would be only practical for very large scale installations. Stirling engines provide a methodology for generating power for use in a small system to drive an electrical generator.

The schematic below illustrates a small scale electric power from solar thermal energy system which utilizes solar Stirling. In this system, the solar heat collector provides heat for the solar Stirling engine which in turn provides AC power. The electrical power can be transferred to a battery charger, then to DC control unit which can either go into a battery or into an inverter. Efficiencies for this type of small scale system can range from 18% to 23% (Communications).



Small Scale Electric Power from Solar Thermal Energy

Figure 22:Solar Stirling Schematic

Solar Stirling has made a tremendous impact on alternative energy in the certain years with companies like Stirling Energy Systems (SES) leading the way. This company in partnership with Sandia National

Lab managed to break the world record for solar-to-grid conversion efficiency at an amazing 31.25 % on January 31, 2008. SES Serial #3 was erected in May 2005 as part of the Solar Thermal Test Facility which produced up to 150kW of grid ready electrical power during the hours of sunlight. Each dish consisted of 82 mirrors that can focus the light into an intense beam (Systems, 2008).

SES solar Stirling engine, named SunCatcher, was awarded the 2008 Breakthrough Award winner by Popular Mechanics for its role as one of the top 10 world-changing innovations. The SunCatcher is a 25 kWe solar dish Stirling system which uses a solar concentrator structure which supports an array of curved glass mirror which are designed to follow the sun and collect the focused solar energy onto a power conversion unit. The diagram below illustrates the workings of SES‟s SunCatcher.

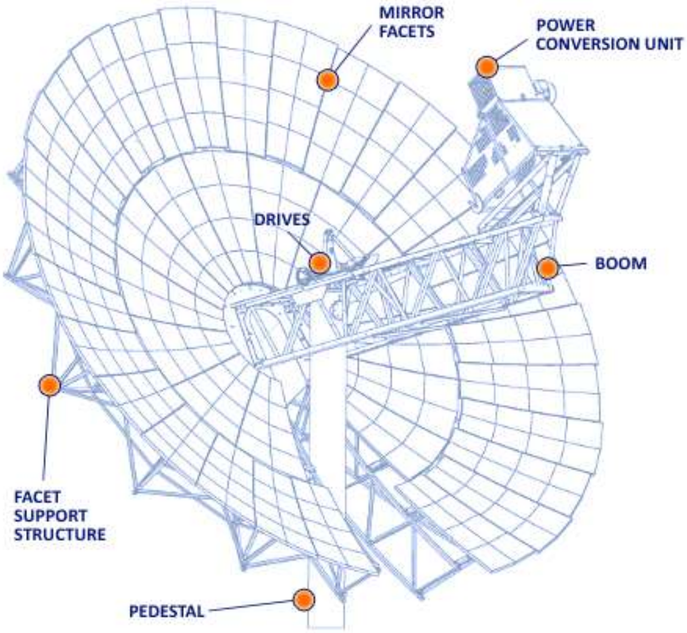


Figure 23:Stirling Energy Systems – SunCatcher(Source Stirling Energy Systems)

Overview

The overall goal of this project is to conceptualize, design, and build a modified solar Stirling engine with a parabolic dish as the solar concentrator.

This solar Stirling engine uses a gamma configuration. This project will be considered a success if the following objectives are met. Firstly, a design is to be made of a gamma Stirling engine which uses a cost effective means of producing the most electricity. This engine should have a large margin of positive net energy and net power to be considered a feasible application.

Second, a proof-of-concept of this configuration should be demonstrated by the creation of a small scale prototype. Lastly, this design should prove itself to be flexible and scalable to fit the needs of varying applications such as use in remote areas and disaster relief.

Design Specifications

In order to meet the objectives of this project, certain specifications need to be ascertained. Due to the nature of Stirling engines, the maximum efficiency is achieved when the temperature difference between the hot end and the cold end is sufficiently large. Therefore, the design specifications focused on achieving this goal.

The solar concentrator used in this project is to be sufficiently powerful to concentrate sunlight on the surface of the engine without noticeable losses due to refraction, medium, and geometry.

The material used for the cylinders, pistons, and flywheel should be able to withstand thermal cyclic loading at the high operating temperature without causing the material to weaken, undergo chemical changes, or fail.

The extended surfaces used in the cold end of the engine to dissipate heat should be of such geometry and material that heat transfer would be maximized between the engine and the ambient fluid.

Constraints and Other Considerations

The major constraint of Stirling engines is the ability to generate enough heat on the hot end while cooling the cold end in order to produce the necessary change in temperature so that power generation in feasible. Therefore, the main constraint of this design is its ability to concentrate enough sunlight on the hot end while chilling the cold end.

The amount of sunlight that can be concentrated is dependent on a few factors, some of which can be controlled by the design and some of which are outside of the engineering design scope. Such factors that are outside of our control are the position of the engine relative to the Earth and the climate of that region. However, these environmental factors can be improved by ensuring that there is no aerial coverage near the engine such as trees and buildings so that the solar concentrator can optimize the solar rays in that region. Due to the constraints of the sunlight in the operating region, the most important consideration when conceptualizing the engine is the optimization of the solar concentrator. In the event of low solar heat throughout the day, season, or location, the efficiency of the engine could be optimized by the following factors which work to counteract the loss due to the availability of the sun.

The efficiency of the engine can be improved significantly by selecting effective extended finned surfaces to assist in the heat dissipation from the cold end. This will cause the cold end temperature to be significantly lower than the heat on the hot end and increase the change in temperature. Another way to increase efficiency is to select a working fluid within the cylinder which can adequately transfer heat.

Design Alternatives

Overview of Conceptual Designs Developed

Three trade studies performed in order to justify the decision made for the design of the solar Stirling engine. The first trade study compares the different methods of generating power through the use of solar energy which includes photovoltaics, and heat engines such as Brayton and Stirling. The second trade study compares the different types of Stirling engine, alpha, beta, and gamma, to justify the selection for use in our design configuration. Lastly, the third trade study compares the different methods of concentrating sunlight which are traditional glass lenses, glass mirrors, and Fresnel plastic lenses.

Each trade studies that was conducted, was ranked based on a desirability scale. This scale consists of four criteria, Cost, Ingenuity, Ability, and Reliability. Each ranking is based on a 1 through 5 score on the desirability of the concept being implemented.

A basic cost analysis was performed for each option in which the expected cost of each design was analyzed. For the cost portion, a 1 corresponds to high cost which is not desirable, and a 5 correlates to low cost which is desirable.

Each alternative was given a ranking for Ingenuity. Ingenuity is defined as the implementations relative degree of current implementation. For the Ingenuity portion, a 1 corresponds to high degree of current implementation which is not desirable, and a 5 correlates to low degree of current implementation which is desirable.

Each alternative was given a ranking for Ability. Ability is defined as the particular concepts ability to perform the intended role. For the Ability portion, a 1 corresponds to low degree of concept not being able to perform intended role which is not desirable, and a 5 correlates to a high degree of concept being able to perform intended role which is desirable.

Each alternative was given a ranking for Reliability. Reliability is defined as the ability of the concept to perform its intended role with the minimal amount of maintenance or failures. For the Reliability portion, a 1 corresponds to a low expected reliability which is not desirable, and a 5 correlates to high reliability which is desirable.

Solar Stirling Trade Studies

Types of Solar Energy Conversion

Throughout the history, there have been many methods explored on gathering sunlight for power generator. Some of the most successful methods of using solar energy in order to produce power are Photovoltaics, Brayton Cycle Steam Engines, and Stirling Engines.

Photovoltaics are an array of cells which contain a special material that can convert solar radiation into electrical current (Placeholder1). Photovoltaics ranked a 1 on our scale for cost due its current price which is about $3/W (Solarbuzz, 2009). Since solar panels have been around since the beginning of the space race in the late 1950‟s, its ingenuity was ranked a 1 even though there have been several advances in their efficiencies in the past few years. Photovoltaics ranked a 4 in ability because of their continuous ability to produce an electrical current whenever it is exposed to sunlight. Because photovoltaics have no moving parts, it makes the system extremely reliable and operates with minimal maintenance. It is also worthy to note that many current solar panels use silicon as the main material in the cells. Though there are many advantages to using photovoltaic, the depletion of silicon from soil and the use of rare earth metals lead to solar panels not being the best solution to our power generation problem (Placeholder2). For the reasons stated above, photovoltaics ranked a total of 11 out of 20 on the desirability scale.

Brayton Cycle is a type of thermodynamic cycle used in heat engine that uses steam as the working fluid in order to produce power (Sandfort, 1962). It ranked a 3 on the cost scale due to its use of rare metals and it cost-benefit analysis is mostly good for very large scale applications but would not make sense for smaller engines. The Brayton cycle, or steam engine, also ranked a 3 on ingenuity since it has existed for many decades but has only recently been applied in solar systems. Brayton cycle was ranked a 5 in ability since it can effectively use a solar concentrator to heat a reservoir of water to create steam which then turns a turbine. However, since it is comprised of moving parts, its reliability cannot be a 5 since its maintenance may cause a problem with long-term applications (Sandfort, 1962). Stirling engine is a type of heat engine that generates power through the compression and expansion of the working gas in its cylinder via a hot end and cold end (Berchowitz, 1984). This engine was given a 4 on the cost scale due to its relative inexpensiveness. The materials used for the engines are neither exotic nor rare therefore making the parts list more cost effective than other means. The solar Stirling engine ranked a 5 in ingenuity because though the Stirling engine has been around for over 100 years, it adaptation to using solar for the hot end as opposed to nuclear is new and innovative. It also ranked a 5 in ability because a Stirling engine will continue to compress and expand a gas as long the temperature difference is present therefore making it a very viable option for power generation with respect to other heat engines. However, like steam engines which use the Brayton Cycle, Stirling engines also have moving parts and though the ability to generate power is very reliable, its long term maintenance plan forces it rank as 4 for reliability (Berchowitz, 1984).

	Cost	**Ingenuity**	**Ability**	**Reliability**	**Total**
Photovoltaic	1	1	4	5	11

Brayton Cycle	3	3	5	4	15
Stirling Engine	4	5	5	4	18

Figure 24:Types of Solar Energy Conversion Ranked

Conclusion

The conclusion of the trade studies is that we will use a Stirling engine for the conversion of solar energy into electrical energy.

Types of Stirling Engine Configurations

Due to the increasing of price for energy gathered from fossil fuels as well as the harmful consequences that they have on the environment, a new way of generating power that is both clean and efficient needs to be explored. A prominent candidate for power generation which uses natural resources are Stirling engines due to their unique functionality which allows for use of different types of fuels including solar heat. Below are listed the most common configurations for a Stirling Engine; Alpha, Beta, and Gamma.

Alpha Stirling Engines ranked a 3 in cost due to lack of durability in the seals which always pose a technical problem. Commercially, alpha configurations require an insulating head in order to move the seals away from the high temperature exposure in the hot end. Though this fixes the seal problem, it also adds dead space so it was assigned a 3 on ability and reliability.

Beta Stirling Engines do not have the seal problem that alpha configurations have and are therefore ranked a 4 in cost and ability respectively. The beta engine is also extremely reliable and was therefore given a 5 on reliability.

Gamma Stirling Engines provides a lower compression ratio but it much simpler mechanically; this earns gamma a 4 in cost. Also, gamma offers a unique ability to be used in multi-cylinder Stirling engines and therefore gets two 5‟s for ability and reliability (Wheeler, 2007).

Cost		**Ingenuity**	**Ability**	**Reliability**	**Total**
Alpha Stirling	3	4	3	3	13
Beta Stirling	4	4	4	5	17
Gamma Stirling	4	4	5	5	18

Figure 25: Types of Stirling Engine

Conclusion

The trade studies for the different Stirling Engines configuration showed that for the intended application and purpose of our project, the best type of Stirling engine to use in the Gamma configuration.

Types of Solar Concentrators

Choosing the right type of solar concentrator for use in our solar Stirling engines will greatly influence the efficiency of the engine and therefore is deserving of special attention. A wide variety of solar concentrators are currently commercially available in order to concentrate solar rays for the purpose of power generation. There are many forms of solar concentrators, but the most common forms are the use of curved, parabolic mirrors and the use of Fresnel lenses.

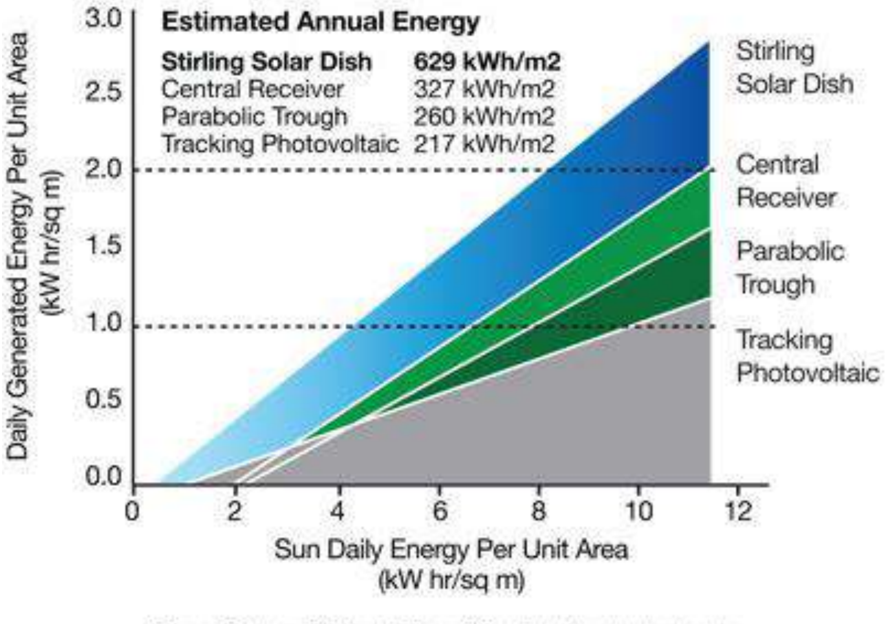
Parabolic mirrors ranked a 3 on our cost scale due the expense of manufacturing curved mirrors. It is one the most common forms of solar concentration and therefore ranks a 2 in ingenuity. However, its popularity is well placed since it is extremely able to perform its task with a noticeable amount of reliability which has earned parabolic mirrors two 5‟s obtained in the reliability and ability.

The Fresnel lens ranked a 5 on cost since it is significantly more cost effective than the parabolic mirror. This is due to is composition of many flat mirrors instead of curved. It also ranked a 5 on ingenuity since it is a fairly new form of concentrating sunlight. Though Fresnel lens is not as efficient at concentrating sunlight, they gather more sunlight over the same amount of area and are therefore ranked a 4 and 5 for ability and reliability respectively.

Cost		Ingenuity	Ability	Reliability	Total
Parabolic Mirrors	3	2	5	5	15
Fresnel Plastic lens	5	5	4	5	19

Figure 26:Types of Solar Concentrators

Figure 23 illustrates the daily generated energy per unit area versus the sun daily energy per unit area for Stirling solar dish, central receiver, parabolic trough, and tracking photovoltaic (Systems, Technology, 2009). This image demonstrates that using Solar Stirling instead of photovoltaics and other heat engines yields a higher estimated annual energy and would therefore be more beneficial as a method of solar energy conversion.



Source: Southern California Edison & Sandia National Laboratories

Figure 27:Power Generation per Square Methods for Different Methods(Source Southern California Edison and Sandia National Laboratories)

Conclusion

The trade studies for the Types of Solar Concentrators showed that for the intended application and purpose of our project, the best type of solar concentrator to use is the solar Stirling dish.

The Gamma type Engine:

This engine is a compromise between the alpha engine and the beta engine. In a cylinder the displacer assumes its function. In the other cylinder, the operating piston controls the variations of the global volume and recovers energy. This type of engine is frequently used to take advantage of small differences in temperature between cold source and hot source.

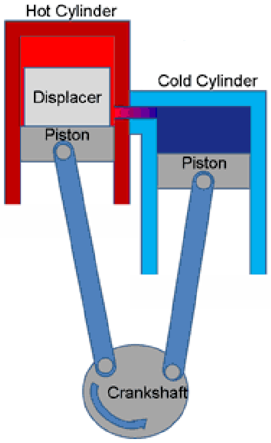


Figure 28:Gamma Configuration (Source:engineering.uiowa.edu)

The Stirling gamma configuration is simply a Stirling beta engine in which the power piston is not mounted coaxially with the displacer piston but in a separate cylinder. This avoids the complications of the of the displacer piston linkage passing through the power piston.

A fixed amount of working fluid (gas) is maintained within the cylinders by the pistons which form a gas tight seal with the cylinder walls. The displacer is a loose fit within the hot cylinder, allowing the gas to pass down the sides as it moves up and down. As with other Stirling engines, the gas is alternately heated and cooled causing it to expand and contract as it shuttles between the hot and cold cylinders transferring its energy to the power piston in the cold cylinder.

The PV diagram :

The volume variations :

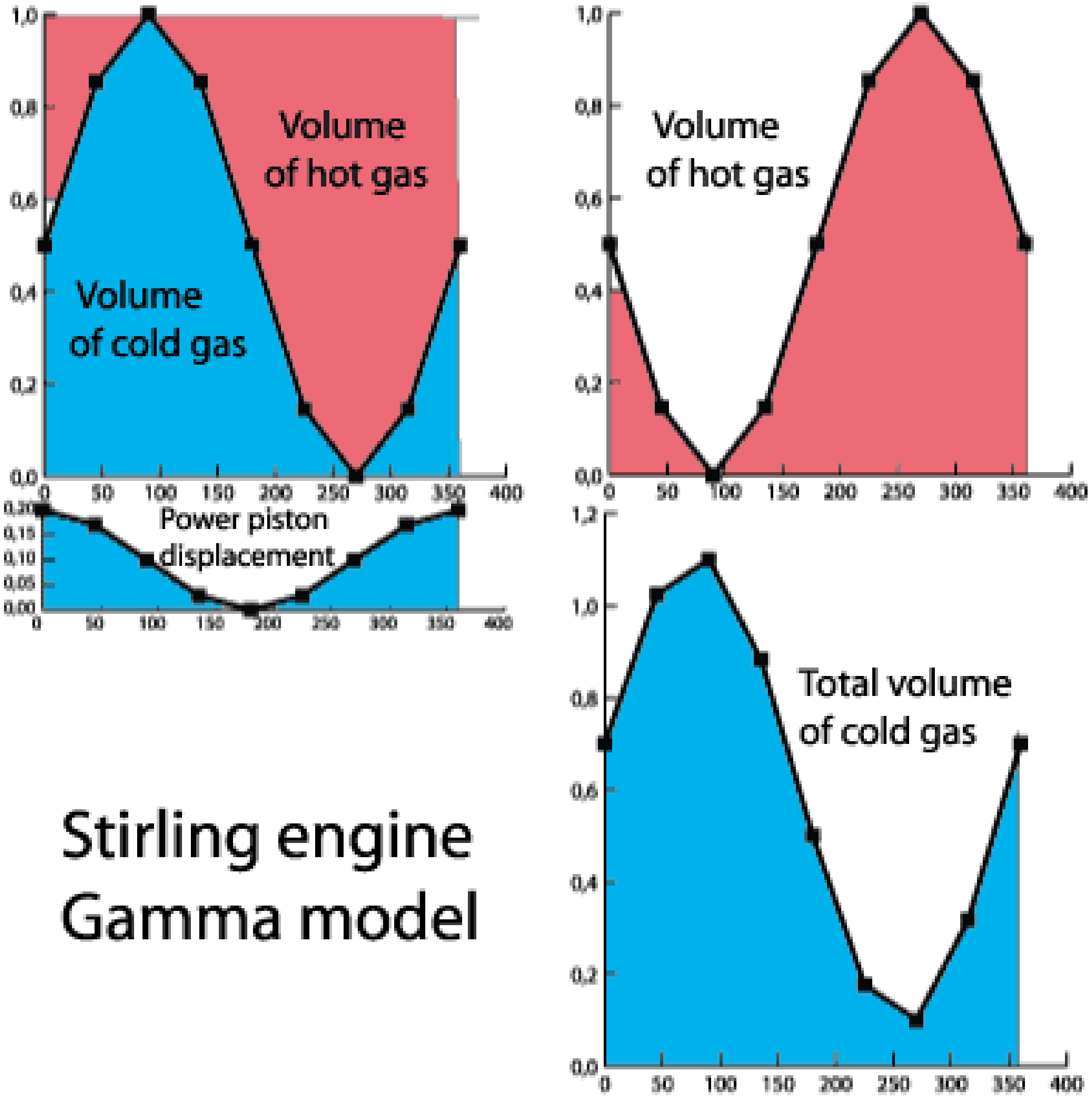


Figure 29 volume variations (Source:Pierre Gras, Author Moteur Stirling)

The PV Diagram of an actual sample gamma engine:

This diagram is characteristic of the engine described above. In the example taken the calculations were made with T_M = 290 K (17°C) et T_m = 348 K (75°C).

The volume covered by the operating piston is 5 times lesser than the one covered by the displacer.

The theoretical efficiency would be 17%.

One can see that this cycle is clearly different from the theoretical cycle.

The important thing is to have the gray area as large as possible. It is representative of the work recovered during a cycle

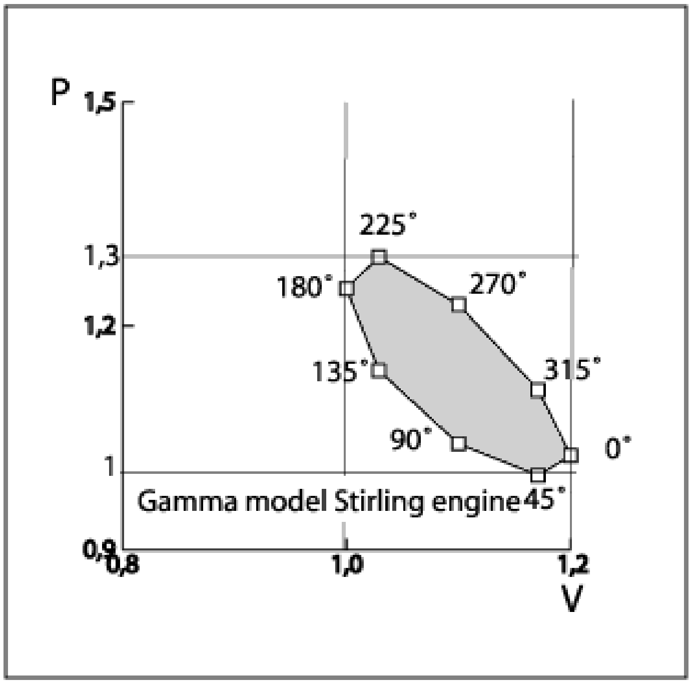


Figure 30 PV Diagram of actual engine (Source: Pierre Gras, Author Moteur Stirling)

Engineering Design and Manufacture

A prototype Stirling engine was to be designed to demonstrate the concept of operating it using solar energy.

The designs obtained were modified to ease machining.

CAD Model

A ProE model of the engine was made to analyze the working of the engine.

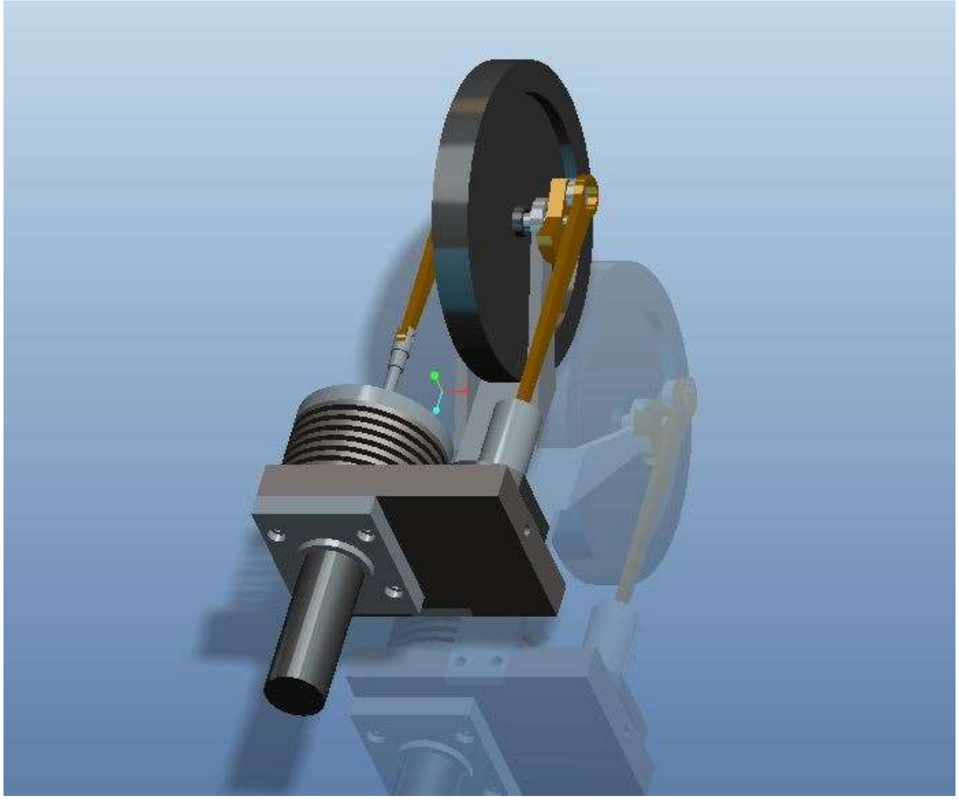


Figure 31: CAD Model Front

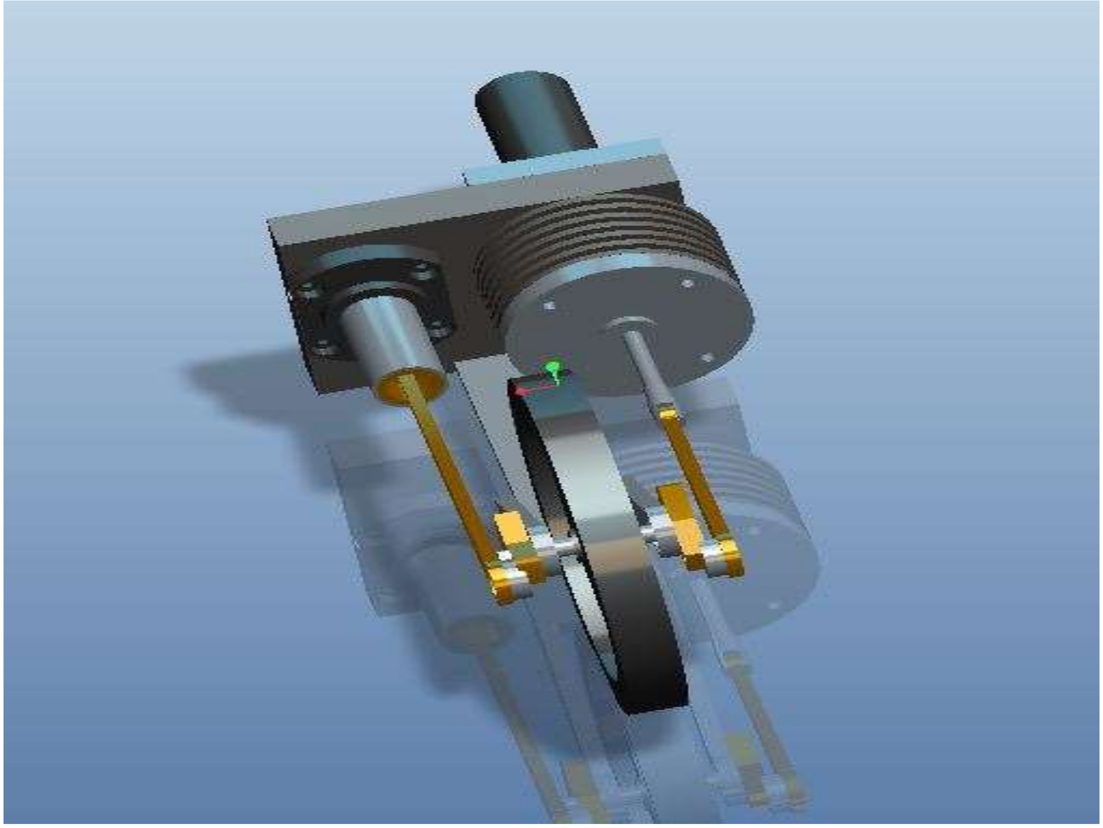


Figure 32:CAD Model Back

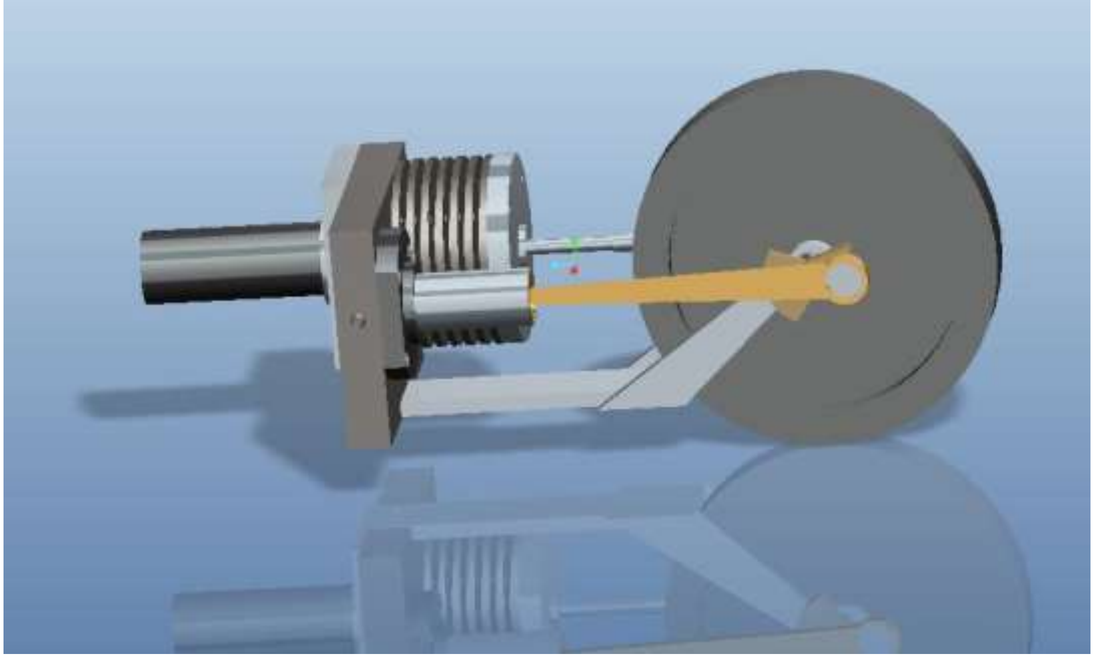


Figure 33:CAD Model Side view

Calculation for stresses on Power cylinder of Stirling engine.

Assumption: - maximum temperature reached within cylinder is 300 C.

Cylinder is closed from one end for calculations.

Calculations are performed on extreme condition that can be reached.

Density of air at 300C = 0.6159 kg/cubic meter

Density of air at 24C = 1.184 kg/cubic meter

Gas constant (R) = 8.31 J/k.mol

Dimensions of cylinder are: - radius (r) = 6.75 mm

Length (l) = 43 mm

Volume of cylinder (v):- v = pi * **r**^2 * l

= 3.14 * (6.75) ^2 * 43

= 6151.8 mm^3

= 6151.8 * 10^-9 cubic meters

Mass of air in cylinder (m):- mass = volume * density (25C)

= 6151.8 * 10^-9 * 1.184

= 7.28*10^-6 kg

Pressure (stress) on cylinder wall (p):- using ideal gas equation at temperature 300C (573k)

P = density * R * T

= 0.6159(8.31) (573)

= 2932.68 pa

Force on cylinder wall (F):- F = p * Area

Where, Area = 2 * pi * r * l

= 2(3.14) (6.75)(43)(10^-6)

= 1.822* 10^-3 square meters

F = 2932.68(1.822)(10^-3) = **5.3433 N**

Force on cylinder base(f) :- f = P * Area(base)

= 2932.68 * Pi * r^2

= 2932.68(3.14)(6.75 * 10^-3)^2

= 0.41 N (in our case cylinder is open from both the ends so it is ignored**)**

Yield Stress range for Aluminium: - 28 **Mpa**

(Selected minimum value of yield and ultimate stresses of aluminium**)**

Ultimate stress range for aluminium: - **69 Mpa**

Comparing the results: - since stress on the wall of cylinder is very less than yield and tensile stress of Aluminium so it's safe to use the power piston cylinder assembly in our project.

Isothermal calculations for Efficiency

1) Efficiency is calculated using isothermal calculations.
2) At intake stage air is considered to be at room temperature and pressure.
3) Volume of air with in power cylinder is calculated using geometry of piston and power cylinder.
4) Calculations performed at minimum temperature of 25C (room condition) and maximum of 150C.
5) Four processes with in power cylinder are :-
    a) Constant volume heat addition. (2-3)
    b) Expansion. (3-4)

c) Constant volume heat rejection. (4-1)

d) Compression. (1-2)

Calculations

Stage 1 (intake):

Intake is at room temperature and pressure.

So, Pressure (P1) = 101.325 kpa

Temperature (T1) = 25C

Volume (V1) = pi * r^2 * l = 6.15185 * 10^-6 m (where r=6.75mm and l=43mm)

Stage 2:

T1 = T2 = 25C

Pressure (P2) = 145.2325 kpa

Volume (V2) = 4.26 * 10^-6 m (r=6.75mm and l=30mm)

Stage 3:

Temperature (T3) = 150C

Pressure (P3) = 206.1521 kpa

Volume (V2) = 4.26 * 10^-6 m (r=6.75mm and l=30mm)

Stage 4:

Temperature (T4) = T3 = 150C

Pressure (P3) = 206.1521 kpa

Volume (V2) = 6.15185 * 10^-6 m (where r=6.75mm and l=43mm)

Mass with in cylinder:

Mass (m) = (P1 * V1) / (R * T1) = 7.28826 * 10^-6 kg

Heat added (Qin):

Qin = m * R * T1 * ln (V4/V3) = 0.31853 KJ/Kg

Heat removed (Qout):

Qout = m * R * T3 * ln (V2/V1) = 0.2244 KJ/Kg

Efficiency:

Efficiency = 1 – Qout/Qin = 0.2955 (29.55%)

FEA Analysis:

Introduction

FEA was performed on the model parts suspected to be under the most stress. The analysis was done in order to confirm that the parts will not fail under normal operating conditions.

The procedure we under took was to first identify the parts with the smallest areas and under the greatest fatigue. The parts identified under these conditions were:

1. The displacer fork.
2. The displacer driving rod axis.

The analysis was performed using ANSYS.

Material Properties

The following material properties were selected. The grade of Aluminum could not be determined as we were told by the salesmen. It was just known as “local” aluminum. Material properties used:

1. Modulus of Elasticity 69 x 10^9 N/m2
2. Density 2700 kg/m3
3. Ultimate tensile Strength 110 x 10^6 N/m2
4. Yield Strength 95 x 10^6 N/m2
5. Poisson’s Ratio 0.334

The displacer fork Analysis

Our theoretical calculations, as explained in the previous report in detail, gave a force of 0.41956 N. we used a force of 0.5 N in our analysis. The following are the results:

1. Figure 1 shows the model without any forces applied

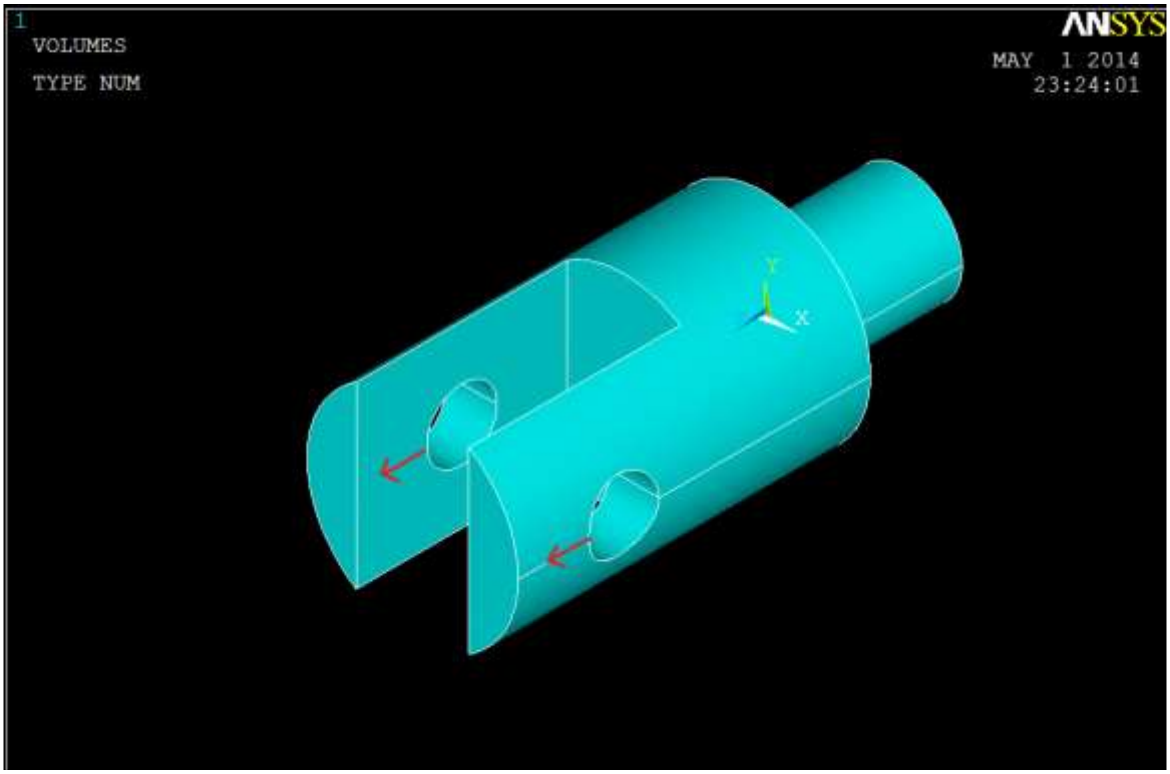


Figure 34 model without any forces applied

2. A lateral force of 0.5 N was applied as shown by the red lines.

3. We were successfully able to generate a result showing that the material had not failed under the given loading. The deformations in each axis are given in the figures below. The structure made by the white lines represents the datum lines. The bending of the part does not show the extent but merely the direction in which the part might deform under the given loading.

All deformations in the results are in millimeters.

Stresses in X- Direction:

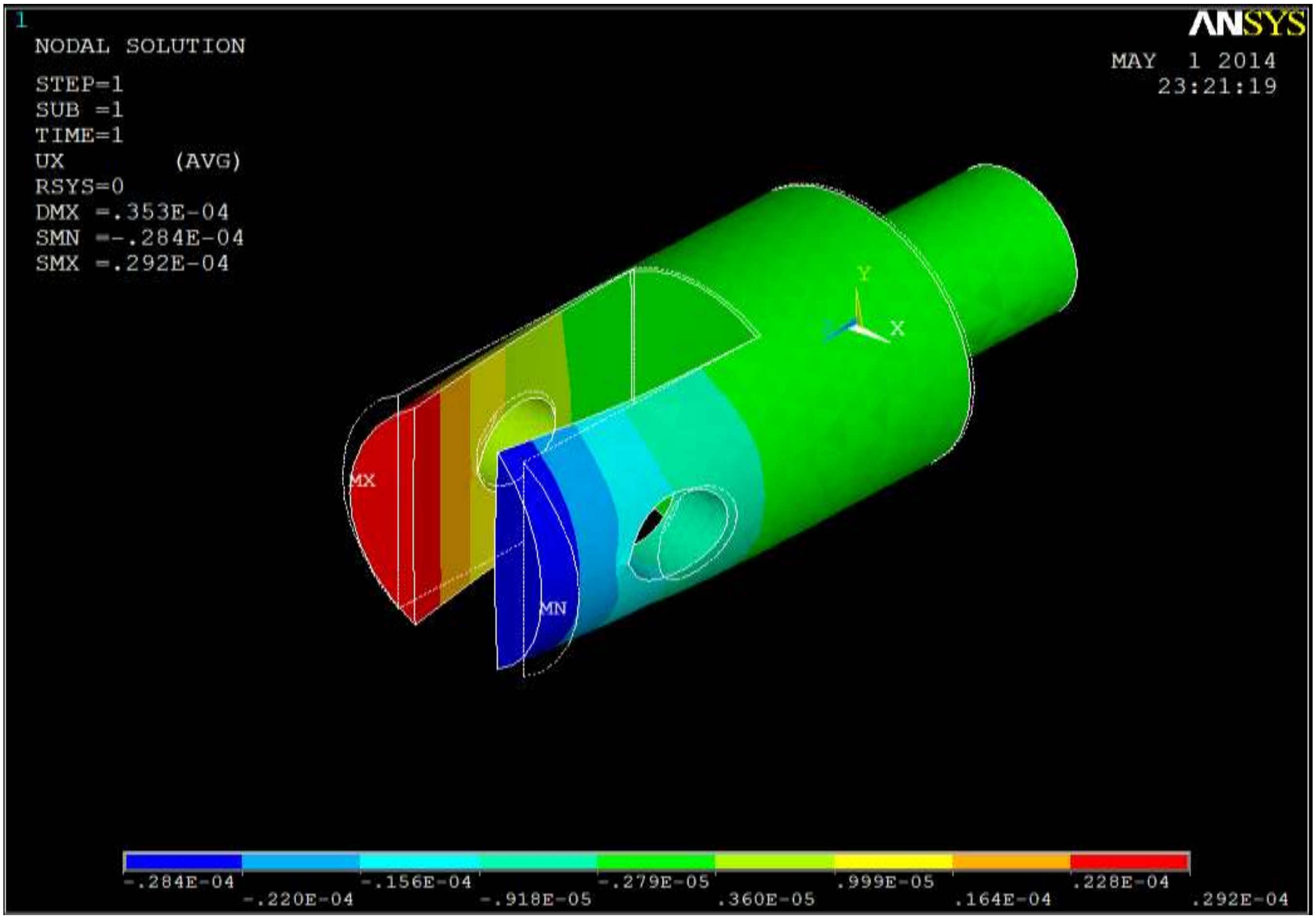


Figure 35: Stresses in X- Direction

It can be seen that the maximum deformation (represented by the red region) was just .228x10^-4 mm.

Stresses in Y- Direction:

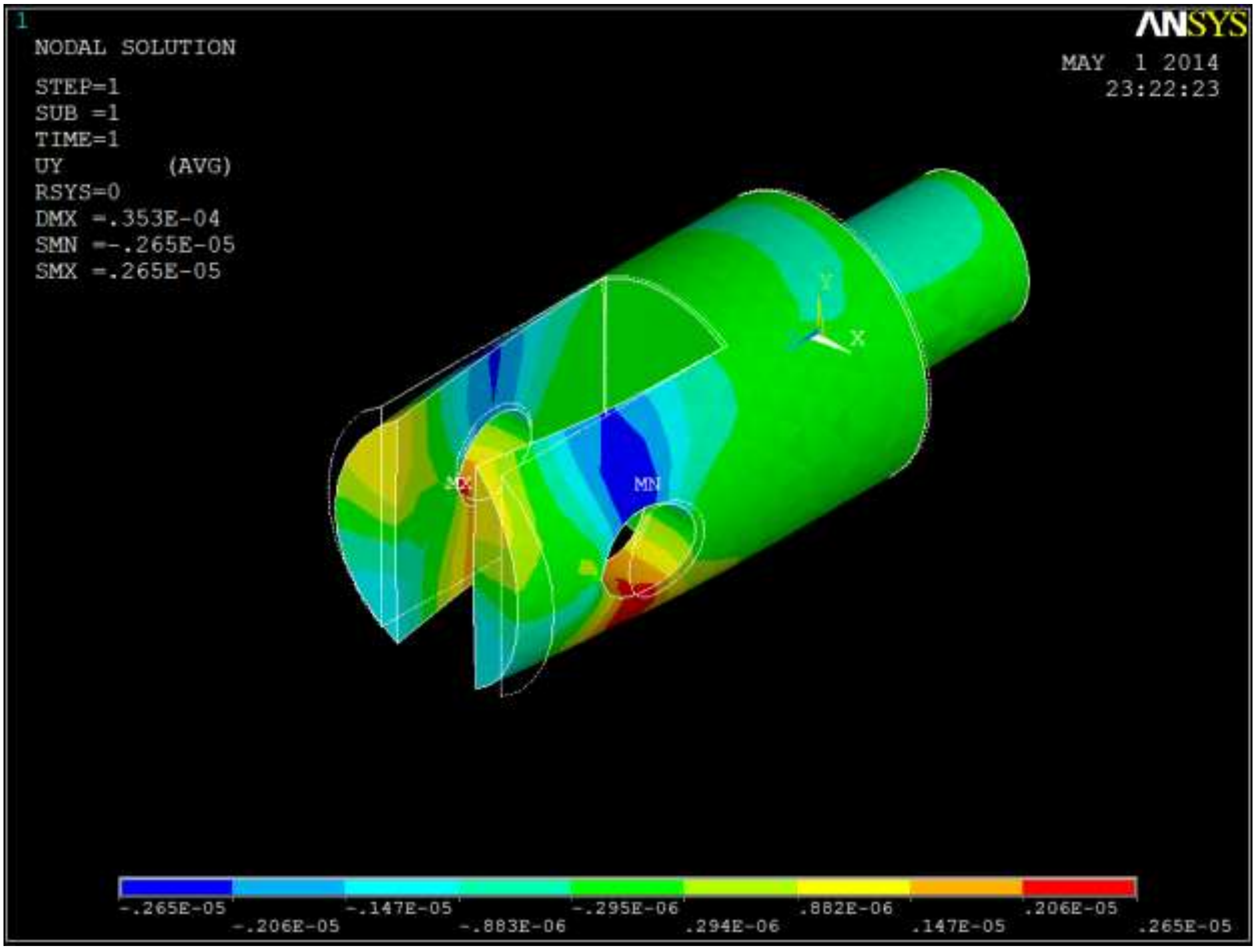


Figure 36:Stresses in Y- Direction

Stresses in Z- Direction:

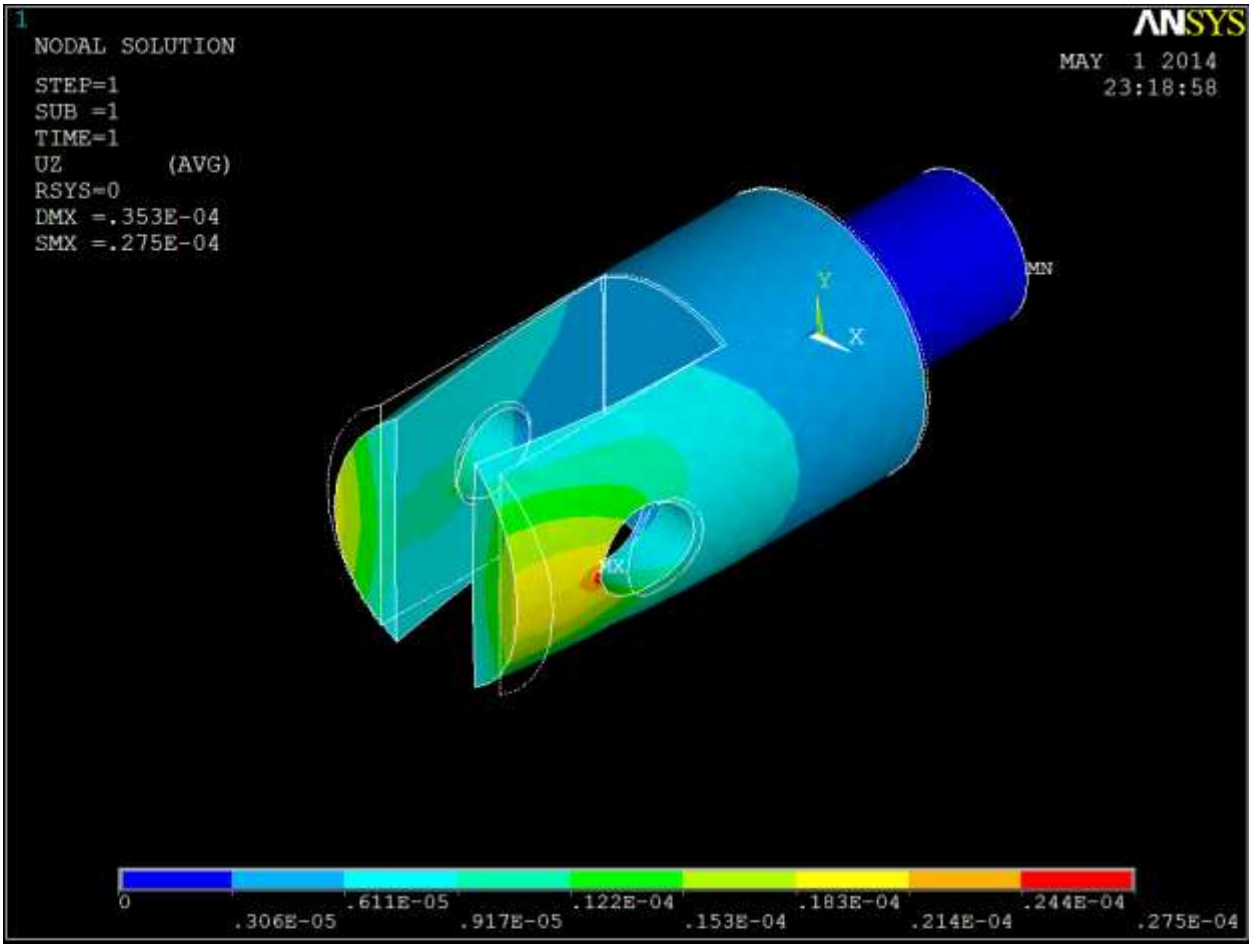


Figure 37:Stresses in Z- Direction

The Von Mises stress:

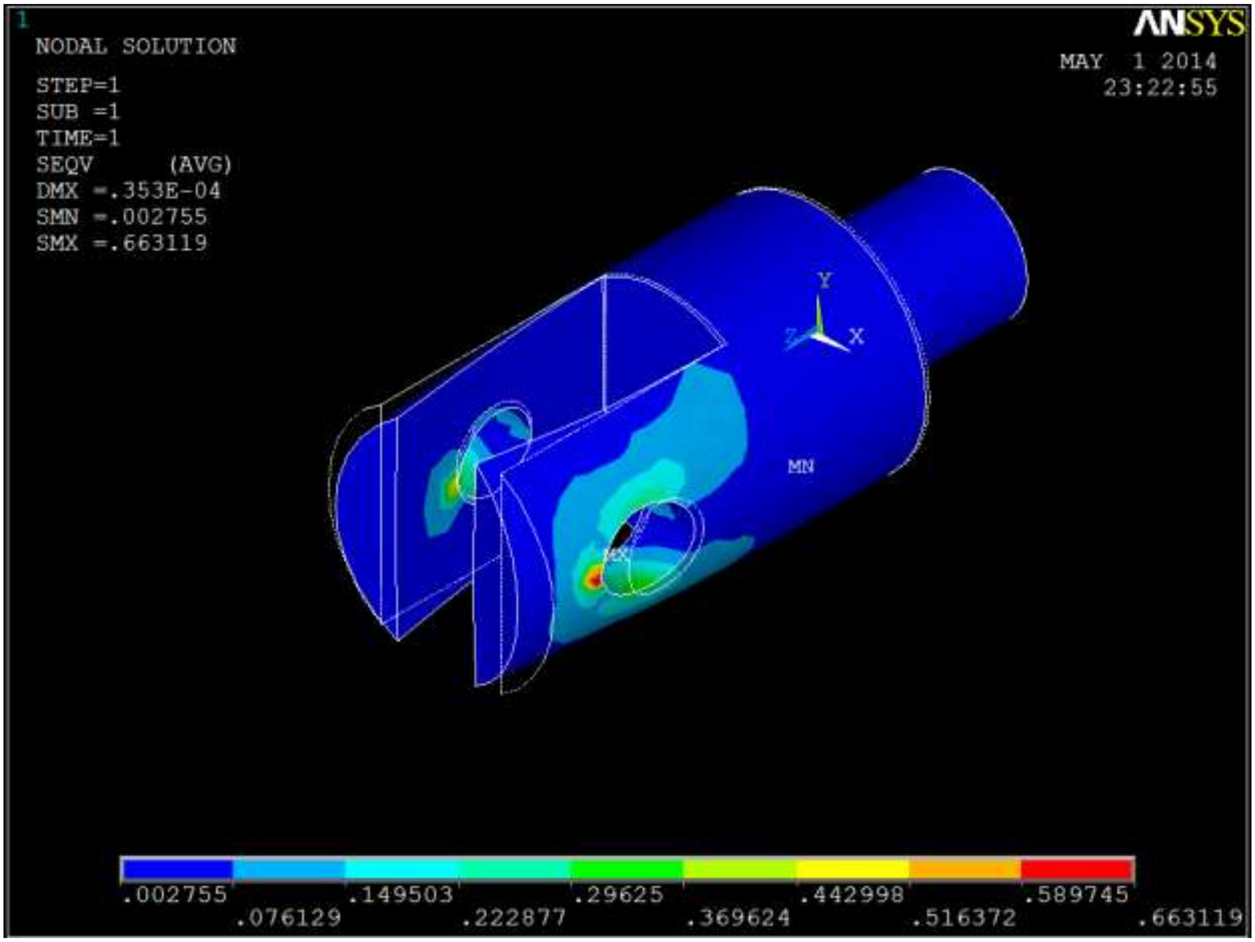


Figure 38:The Von Mises stress

Driving rod axis analysis

The second part that was analysed was the driving rod axis

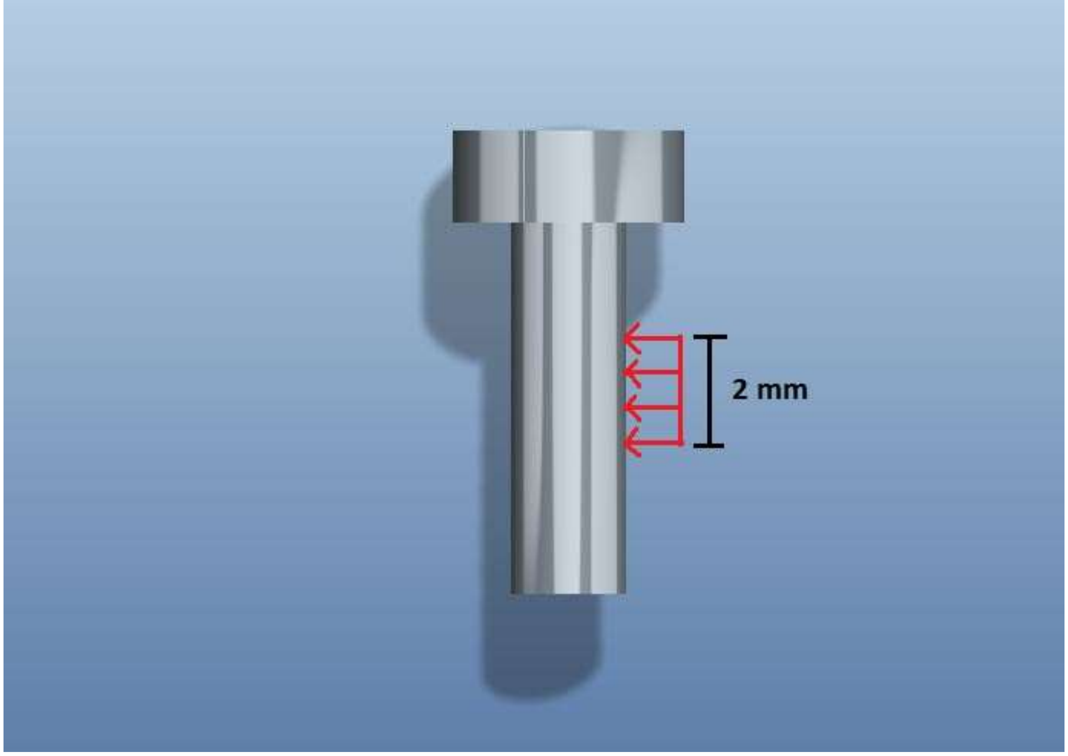


Figure 39:driving rod axis

Displacement Vector Sum:

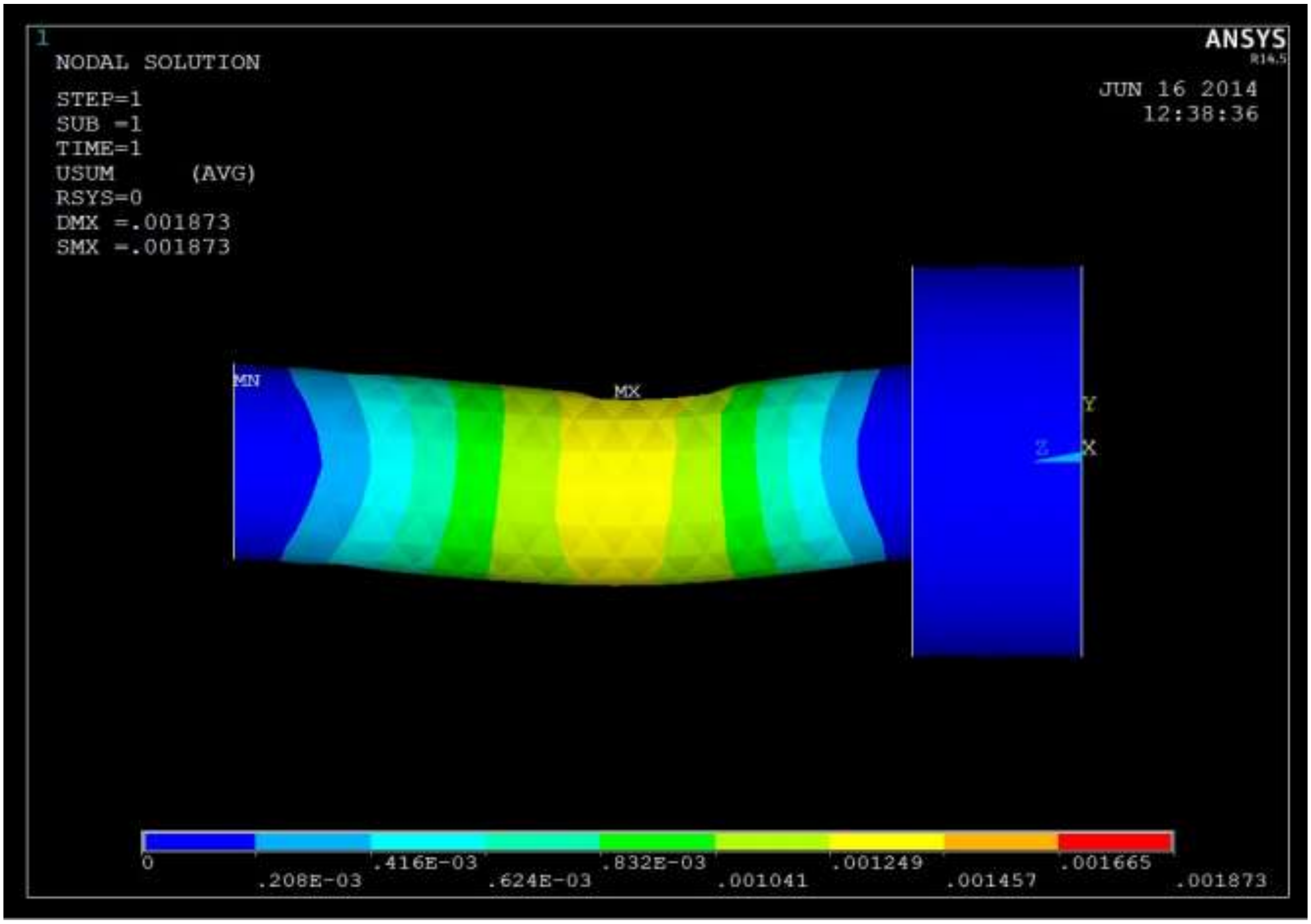


Figure 40:Displacement Vector Sum

Deformation Y Axis:

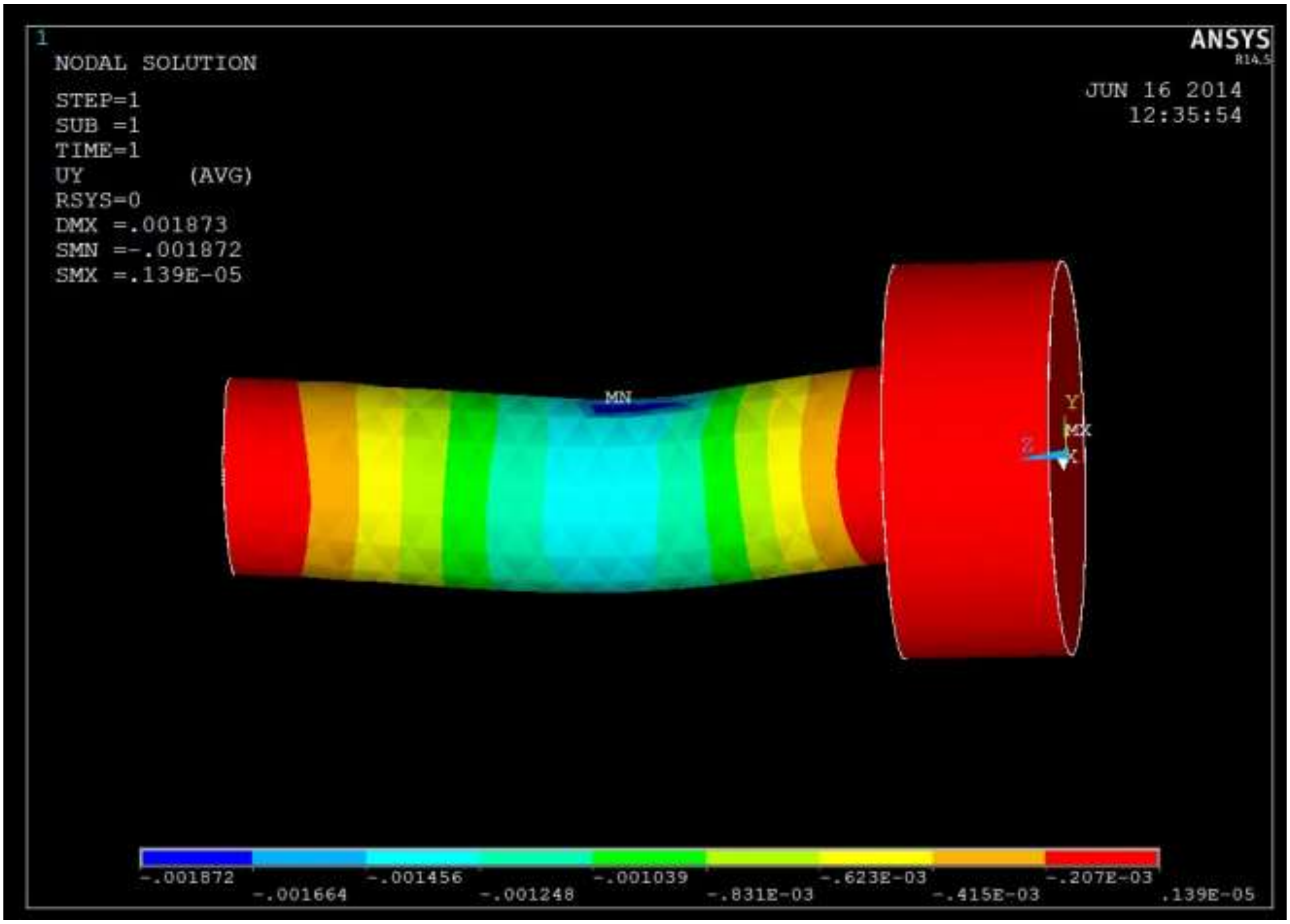


Figure 41:Deformation Y Axis

Deformation X Axis:

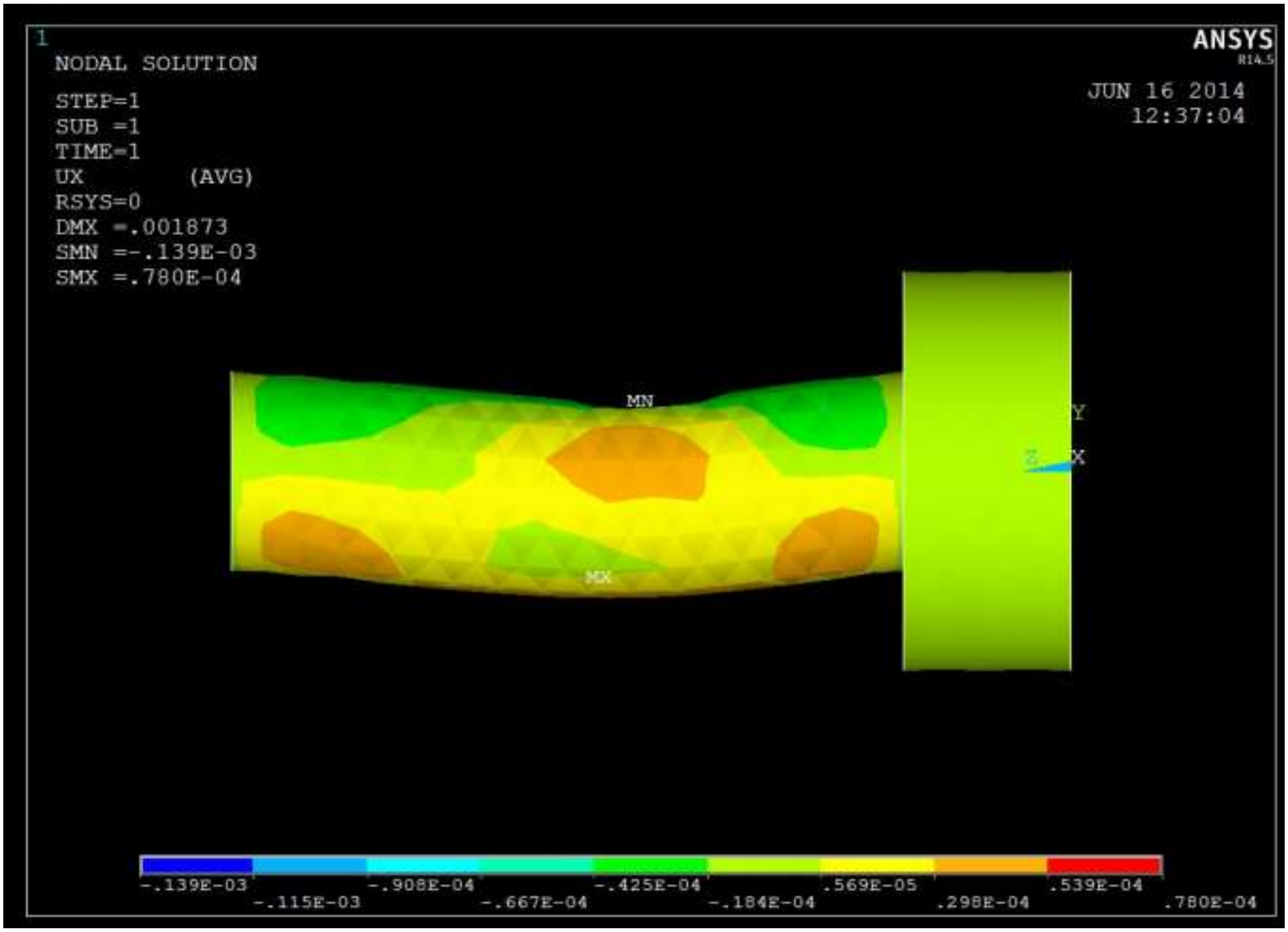
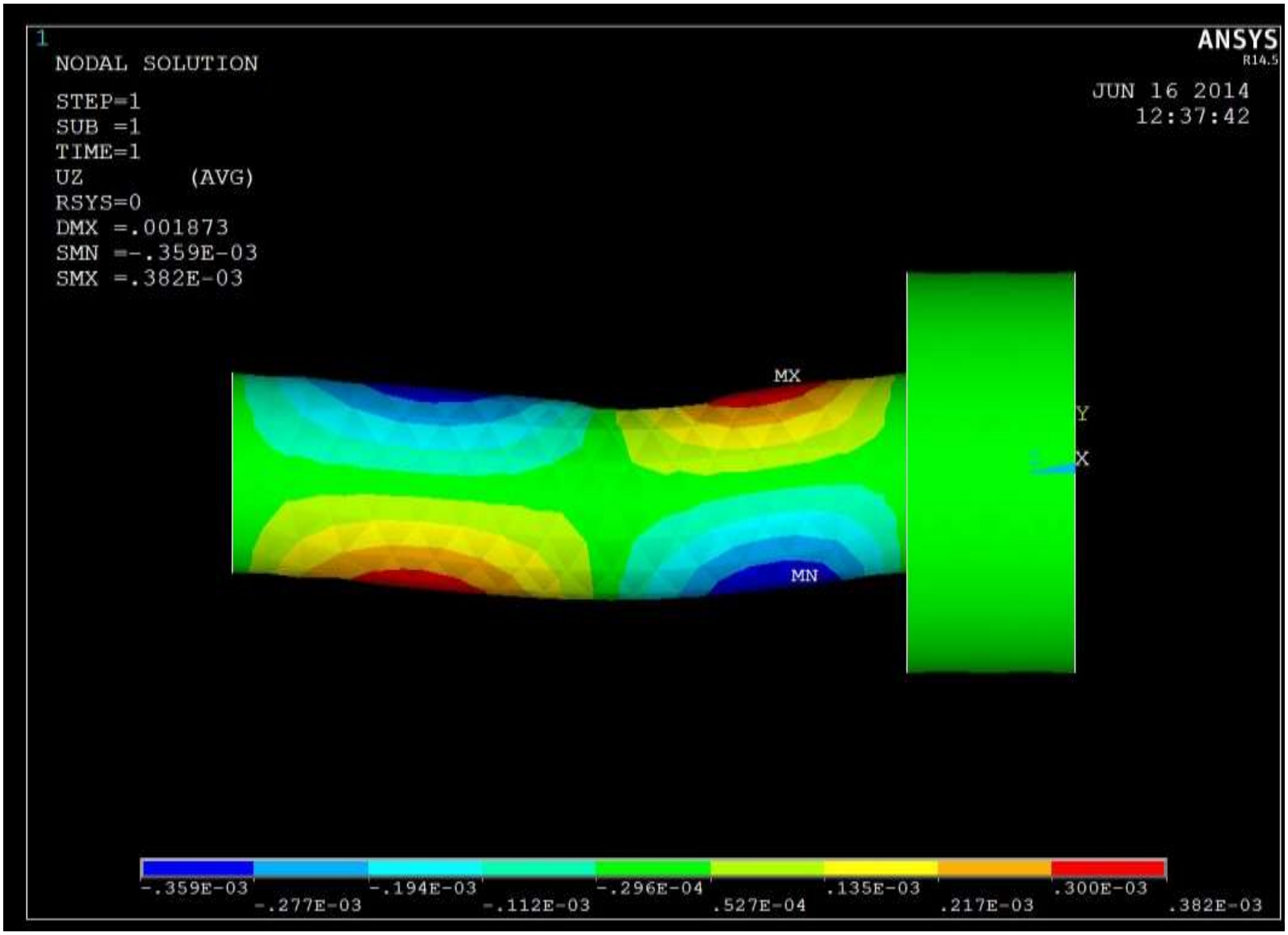


Figure 42:Deformation X Axis

Deformation Z Axis



```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
UZ        (AVG)
RSYS=0
DMX =.001873
SMN =-.359E-03
SMX =.382E-03
```

Figure 43:Deformation Z Axis

Von Mises Stresses:

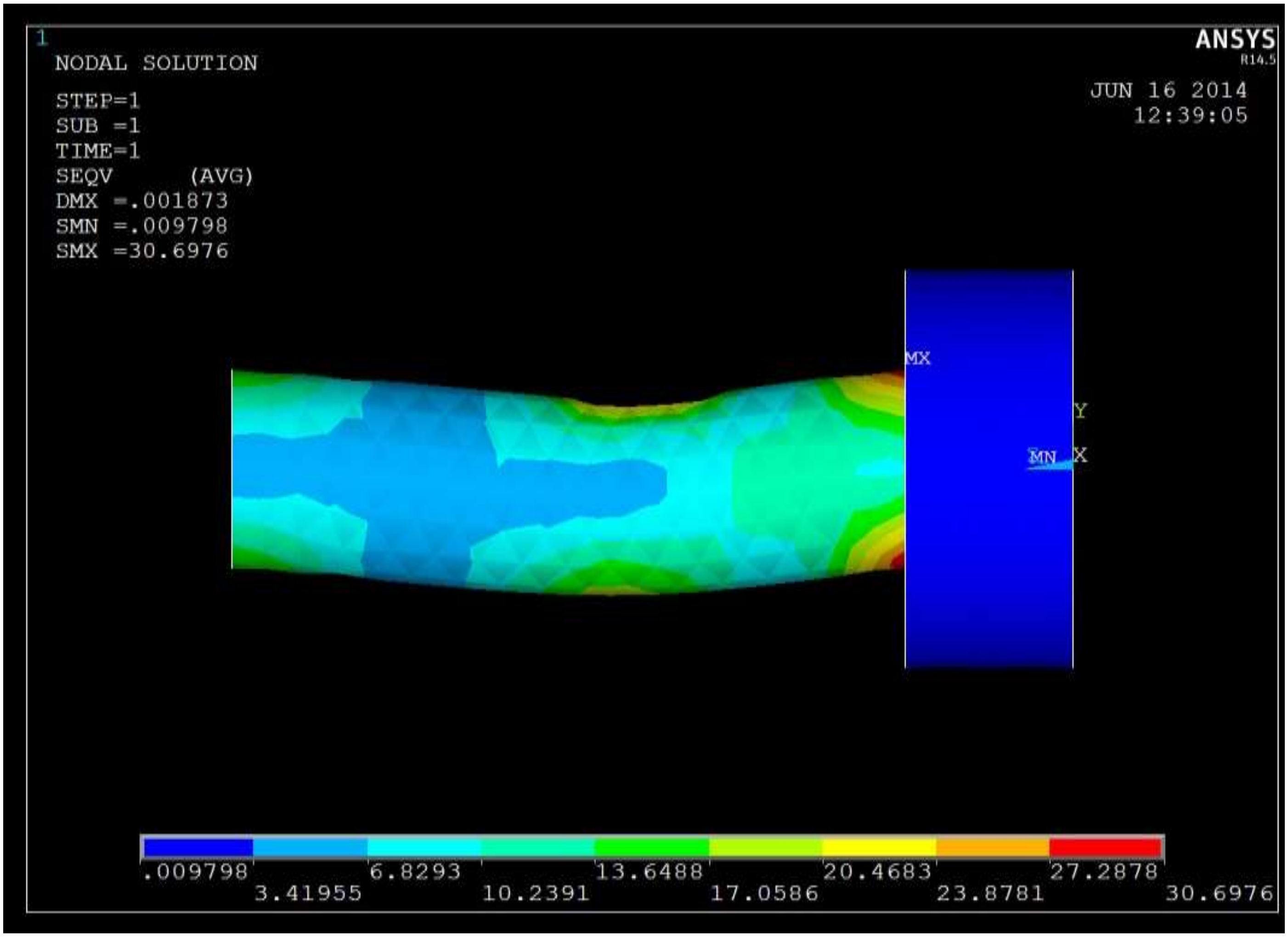


Figure 44:Von Mises Stresses

Manufacturing:

All the parts were manufactured at SMME Manufacturing Resource Center. The material was procured from City Sadder Road Rawalpindi. An image of some of the parts manufactured is given below.

Figure 45: Machined Parts

The list of materials and their prices are mentioned below:

Name of material	**Dimensions**	**Location**	**Price**
1) Aluminium Rod	Dia = 22mm Length = 200mm	Iqbal shop, city sadder	Rs 200
2)Aluminium stripes	Length = 120mm Width = 30 mm Breath = 6 mm	Ismail shop, sadder	Rs 100
3)Aluminium Plate	Length = 150mm Width = 70 mm Breath = 20 mm	Ismail shop, sadder	Rs 650
4)Aluminium Rod	Dia = 90mm Length = 150mm	Iqbal shop, city sadder	Rs 900
5)Brass Rod	Dia = 22mm Length = 200mm	Ismail shop, sadder	Rs 250
6)Brass stripes	Length = 120mm Width = 30 mm Breath = 6 mm	Ismail shop, sadder	Rs 200
7)Bearings (3)	Outer dia = 10mm Inner dia = 3mm	City sadder	Rs 180
8)Rubber seals	Outer dia = 23mm Inner dia = 18mm	City sadder	Rs 150
9)Screws and Bolts	Dia = 4mm	City sadder	Rs 200
10)steel rod	Dia = 90mm Length = 25mm	Iqbal shop, city sadder	Rs 150
TOTAL			Rs 2900

Figure 46:Bill of Materials

The individual parts manufactured are shown as under. The main processes involved in making the parts were:

1. Turning
2. Milling
3. Shaping
4. Drilling
5. Welding
6. Polishing
7. Painting
8. Bench fitting

Some parts were modified from their original designs in order to ease machining. These parts were:

1. Mounting Block
2. Displacer flange
3. Flywheel

The entire process of manufacturing and assembly took 2 months. During this period a total of 5 technicians at the MRC were involved with the project.

Below are picture of the final assembled engine:

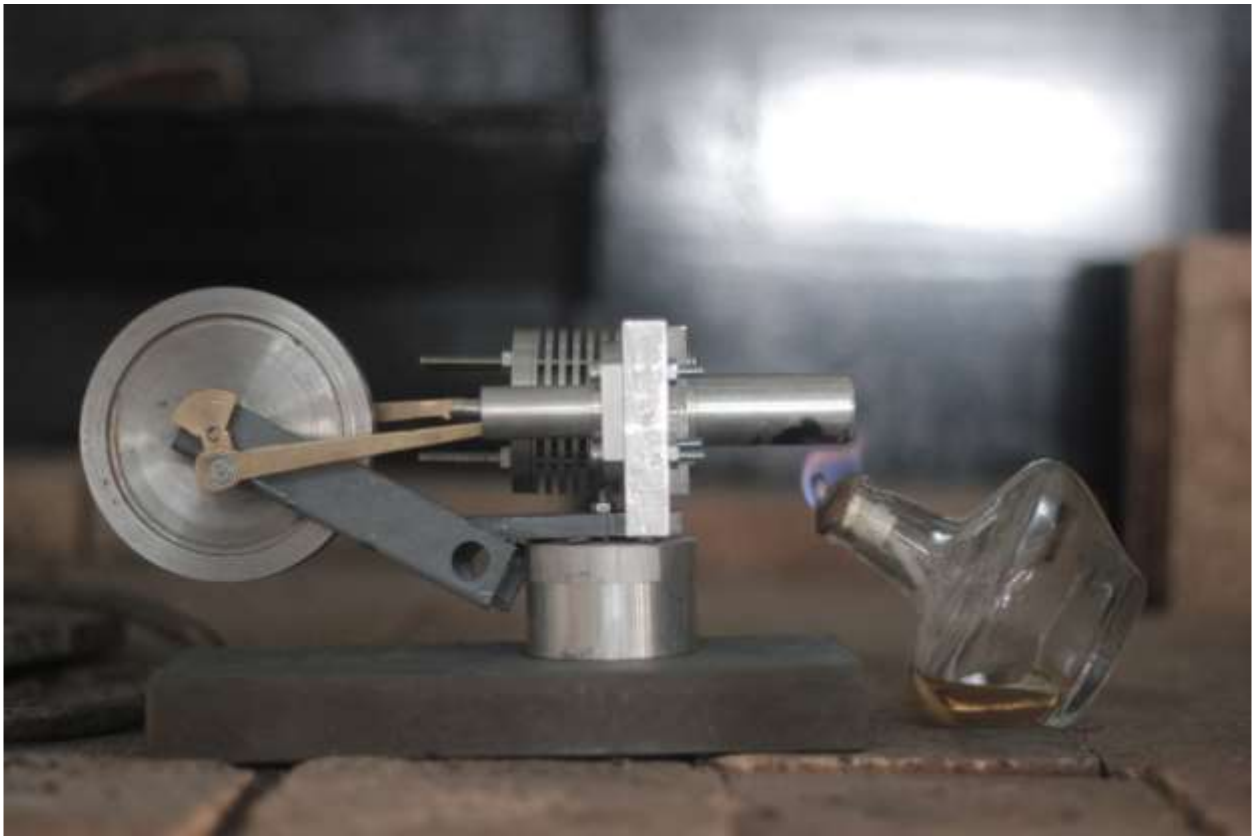


Figure 47: Final assembled engine(sideview)

Figure 48:Final assembled engine(rear view)

Process Tolerances

Figure 49 presents a collection of the most common manufacturing processes and the tolerances commonly associated with each of them. As explained in the legend, the shaded portions of the bars represent the average application of these processes and mean virtually any manufacturing shop should be able to achieve these tolerances. The remaining portion of the bar indicates the "less frequent application", which means one of two things: (1) highly skilled operators and equipment in excellent condition are required to obtain the tolerances on the higher precision end of the range or (2) the process can easily achieve the tolerances on the lower precision end of the range, but a cheaper alternative likely exists, which could significantly reduce part cost.

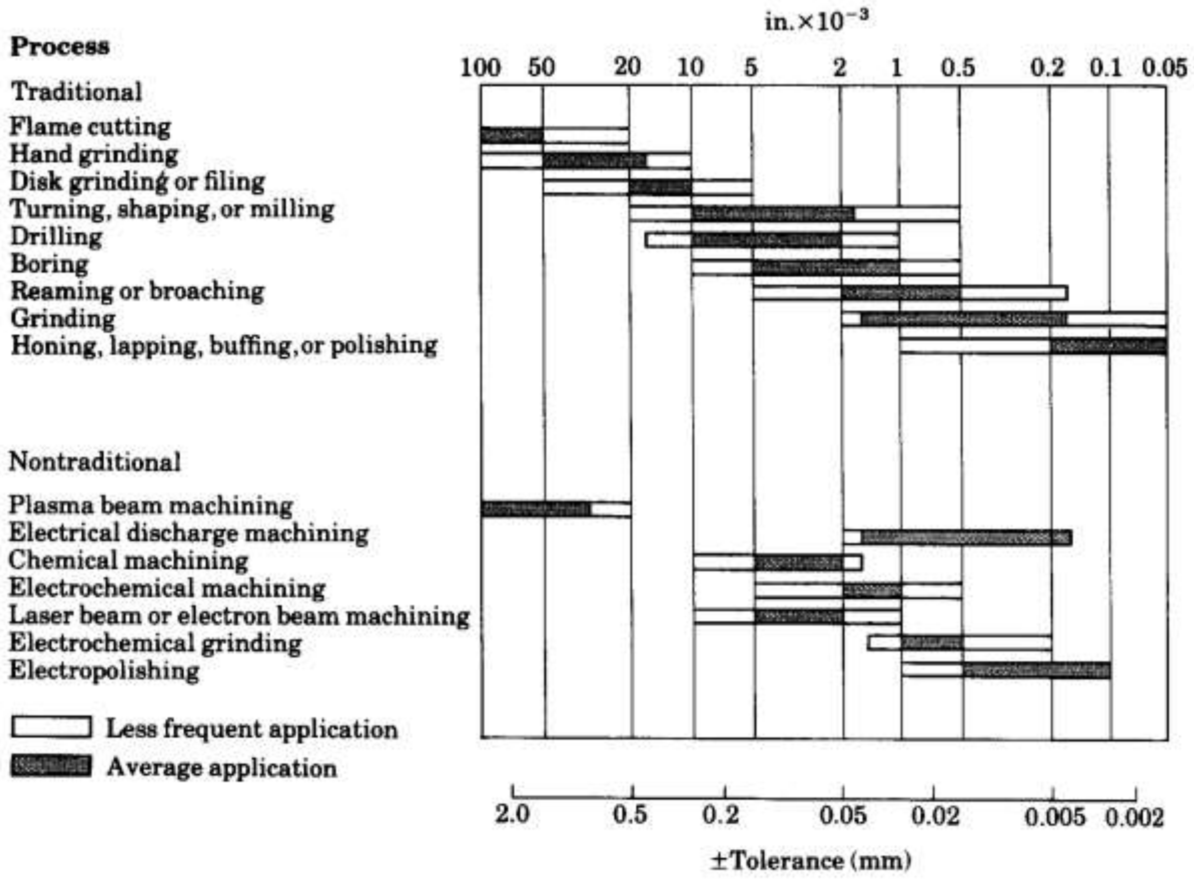
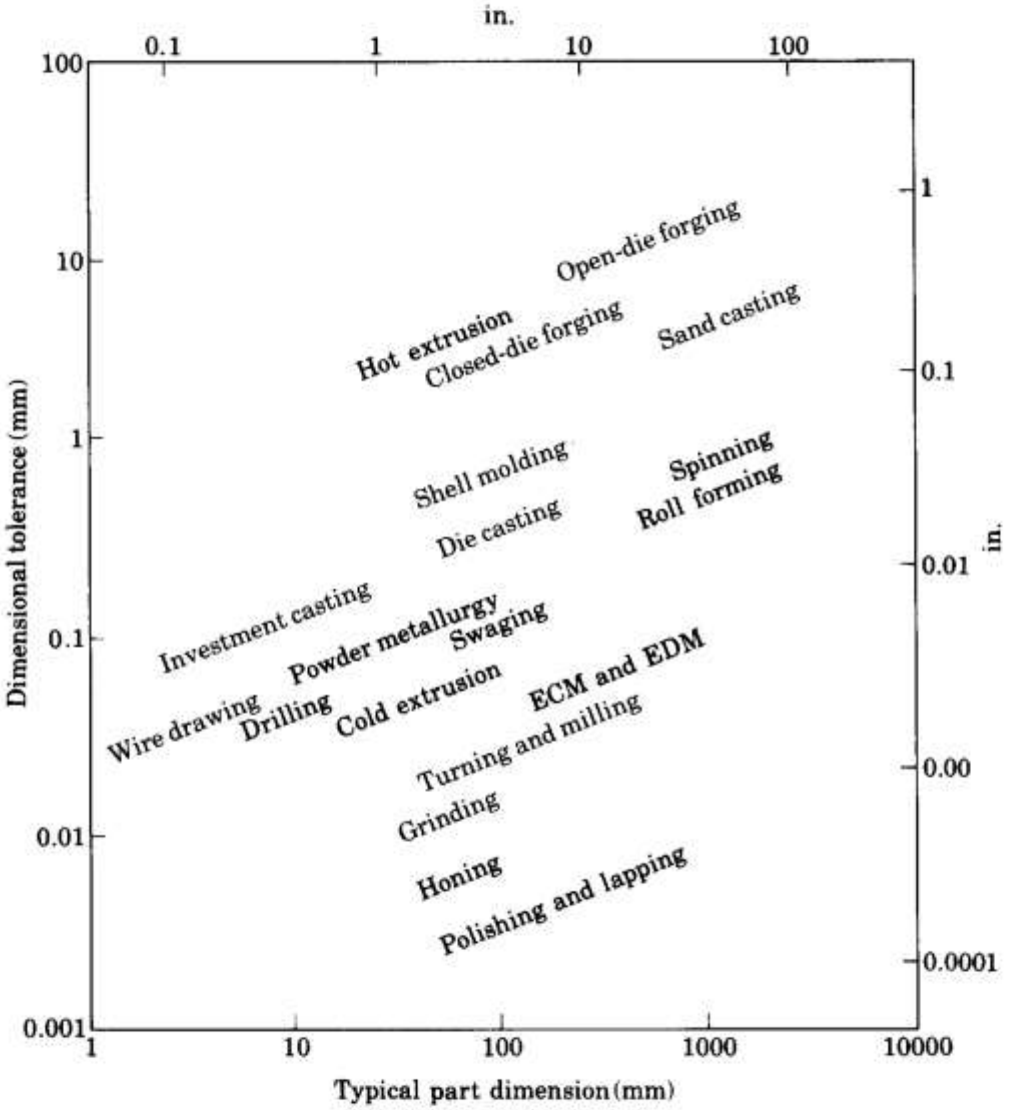


FIGURE 15.5
Tolerances produced by various processes.

Figure 49 Tolerances produced by various processes (Source American Machinist)

Tolerance vs. Feature Size



Pro
ces
s

FIGURE 15.6

Tolerances as a function of component size for various manufacturing processes. Note that, because many factors are involved, there is a broad range for tolerances.

Figure 50: Tolerance as a function of component size (Source American Machinist)

Figure 50 presents another collection of the most common manufacturing processes and common tolerances associated with them *as a function of typical part size.* The important point to take away from this figure is *the general trend showing typical achievable part tolerances grow as a function of parts size.* In other words, the ability to achieve a certain tolerance is a function of part size. As an example, let's use a pair of the 6" measuring calipers found in lab. Do these calipers measure the size of a feature perfectly? No, they do not, as nothing can. However, they do an adequate job for the tolerances we try to hold on the parts we produce. To quantify this point, these calipers have an error associated with them of approximately 0.001" per one inch of measurement. That means if I measure a 1" part dimension, that measurement is really 1.000 ± 0.001". This is not a big deal to us because we often us a tolerance of ± 0.005" on hole features that need to be accurately located. But what happens when I use a measuring instrument of similar accuracy to check a part that is 10" in length? Now my measurement is really 10.000 ± 0.010. So if I still require this part to be within the ± 0.005" tolerance, it should be obvious I now have a serious problem. The same problem exists with digital calipers, digital read outs on machine tools, and position feedback encoders on CNC machines. *All measuring instruments have a positioning error associated with them that is linearly compounded over larger travels.*

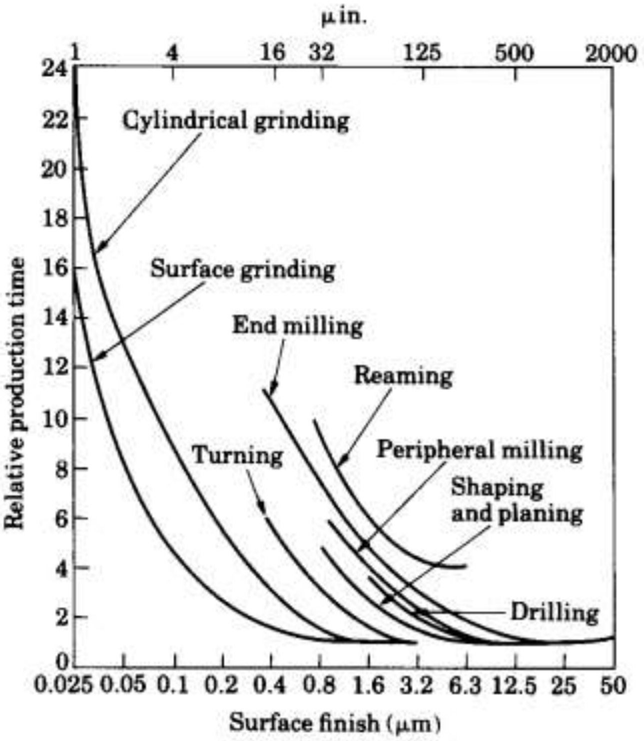


FIGURE 15.8

Relative production time as a function of surface finish produced by various manufacturing methods.
Source: American Machinist.

Figure 51:Surface Finish vs. Production Time (Source American Machinist)

Figure 51 shows relative production time as a function of surface finish for common manufacturing processes. Although the curve for each process is slightly different, *the general trend shows that the relative production time increases exponentially as a function of achieved surface finish.* In other words, doubling the surface finish requirements translates to more than twice the part cost. Therefore we should always be able to justify the surface finish requirement we list on each surface of the parts we design. Saving ten minutes of machining time on one part surface might not seem like a worthwhile achievement, but remember that “pennies make dollars” and the savings can be substantial for a properly designed part. Worded differently, *failure to specify the roughest surface finishes permissible on each surface can easily increase part cost by an order of magnitude!*

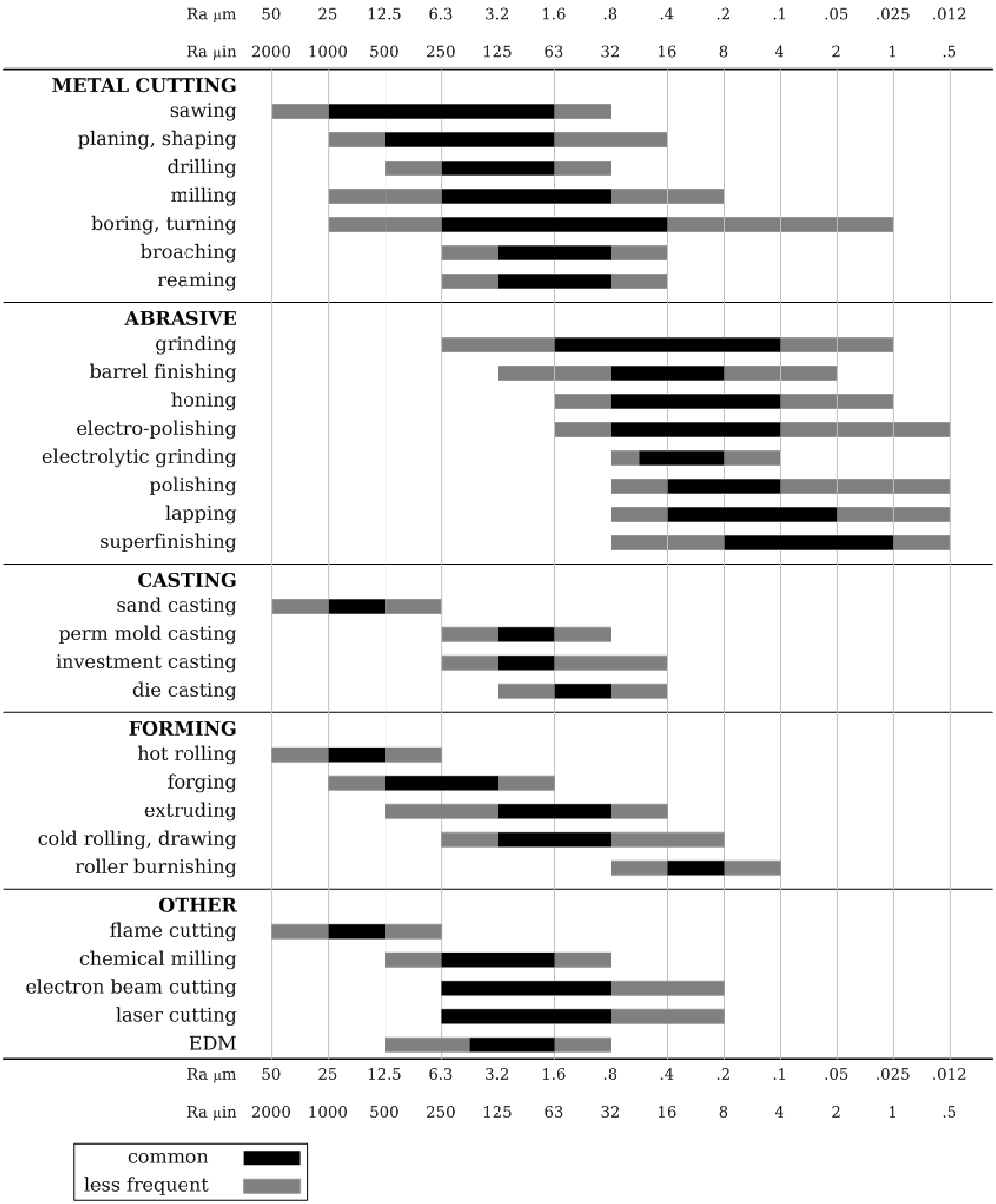


Figure 52: Surface finish produced by various processes.(Source American Machinist)

Figure 52 presents a collection of the most common manufacturing processes and the surface finishes commonly associated with each of them. As explained in the legend, the shaded portions of the bars represent the average application of these processes and means almost any shop should be able to achieve these finishes. The remaining portion of the bar indicates the “less frequent application”, which means one of two things: (1) highly skilled operators and equipment in excellent condition are required to obtain the surface finishes on the higher precision end of the range or (2) the process can easily achieve the finishes on the lower precision end of the range, but a cheaper alternative likely exists, which could significantly reduce part cost.

Testing

The engine was tested with a spirit lamp placed as the heat source.

Figure 53:Testing with spirit lamp

Problems faced

The engine was unable to run due to air leakage from the cold cylinder. Because there was a gap between the displacer axis and the cold plate there was a leakage of air from the chamber. Due to this pressure could not be developed within the chamber to move the piston. This was due to constraints of the facilities available at MRC.

Solution suggested:

Employ cylindrical grinding to fine finish piston and displacer assembly.

List of CAD drawings of manufactured parts:

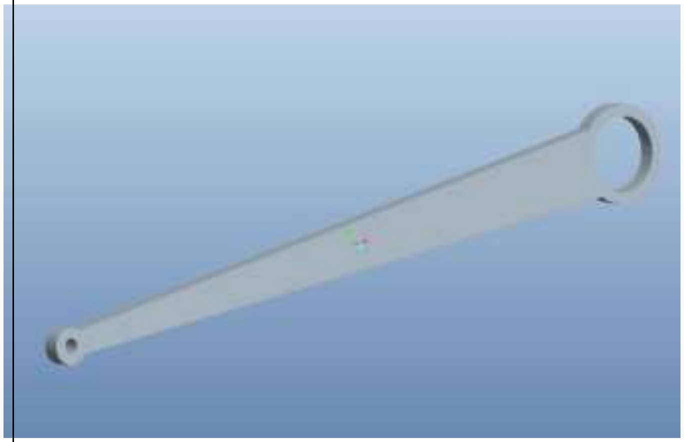


Figure 54:piston driving rod

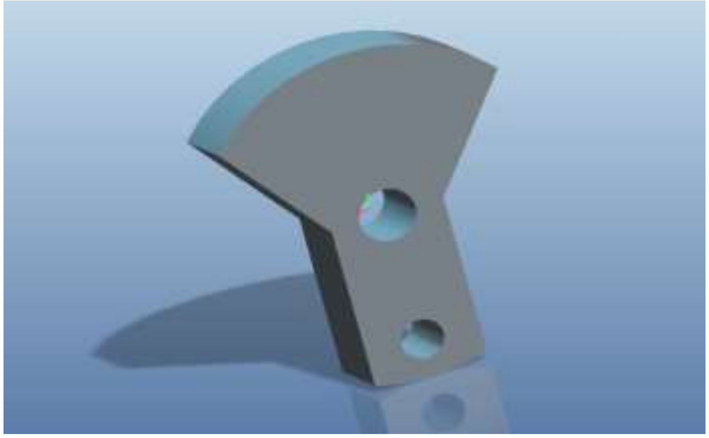


Figure 55:crank web X2

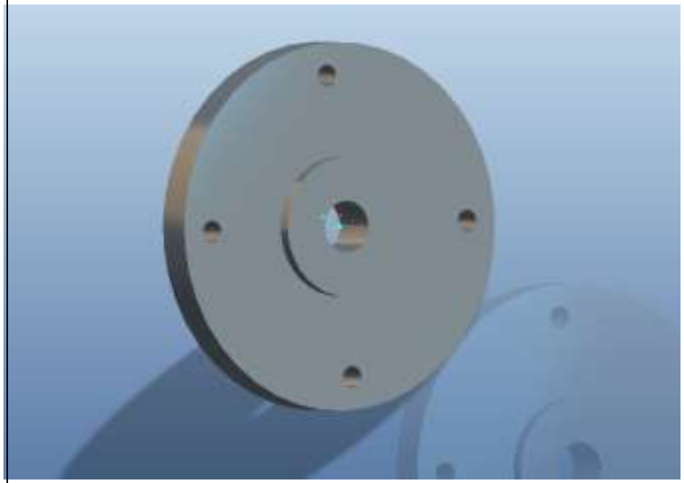


Figure 56:Cylinder plate

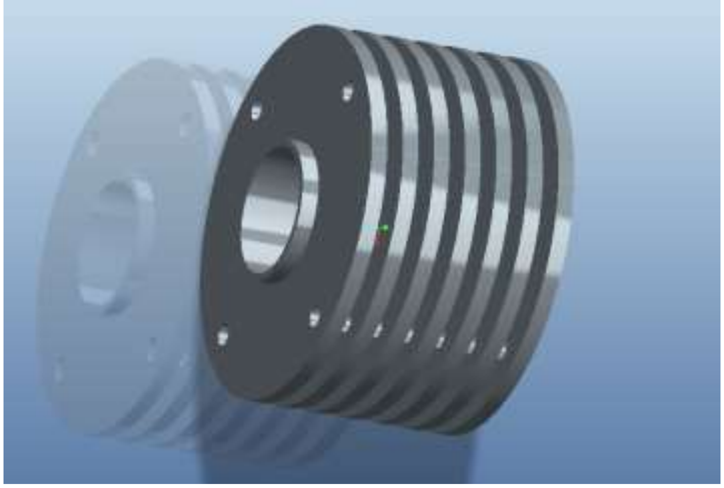


Figure 57:Cold Cylinder

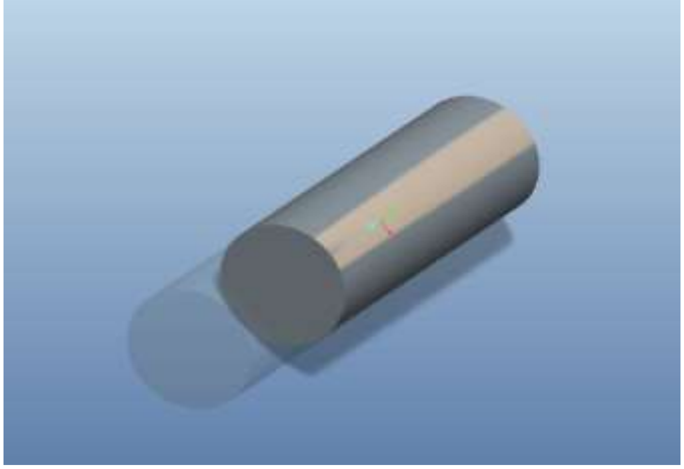


Figure 59:displacer cylinder

Figure 58: displacer

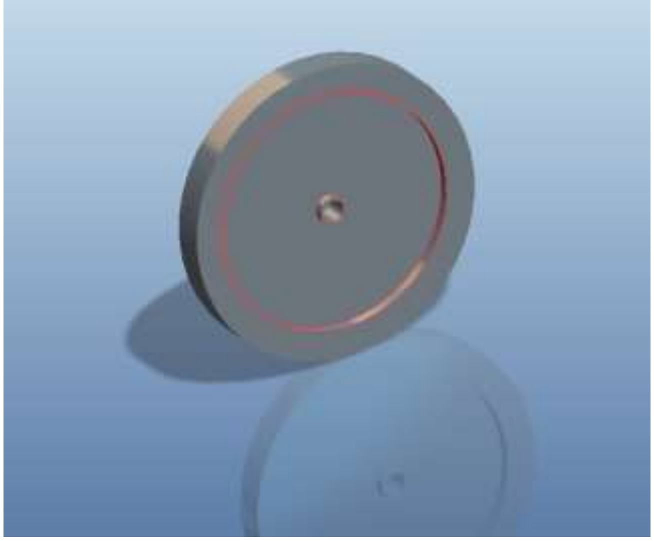


Figure 61: flywheel

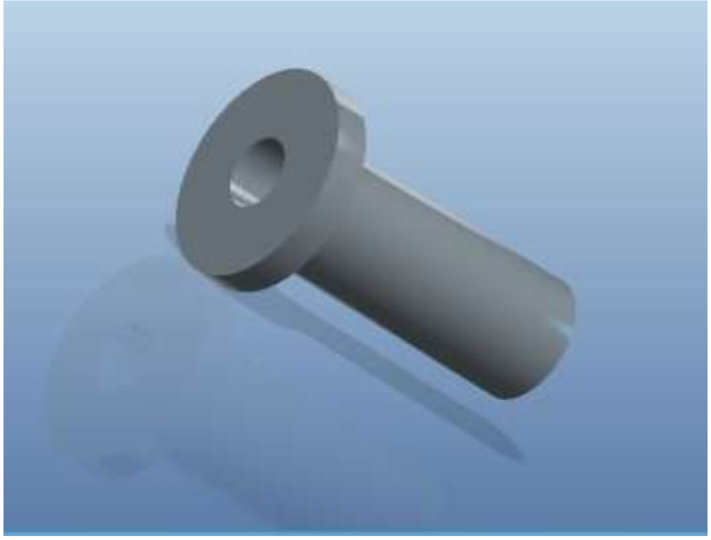


Figure 60: glide bearing displacer axis

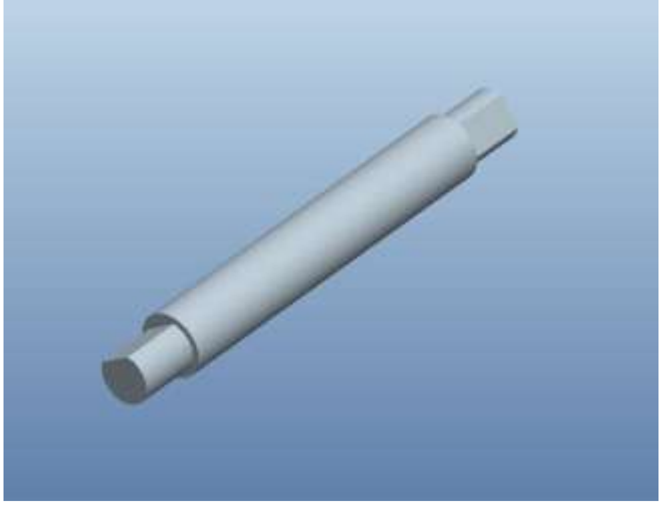


Figure 63: Flywheel axis

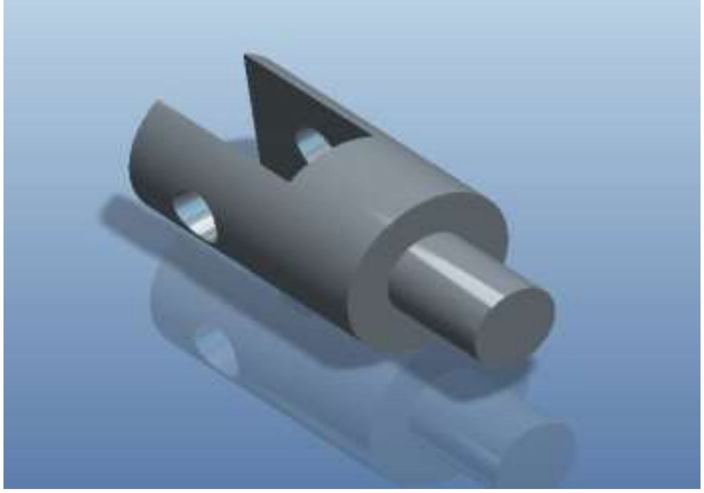


Figure 62 piston fork

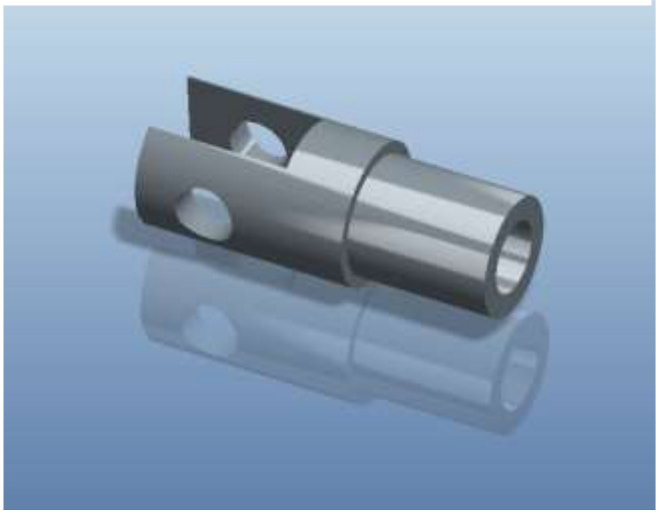


Figure 65 fork displacer rod

Figure 64 support frame

Figure 66 displacer axis

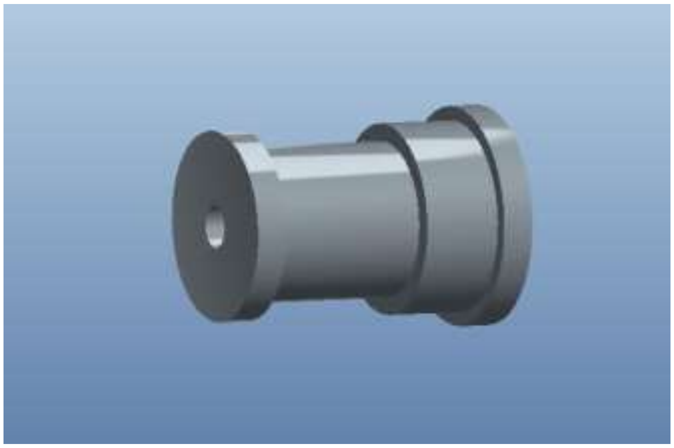


Figure 67 displacer kernel

Figure 69 displacer driving rod

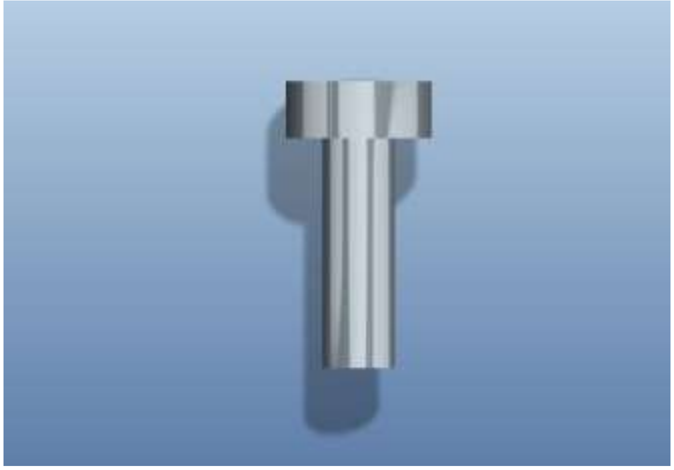


Figure 70 driving rod axis

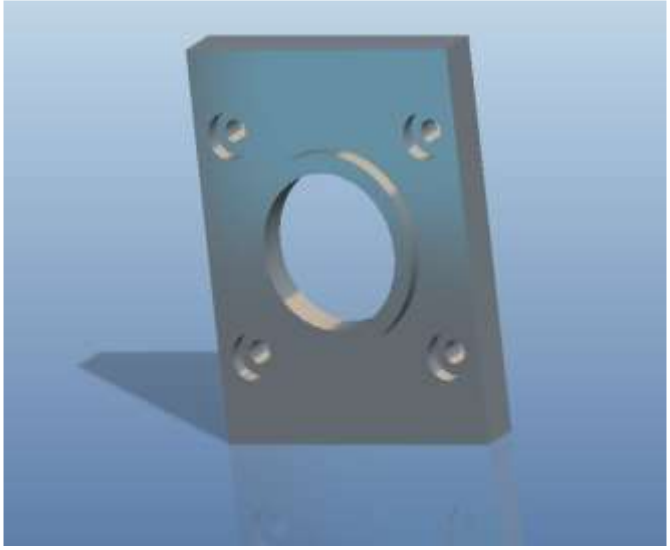


Figure 68 displacer flange back

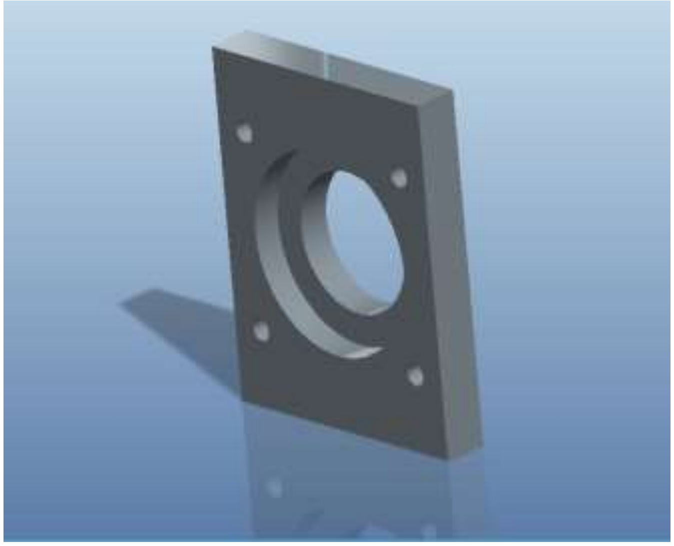


Figure 71 displacer flange front

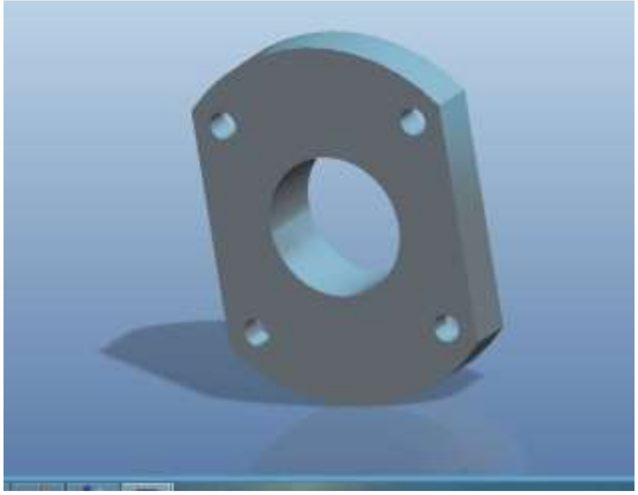


Figure 73 power piston flange back

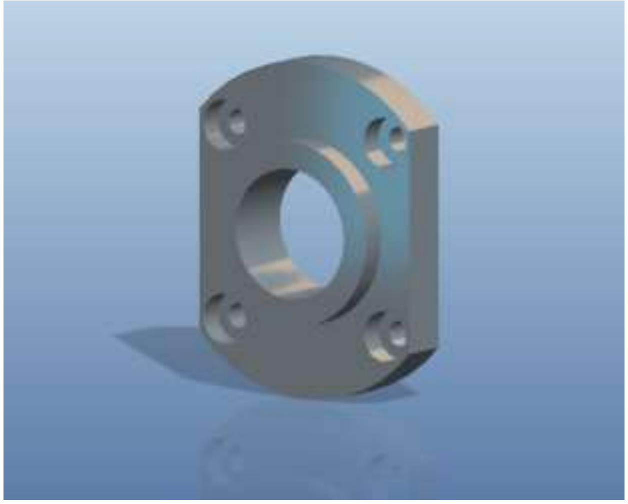


Figure 72power piston flange front

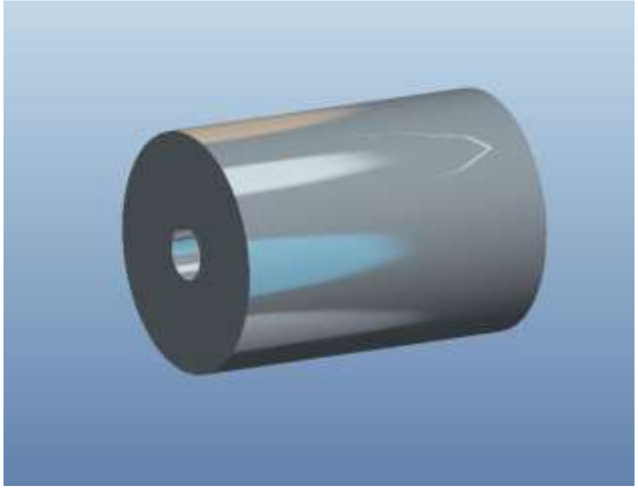


Figure 75 piston front

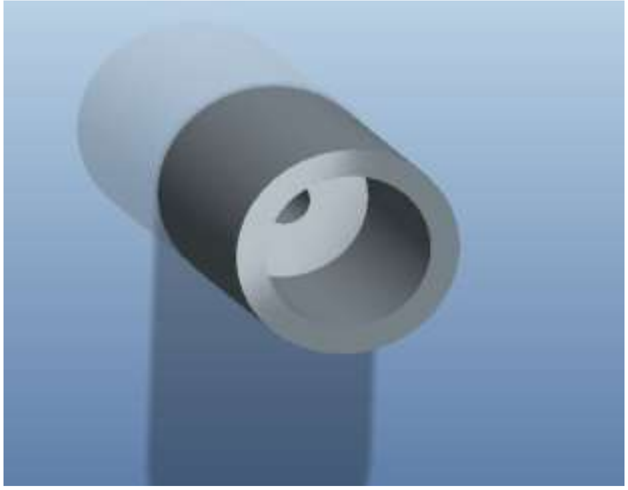


Figure 74 piston back

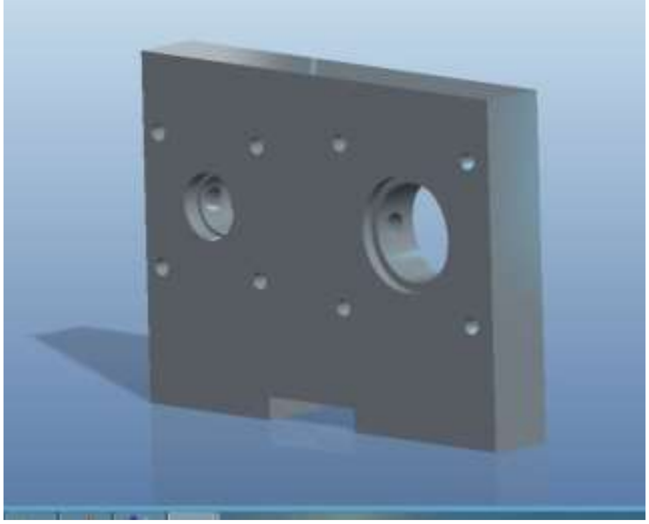


Figure 77 mounting block back

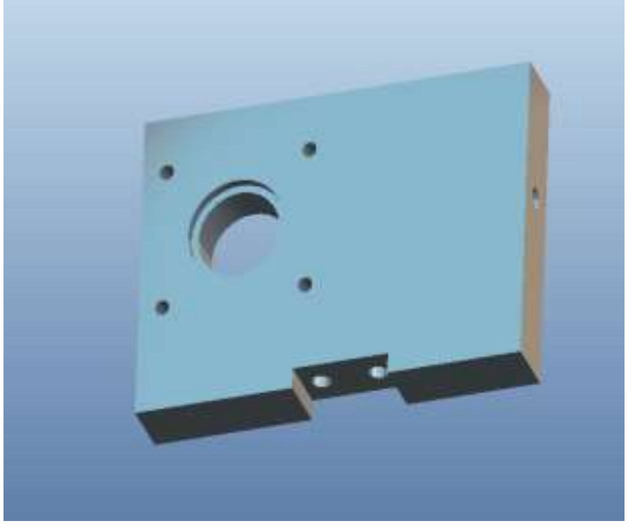


Figure 76 mounting block front

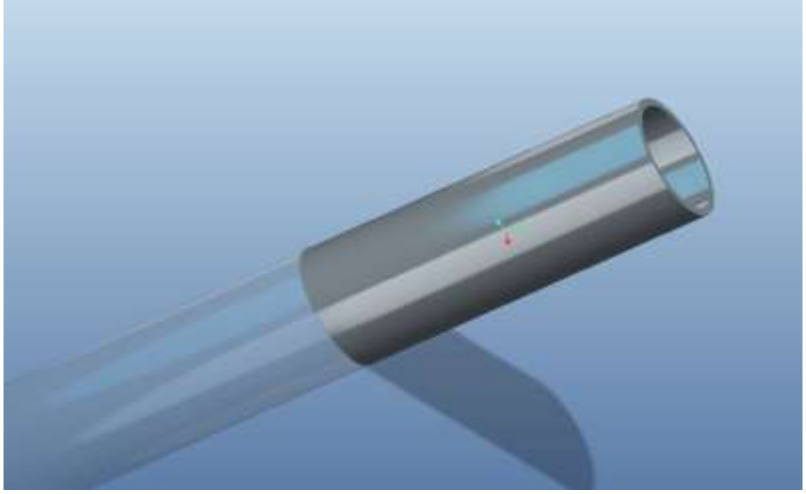


Figure 78 power piston

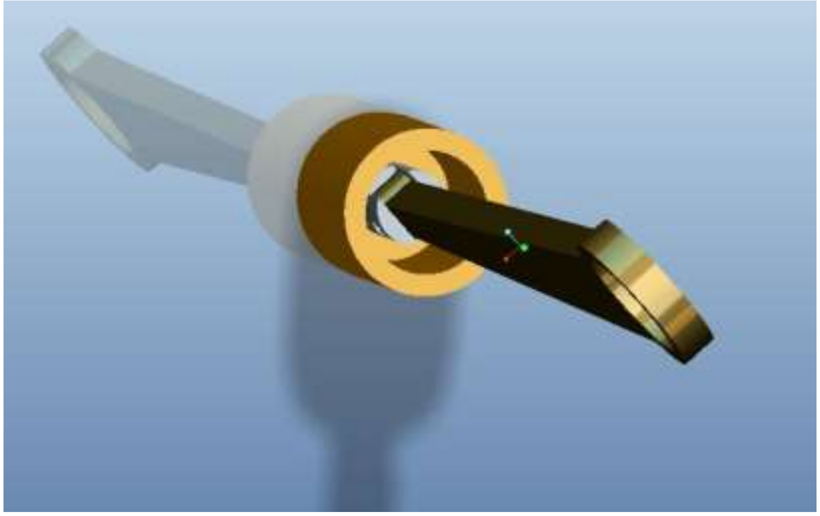


Figure 79 piston assembly

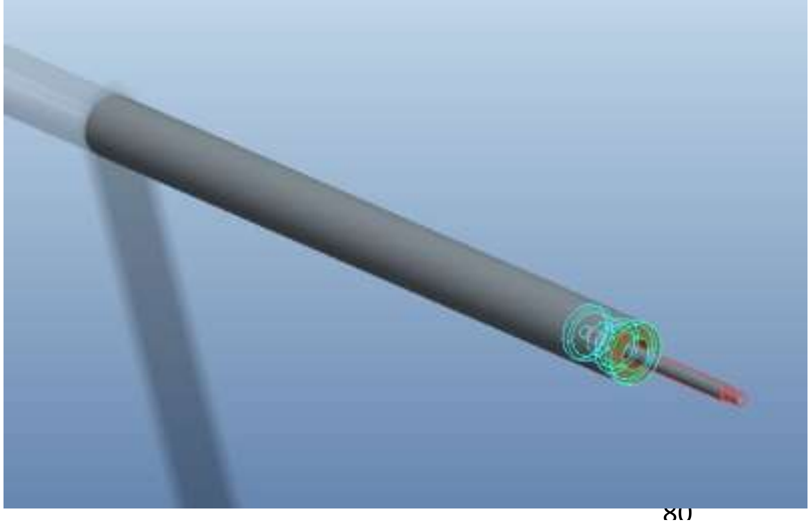


Figure 80 displacer assembly

Drawings

1. Source: Jan Ridders, Stirling Engine Design.Website: http://ridders.nu/. Retrieved January 2014.

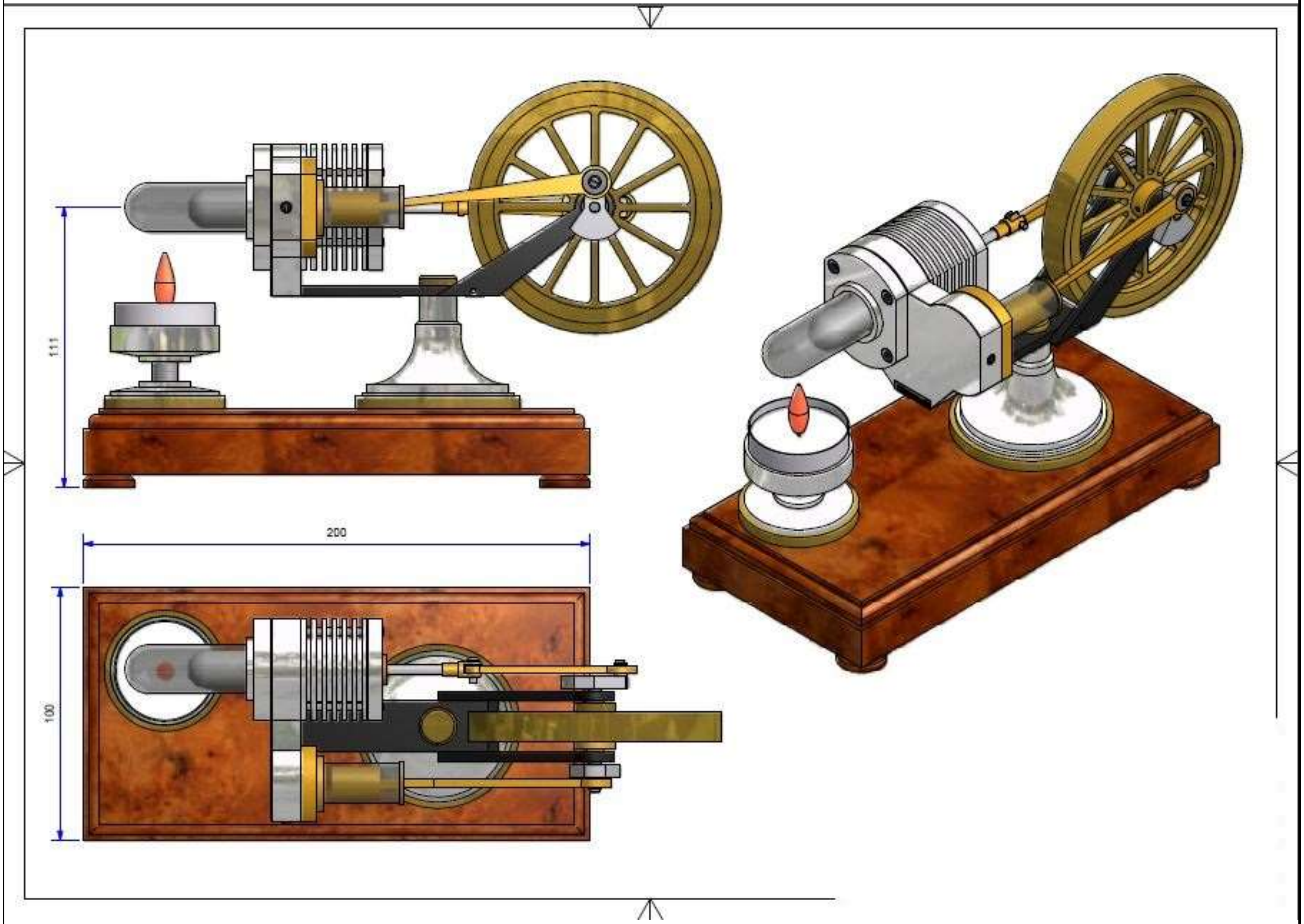


Figure 81

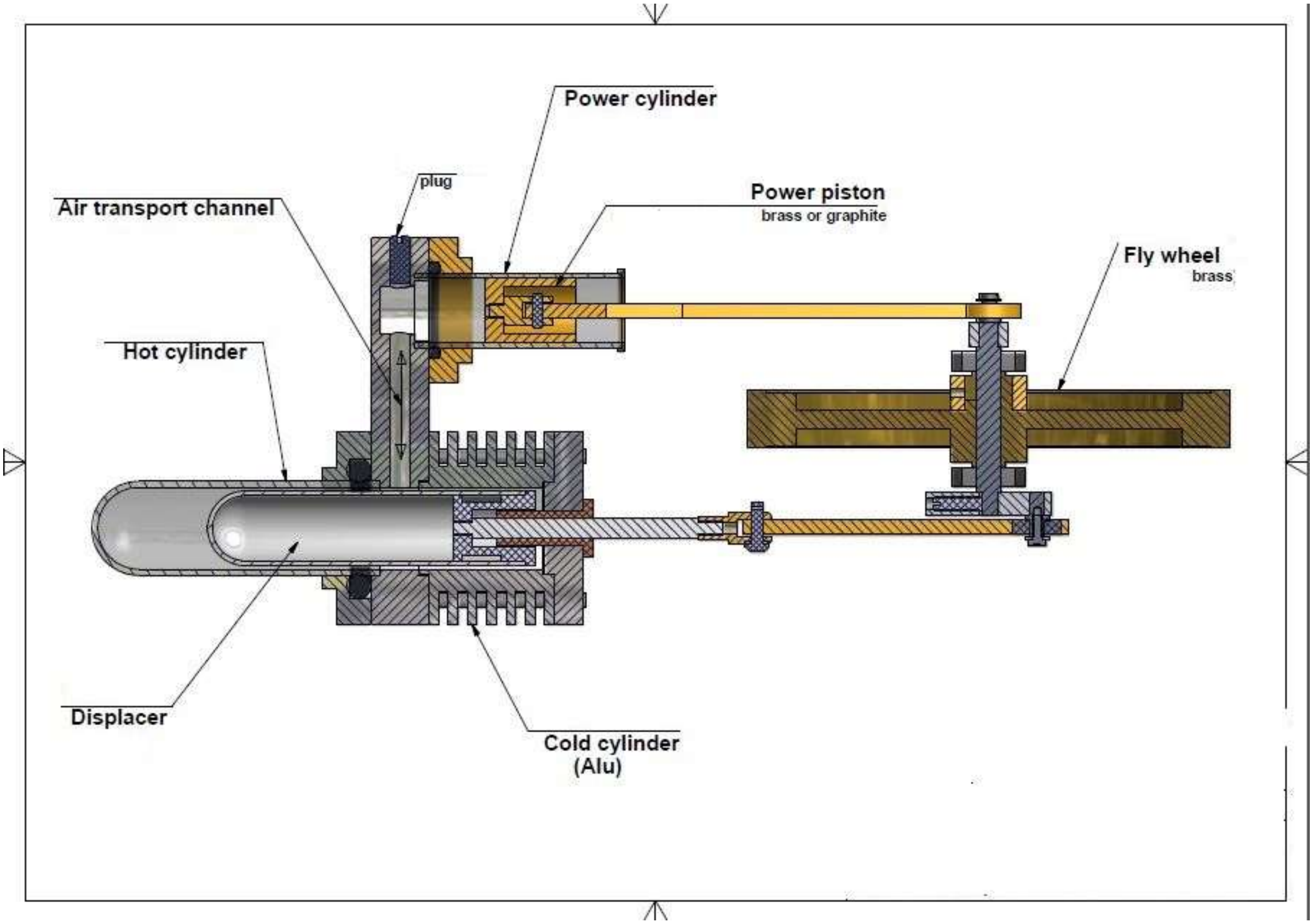

Power cylinder
plug
Air transport channel
Power piston
brass or graphite
Fly wheel
brass
Hot cylinder
Displacer
Cold cylinder
(Alu)

Figure 82

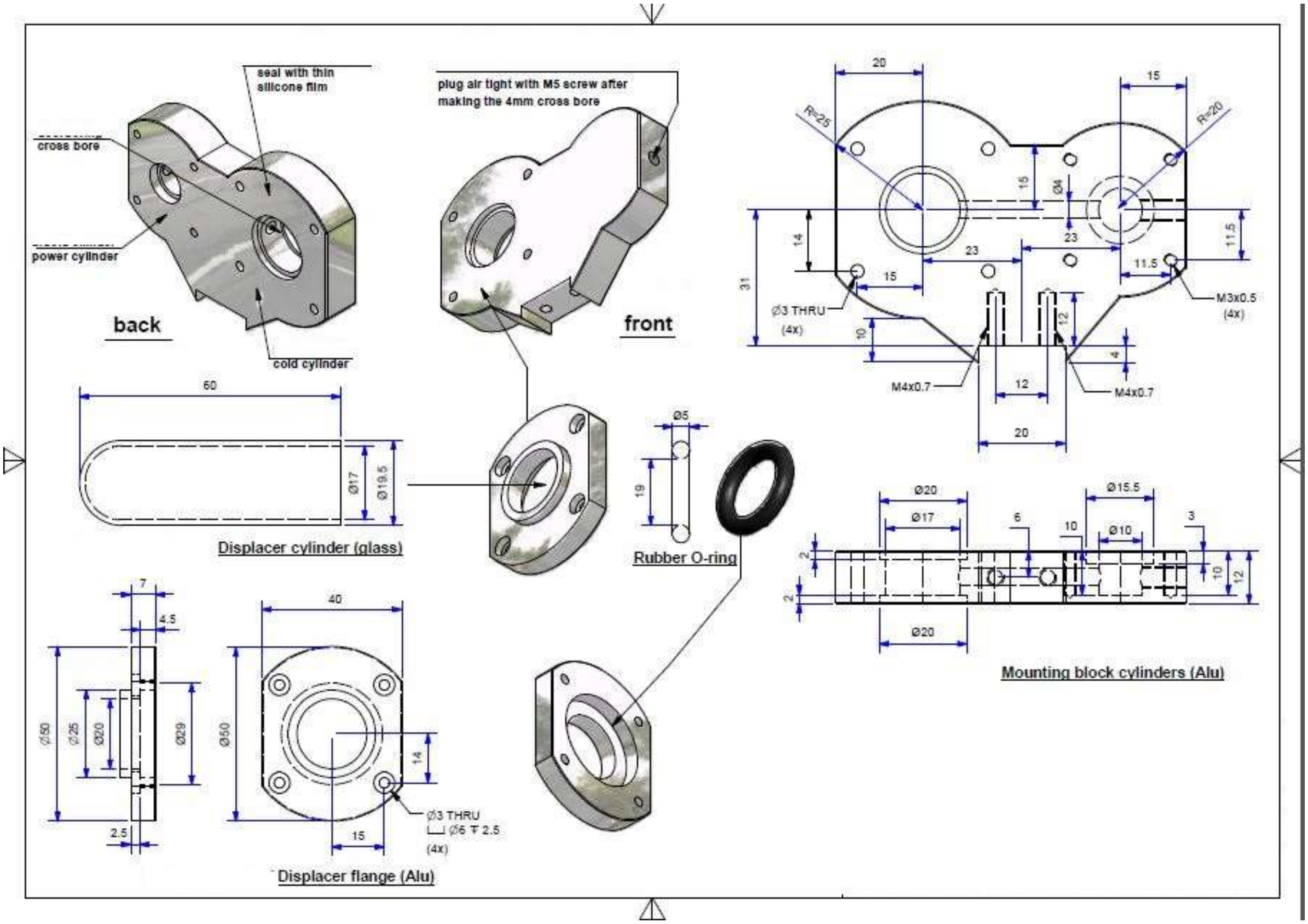

seal with thin silicone film
cross bore
power cylinder
back
cold cylinder
plug air tight with M5 screw after making the 4mm cross bore
front
60
Ø17
Ø19.5
Displacer cylinder (glass)
Ø5
19
Rubber O-ring
20
15
R=25
R=20
15
Ø4
14
31
23
23
11.5
11.5
15
Ø3 THRU (4x)
M3x0.5 (4x)
10
12
4
M4x0.7
12
M4x0.7
20
Ø20
Ø17
Ø15.5
6
10
Ø10
3
2
2
10
12
Ø20
Mounting block cylinders (Alu)
7
4.5
Ø50
Ø25
Ø20
Ø29
2.5
40
Ø50
14
15
Ø3 THRU
⌴ Ø6 ⧯ 2.5
(4x)
Displacer flange (Alu)

Figure 83

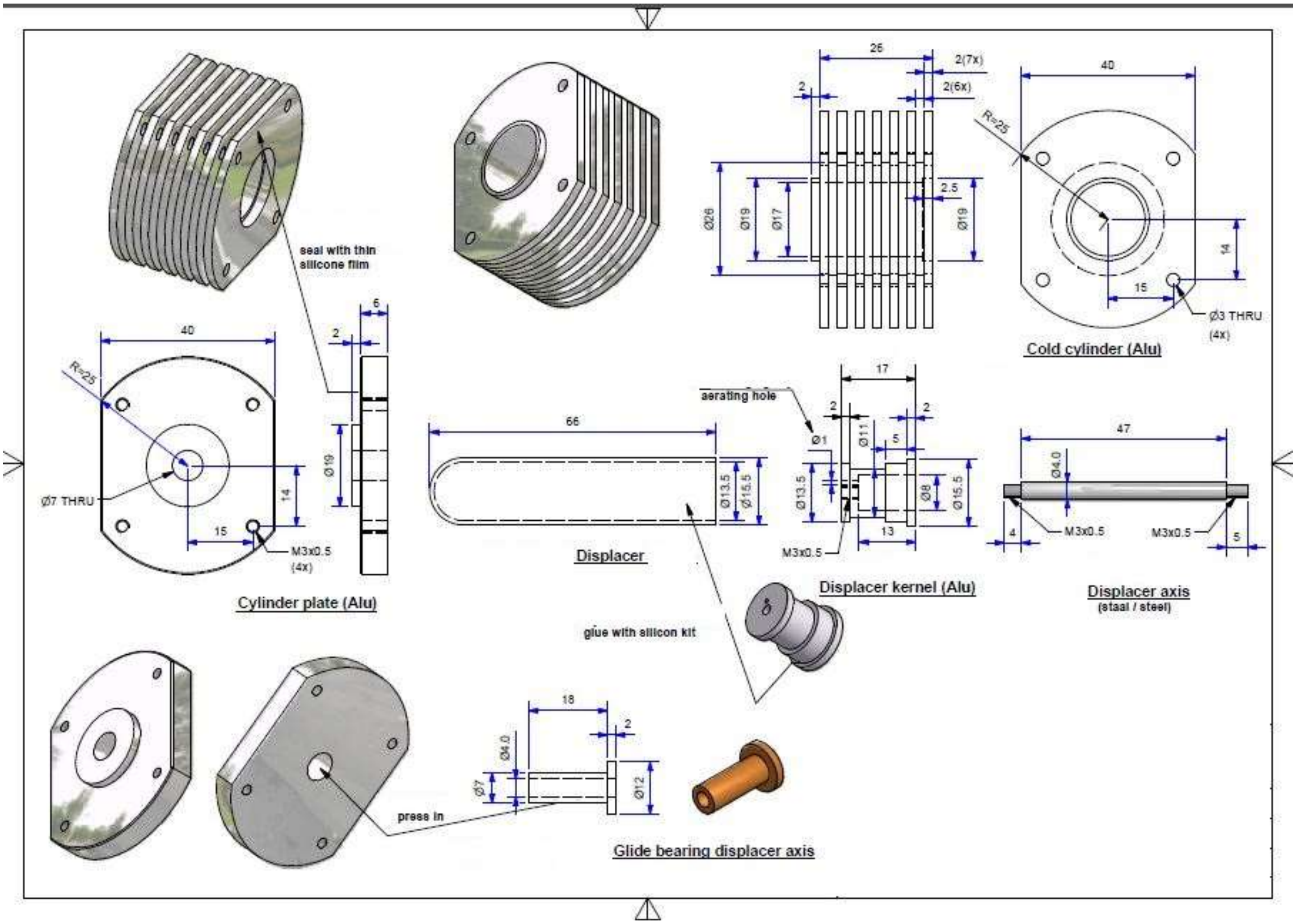

seal with thin silicone film
26
2(7x)
2(6x)
2
Ø26
Ø19
Ø17
2.5
Ø19
40
R=25
14
15
Ø3 THRU
(4x)
Cold cylinder (Alu)
40
R=25
6
2
Ø7 THRU
Ø19
14
15
M3x0.5
(4x)
Cylinder plate (Alu)
66
Ø13.5
Ø15.5
Displacer
aerating hole
17
2
2
Ø1
Ø11
5
Ø13.5
Ø8
Ø15.5
13
M3x0.5
Displacer kernel (Alu)
47
Ø4.0
4
M3x0.5
M3x0.5
5
Displacer axis
(staal / steel)
glue with silicon kit
18
2
Ø4.0
Ø7
Ø12
press in
Glide bearing displacer axis

Figure 84

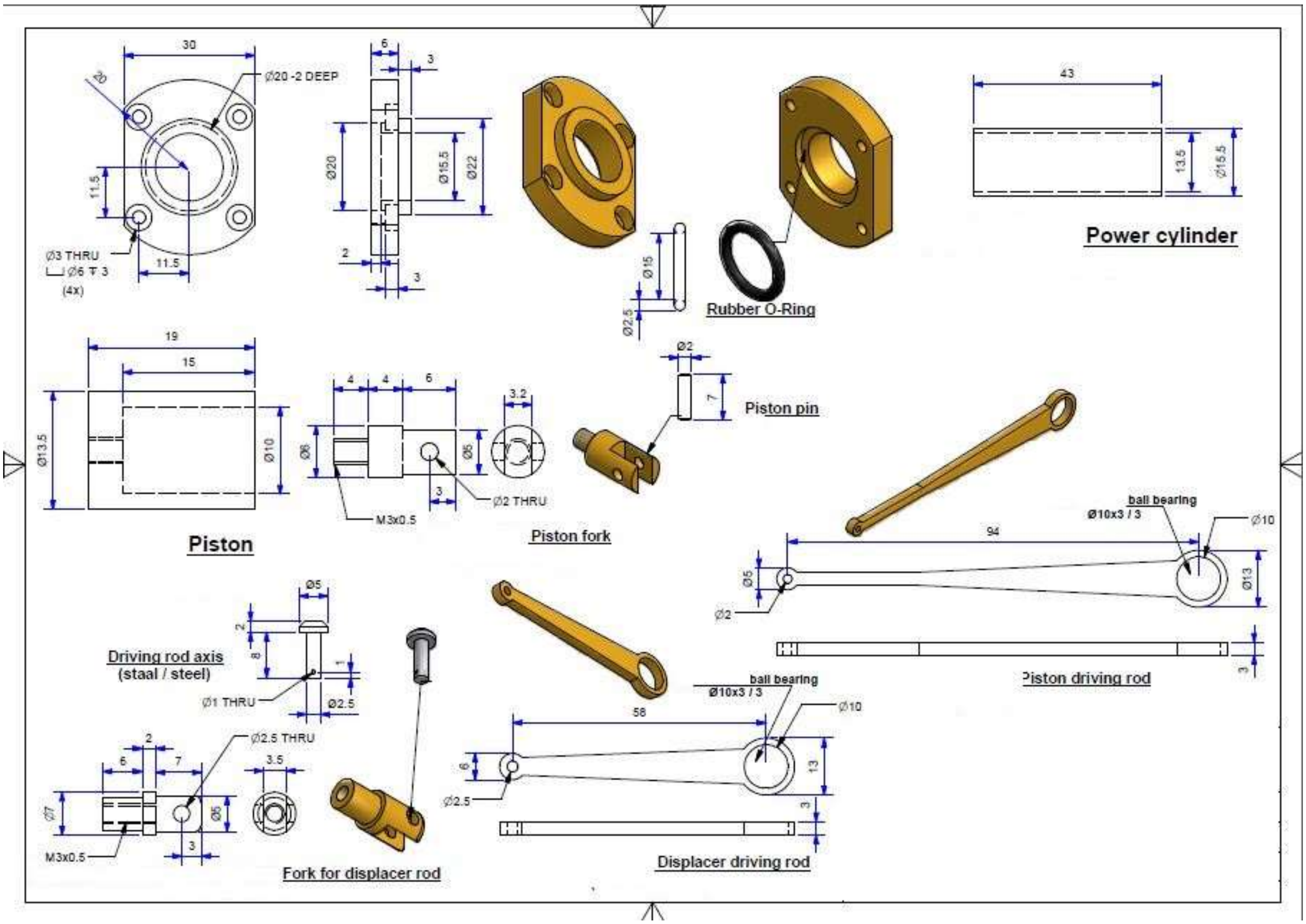
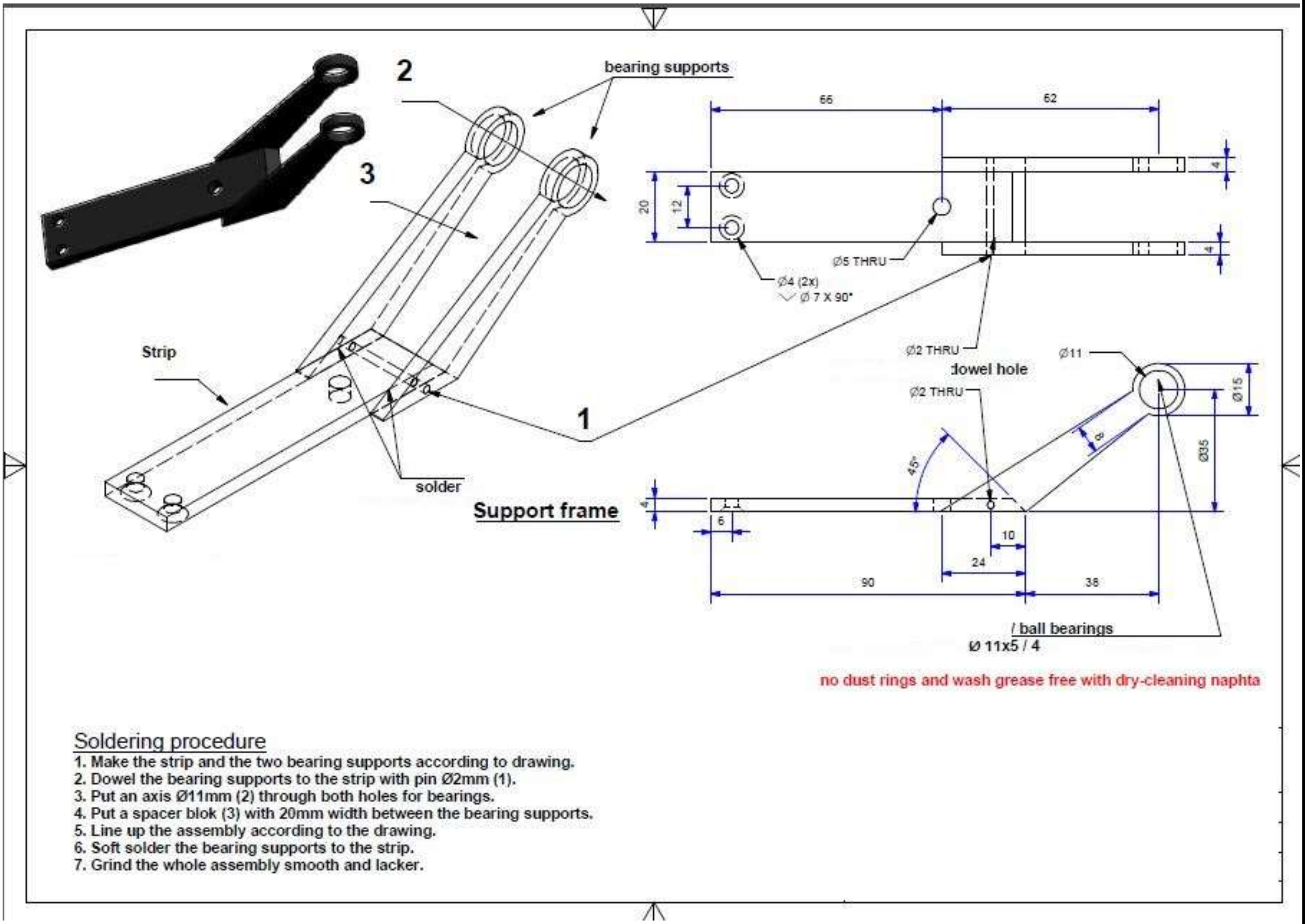

30
Ø20 -2 DEEP
11.5
11.5
Ø3 THRU
⌴ Ø6 ↧ 3
(4x)
6
3
Ø20
Ø15.5
Ø22
2
3
Ø15
Ø2.5
Rubber O-Ring
43
13.5
Ø15.5
Power cylinder
19
15
Ø13.5
Ø10
Piston
4
4
6
Ø6
Ø5
3.2
3
Ø2 THRU
M3x0.5
Piston fork
Ø2
7
Piston pin
ball bearing
Ø10x3 / 3
Ø10
94
Ø5
Ø13
Ø2
3
Piston driving rod
Ø5
2
8
1
Driving rod axis
(staal / steel)
Ø1 THRU
Ø2.5
2
6
7
Ø2.5 THRU
3.5
Ø7
Ø5
3
M3x0.5
Fork for displacer rod
ball bearing
Ø10x3 / 3
Ø10
58
6
13
Ø2.5
3
Displacer driving rod

Figure 85



no dust rings and wash grease free with dry-cleaning naphta

Soldering procedure

1. Make the strip and the two bearing supports according to drawing.
2. Dowel the bearing supports to the strip with pin Ø2mm (1).
3. Put an axis Ø11mm (2) through both holes for bearings.
4. Put a spacer blok (3) with 20mm width between the bearing supports.
5. Line up the assembly according to the drawing.
6. Soft solder the bearing supports to the strip.
7. Grind the whole assembly smooth and lacker.

Figure 86

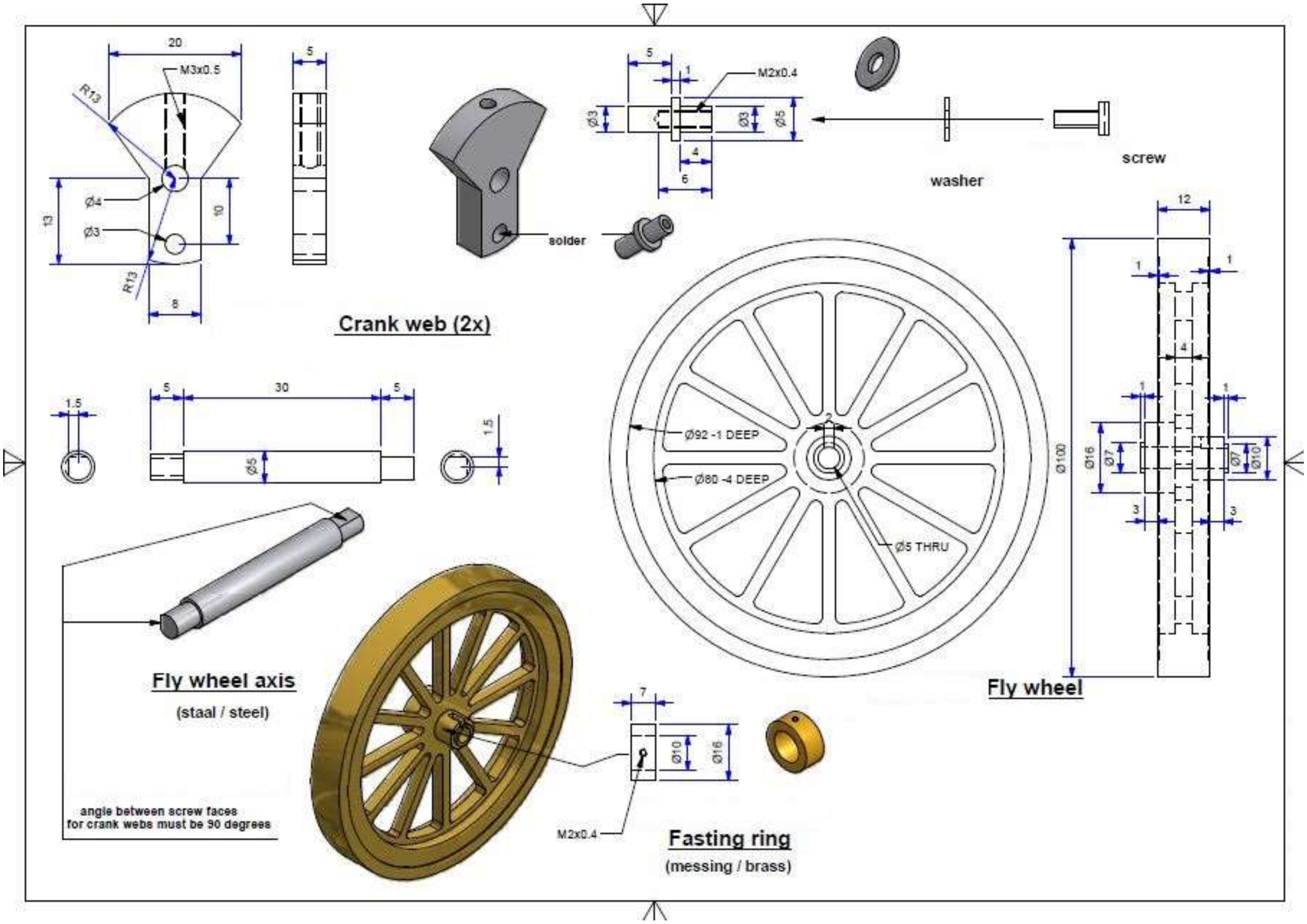

20
M3x0.5
R13
Ø4
Ø3
13
10
R13
8
5
solder
Crank web (2x)
5
1
M2x0.4
Ø3
Ø3
Ø5
4
6
washer
screw
12
1
1
4
1
1
Ø100
Ø16
Ø7
Ø7
Ø10
3
3
2
Ø92 -1 DEEP
Ø80 -4 DEEP
Ø5 THRU
Fly wheel
1.5
5
30
5
Ø5
1.5
Fly wheel axis
(staal / steel)
angle between screw faces
for crank webs must be 90 degrees
7
Ø10
Ø16
M2x0.4
Fasting ring
(messing / brass)

Figure 87

References and Acknowledgements:

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   ISBN: 978-606-605-038-8
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26. Solar Electric Dish Stirling Development, Thomas R. Mancini, Sandia National Laboratories.
27. “Solar Radiation Basics”, University of Oregon Solar Radiation Monitoring Laboratory, http://solardat.uoregon.edu/SolarRadiationBasics.html. Retrieved April 2014.