UNIVERSITY OF CANTERBURY

Department of Mechanical Engineering

ENME406 Engineering Product Design and Analysis

Assessment 1: CAE Water Bottle

Figure 1: An example of a stainless steel water bottle on the market today

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1. Design Summary

The design and analysis of the drink bottle concept yielded a design with a complex geometry suitable for applications where pressures are in the range of 0.3 atmospheres to -3 atmospheres. The bottle was also modelled when subjected to a heat of $200\ ^\circ\mathrm{C}$ for use as a thermette.

The results of the finite element analysis produced were in the vicinity of five times the magnitude of the stresses predicted from the hand calculations. This was expected due to the fact that the vessel was assumed to be perfectly cylindrical in the hand calculations, when in reality the part had a more complex geometry with areas which would be subject to higher stress concentrations. The accuracy of the FEA results could have been improved further by decreasing the mesh size. However, a medium sized mesh was selected for FEA for its relative accuracy and reasonable computation time.

Most importantly, the stresses that were produced within the body of the bottle were below the yield points of the stainless steel material. This meant that for these simple loading cases the bottle would perform safely as intended.

A secondary analysis was conducted to determine the behaviour of the bottle under a thermal load. The results of this investigation suggested that the stresses in the base of the bottle were above the yield point of the material. In response to this, a 10 mm thick base was added to the bottle to distribute the thermal load. This had the desired affect of reducing the overall deformation of the geometry and lowering the maximum von-mises stress in the shape. However, the stresses were still not below the target yields. Therefore further investigation of this issue is needed, as outlined in the V-diagram in the discussion section. The possibility of using an alternative heat-resistant material for the base or making the base thicker still could also be explored further.

The manufacturability of the vessel was also considered and deep-drawing of the stainless steel was deemed to be the optimal method. The design and analysis of the water bottle have been sufficiently completed so that construction and testing phases of the product development are ready to take place.

2. Context

The task of the assignment was to design and analyse a water bottle for a reasonable range of hand pressures, in-use forces and positive and negative pressure. A CAD model of the geometry was created and classical pressure-vessel hand calculations were performed to gain an indication into the stresses acting on the part. A static structural analysis was then performed using the ANSYS software tools. Additionally an analysis of the performance of the bottle when used as a thermette was performed.

The design specifications for the water bottle were as follows:

- As light as practical
- Material: stainless steel SS 304
- Wall thickness 0.45mm
- Volume contained: 1 litre

- Loading: make and document reasonable assumptions

A water bottle design was selected for its complex and interesting shape and appropriate stainless steel material properties. A CAD geometry was created in SolidWorks solid modelling software to meet the design specifications. Table 1 below displays the material properties of the selected stainless steel.

Table 1: Material Properties of SS 304

Young's modulus	200 GPa
Poisson's ratio	0.29
Tensile yield strength	215 MPa
Compressive yield strength	505 MPa

In order to proceed with a classical pressure vessel analysis and later a finite element analysis of the actual geometry, the pressures that the bottle would be subjected to needed to be defined. To model the bottle's performance when subjected to internal positive pressure, it was assumed that the bottle was full of air at standard atmospheric pressure (sea level) and was taken in an unpressurised airplane hold to a height of 30,000 feet, or 9144 m. At this height, the bottle would be subjected to 30.1 kPa less pressure than if it was at sea level, meaning the air inside is exerting a positive pressure on the walls of the bottle of 0.0301×10^{6} MPa.

To model the bottle for negative pressure cases, the scenario of the bottle being taken to a depth of 30m underwater was considered. In this case, the water on the outside of the bottle would exert a negative (inwards) pressure on the outer walls of the vessel of 0.302361 MPa. Please refer to the attached MathCAD documentation for evidence of these calculations.

Further assumptions that were made in order to complete the analysis. To complete the hand calculations the geometry of the vessel was assumed to be perfectly cylindrical.

3. Classical calculations for pressure vessel

MathCAD was used to conduct a series of hand calculations for the drink bottle as a pressure vessel, assuming its shape was perfectly cylindrical. The documentation is outlined below.

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Hand Calculations for positive and negative pressure

Dimensions of pressure vessel (assumed cylindrical shape):

$D := 82.0\,mm$ $\quad t := 0.45\,mm$ $\quad Sy := 215000000\,Pa$

Internal Pressure

$Pi := 30100\,Pa$ If in an unpressurised airplane hold at 30,00 ft or 9144 m

Hoop Stress:

$$h := 0.5 \cdot Pi \cdot \left(\frac{D}{t}\right) \qquad h = 2.742 \times 10^{6}\,Pa$$

Longitudinal Stress:

$$long := 0.5 \cdot h \qquad long = 1.371 \times 10^{6}\,Pa$$

Von Mises Stress:

$$Vm := \left[h^{2} + long^{2} - (h \cdot long)\right]^{0.5} \qquad Vm = 2.375 \times 10^{6}\,Pa$$

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Factor of Safety:

$$SF := \left(\frac{Sy}{Vm}\right)$$

$$SF = 90.525$$

External Pressure:

$$Pe := 0.302361 \cdot 10^{6} Pa$$

Hoop stress:

$$h := 0.5 \cdot Pe \cdot \left(\frac{D}{t}\right)$$

$$h = 2.755 \times 10^{7} Pa$$

Longitudonal Stress:

$$long := 0.5 \cdot h$$

$$long = 1.377 \times 10^{7} Pa$$

Von Mises Stress:

$$Vm := \left[h^{2} + long^{2} - (h \cdot long)\right]^{0.5}$$

$$Vm = 2.386 \times 10^{7} Pa$$

Factor of Safety:

$$SF := \left(\frac{Sy}{Vm}\right)$$

$$SF = 9.012$$

Pressures bottle is subject to:

Positive Pressure

At h = 9144 m = 30,000 ft

Airplane

P = 0.30 atm = 30.1 kPa = 0.0301 MPa

Underwater

Negative Pressure

Pressure at depth = 30 m P = 0.403 MPa

Pressure at sea level = 0 m P = 101.325 kPa = 0.101325 MPa (at T = 15 deg C)

Therefore Pressure on vessel walls = Pw = 0.403 - 0.101325 = 0.302361 MPa

The results of the hand calculations are summarised below in tables 2 and 3.

Table 2: Pressures determined for positive and negative pressure analysis of the vessel

Internal Pressure (positive)	0.0301 MPa
External Pressure (negative)	0.302361 MPa

Table 3: Results of classical pressure vessel hand calculations

	Hoop stress	Longitudinal Stress	Von-Mises Stress	Factor of Safety
Internal Pressure	2.74 MPa	1.73 MPa	2.375 MPa	90.525
External Pressure	27.55 MPa	13.77 MPa	23.9 MPa	9.012

4. Finite element analysis (structural analysis) for pressure vessel

The CAD geometry was quartered for ease of analysis and imported into the ANSYS finite element analysis software. Please see the attached CAD files in the appendix to see the geometry which was created. The bottle was modelled for positive and negative pressure inputs.

4.1 Positive pressure modelling

The drink bottle's performance was modelled in the case of it being subjected to the pressure of an unpressurised luggage hold on an aeroplane. It was assumed that the aeroplane was flying at a height of 30,000 ft, which equates to 9144 m. Taking the density of air as 1.255 kg/m^3 the outwards pressure on the bottle would be 30.1 kPa at this height. Table 4 below displays the key results of the FEA analysis using ANSYS software.

Table 4: Positive pressure FEA results

Max Stress (Von-Mises)	Max Strain (Von-Mises)	Total deformation
5.9342 MPa	4.3983e-005 mm/mm	1.4925e-003 mm

The maximum stress was determined to be below the yield point of the material that the bottle was made of. Therefore, it was determined that with a factor of safety of 36.2, the bottle was safe from causing pressure related harm to the user.

The following figures illustrate the results of the analysis for the positive pressure model.

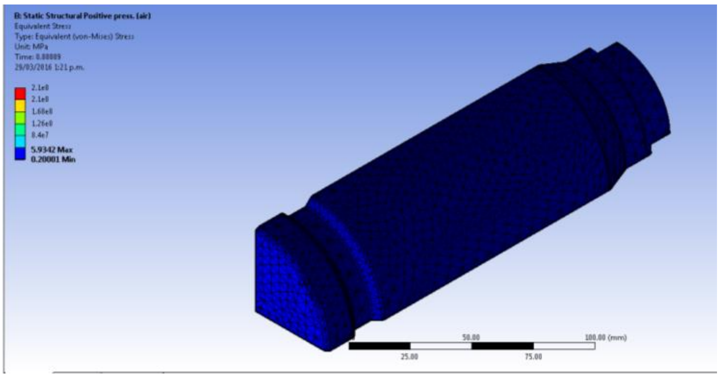

Figure 2: Equivalent stress distribution

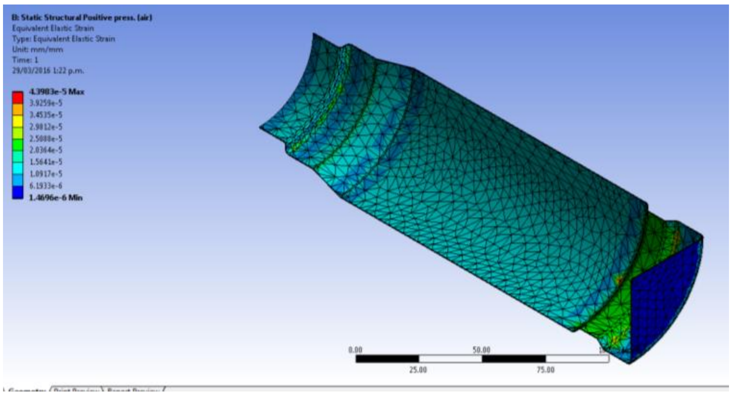

Figure 3: Equivalent strain distribution

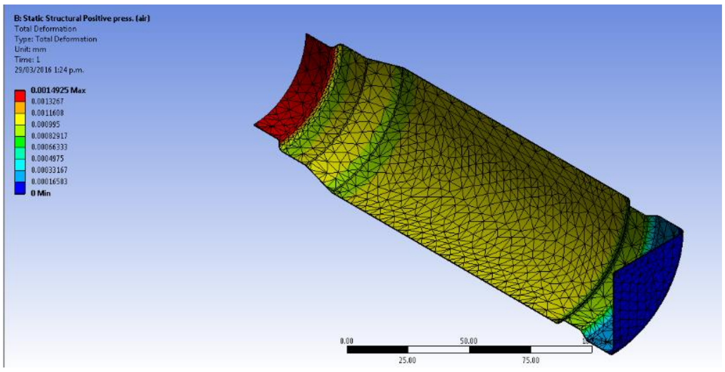

Figure 4: Total deformation of the bottle

4.2 Negative pressure modelling

The bottle was next modelled through the use of finite element analysis to determine its performance if it were to be subjected to a negative pressure mode in the case that it was taken to a depth of 30 m underwater. Assuming the water had a density of 1000 kg/m^3, a pressure model was created and the associated stresses were determined for a pressure of 0.3024 MPa. Table 2 below summarises the results.

Table 5: Negative Pressure FEA results

Max Stress (Von-Mises)	Max Strain (Von-Mises)	Total deformation
56.958 MPa	5.0498e-004 mm/mm	1.4668e-002 mm

The maximum stress was determined to be below the yield point of the material that the bottle was made of. Therefore, it was determined that with a factor of safety of 3.77, the bottle was safe from causing pressure related harm to the user.

The following figures illustrate the results of the analysis for the negative pressure model.

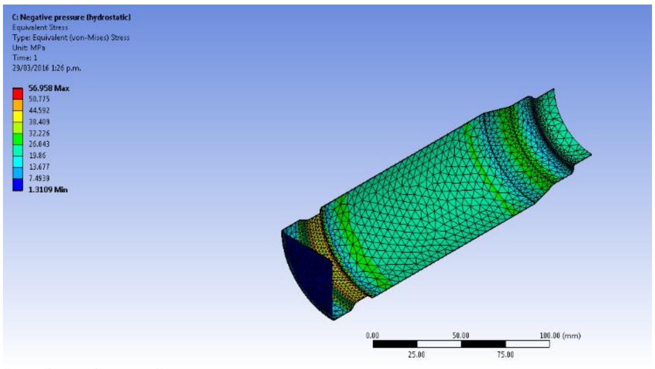

Figure 5: Equivalent stress distribution

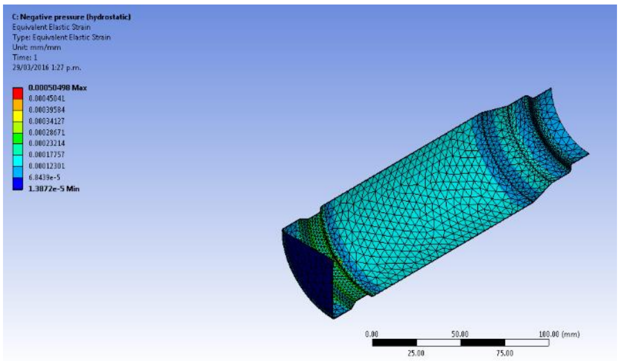

Figure 6: Equivalent elastic strain distribution

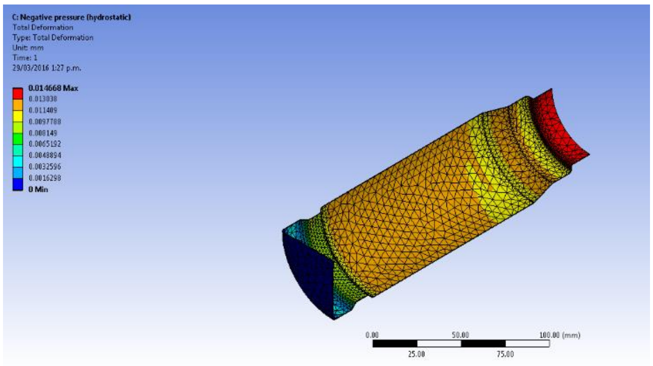

Figure 7: Total deformation of the bottle

5. Second work stream activities report

A secondary analysis was completed on the drink bottle assembly in the form of designing the vessel as a 'thermette.' A thermal and stress analysis was conducted to determine the effect on the product in the event that it was used in an outdoor emergency situation to heat water over an open flame. The boundary conditions were set as follows:

- The drink bottle was subjected to a uniform heat of 200 °C across its external surfaces
- The bottle was full of water and surrounded by air at an ambient temperature of 20°C

An initial thermal analysis of the quarter-bottle was conducted. Air was used as the convection material around the outside of the bottle, with a convection coefficient of $5 \times 10^{-6}\ W/mm^2$°C. Water was used as the convection material on the inner surface of the bottle, with a convection coefficient of $1.2 \times 10^{-3}\ W/mm^2$°C. Finite element analysis was completed to determine the temperature distribution, total heat flux and directional heat flux through the body of the bottle.

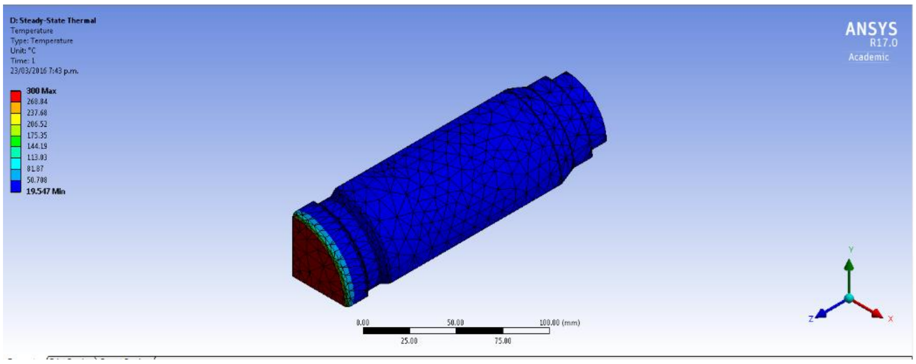

Figure 8: Temperature distribution

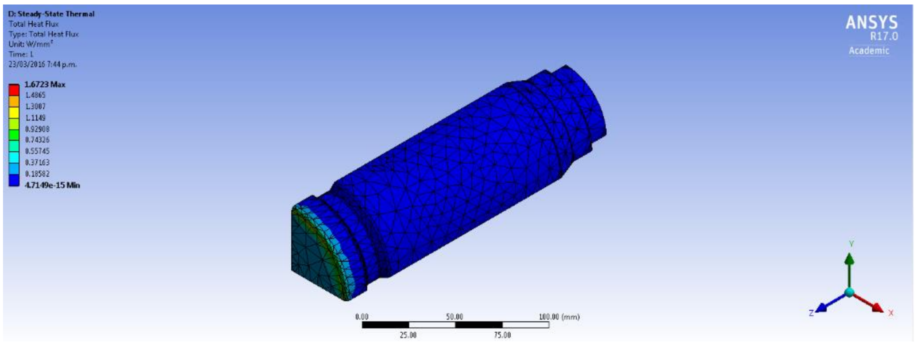

Figure 9: Total heat flux

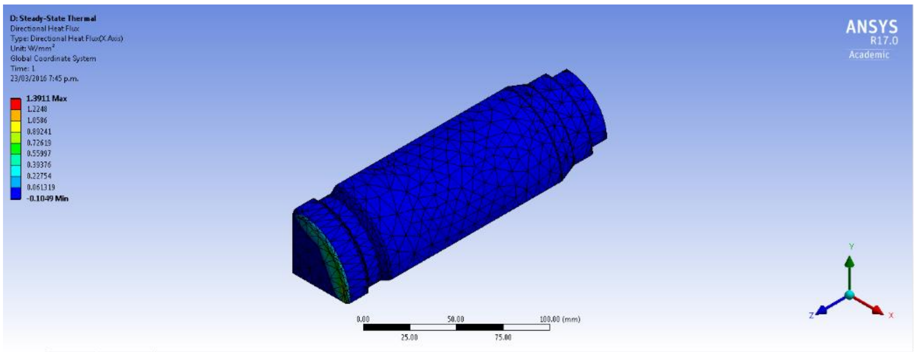

Figure 10: Directional heat flux

To establish the expansion effects of heating the bottle with a 200 °C flame and its effect on the function and geometry of the bottle further analysis was required. This was achieved by running a static-structural analysis and by applying a thermal condition with the base of the bottle established as a fixed support.

Figure eleven highlights clearly that at the yield strength of the stainless steel material, the area on the bottom of the drink bottle is under a large amount of stress and would be likely to fail.

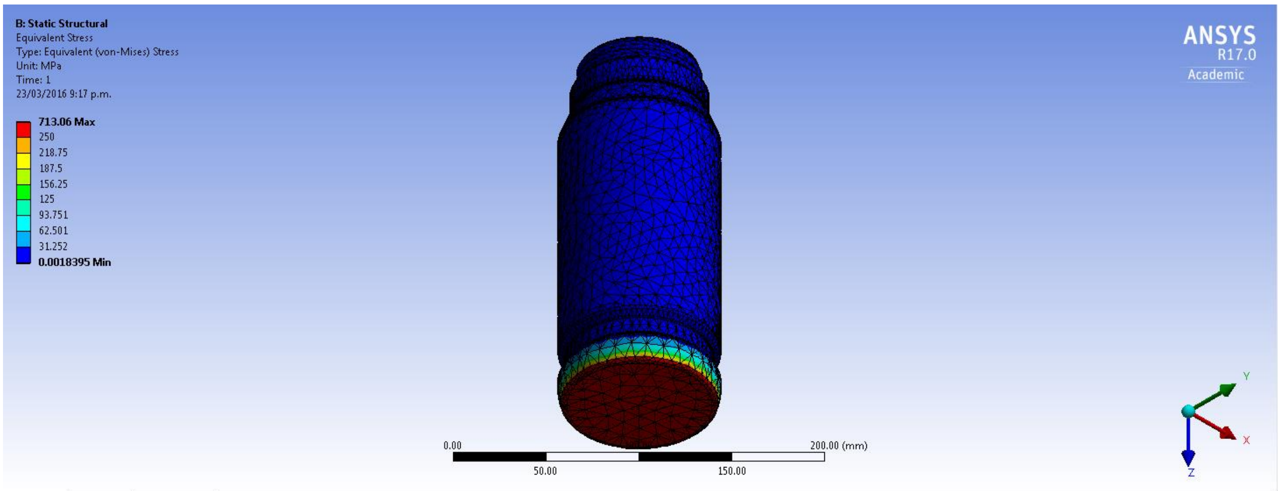

Figure 11: High stress on bottom of bottle due to thermal expansion

Following this result it was identified that a redesign of the product was necessary for it to be used safely as a thermette. The CAD geometry of the part was redesigned to include a 10 mm thick plate on the bottom to distribute the heat through the bottle easily and to allow the structure to cope with the added thermal stresses. The revised CAD geometry is attached in the appendices section.

Figure twelve below illustrates how with the addition of the 10 mm plate on the base of the drink bottle, the stresses in the structure as a result of the thermal expansion are reduced. This is because they are unable to reach the main structure of the bottle and the stress is mostly contained in the additional 10 mm plate.

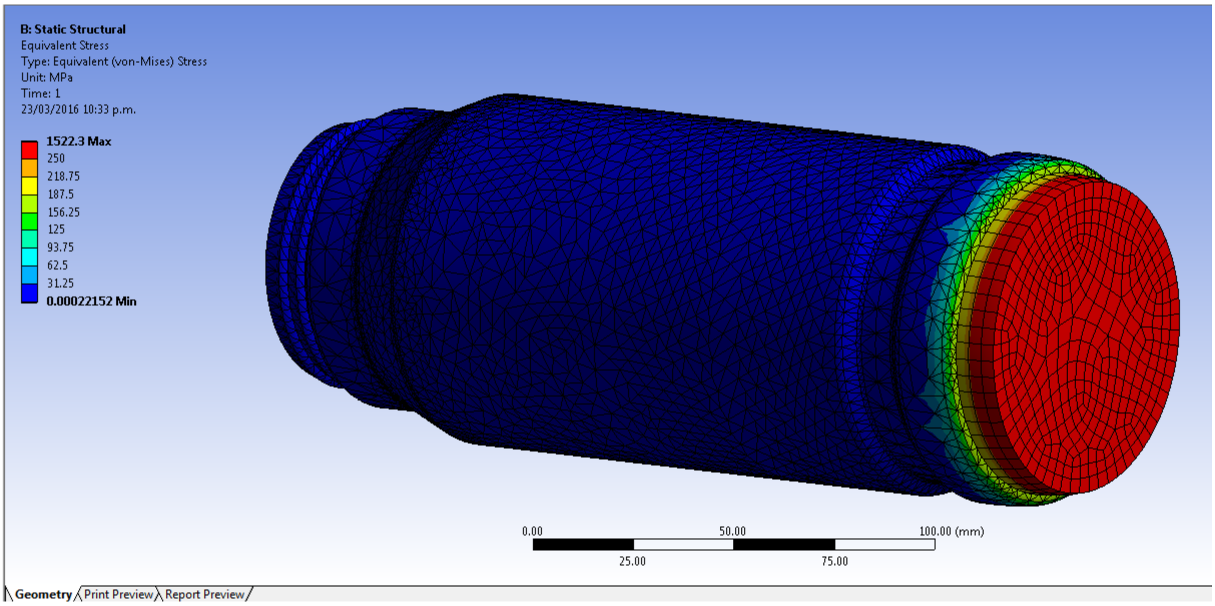

Figure 12: Thermal stresses reduced in main bottle structure as a result of additional base plate

Next, the equivalent elastic strain on the drink bottle was considered as a result of the thermal expansion. The indication that the FEA analysis using ANSYS is a positive sign that the strain is within tolerable limits and is not likely to cause failure. This is illustrated below in figure thirteen.

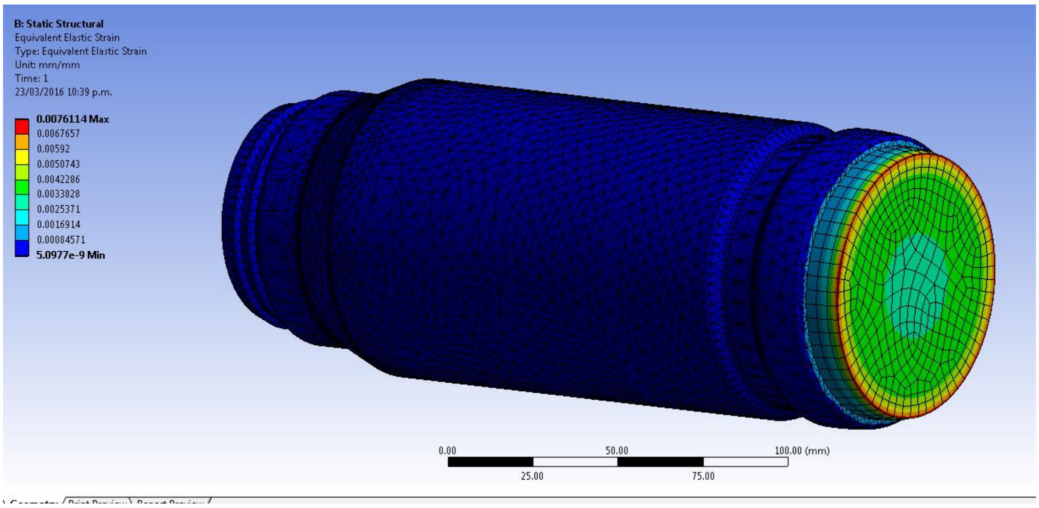

Figure 13: Elastic strain in the part due to thermal expansion

An illustration of the total deformation of the part as a result of the thermal energy exposure is shown below in figure nine. The deformation was as expected for the energy input and is not considered to be hazardous to the user (quantify (with numbers) these results.)

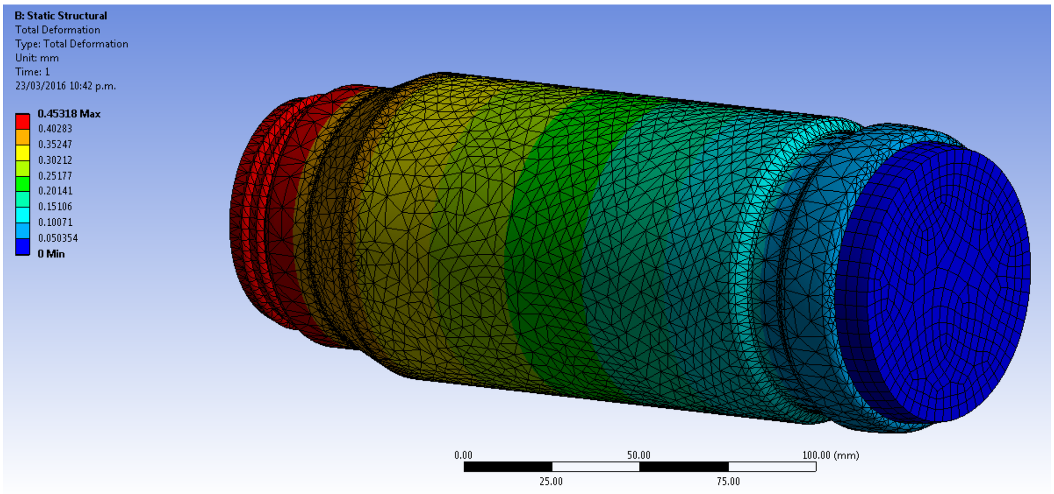

Figure 14: Overall deformation of the bottle

Table 6: Thermette FEA modelling results

	Stress (from thermal expansion)	Strain (from thermal expansion)	Overall deformation of bottle
Without base	1294.1 MPa	6.4704e-003 mm/mm	0.47085 mm
With base	1522.3 MPa	7.6114e-003 mm/mm	0.45318 mm

6. Discussion and interpretations

A drink bottle concept design with a complex geometry suitable for applications where pressures are in the range of 0.03 MPa to -0.302 MPa was created. The bottle was also modelled when subjected to a heat of 200 °C for use as a thermette.

Preliminary hand calculations were conducted to determine a ballpark figure for the stresses acting on the pressure vessel. The internal pressure loading case yielded a maximum von-mises stress of 2.375 MPa while the external pressure loading case yielded a maximum von-mises stress of 23.9 MPa. The results of the finite element analysis produced were in the vicinity of five times the magnitude of the stresses predicted from the hand calculations. This was expected due to the fact that the vessel was assumed to be perfectly cylindrical in the hand calculations, when in reality the part had a more complex geometry with areas which would be subject to higher stress concentrations.

The accuracy of the FEA results could have been improved further by decreasing the mesh size. However, a medium sized mesh was selected for FEA for its relative accuracy and reasonable computation time.

Critically, the stresses that were produced within the body of the bottle were below the yield points of the stainless steel material, the smallest safety factor having a value of 3.77 in the negative loading case.

The behaviour of the bottle when subjected to a 200 °C uniform heat source was also investigated. The results suggested that the stresses in the base of the bottle were above the yield point of the material and that failure of the vessel would occur as a result of the heat load.

In response to this, a 5 mm thick base was added to the bottle to distribute the thermal load. The results and animation from ANSYS clearly show that the stresses within the body of the bottle were reduced and that the thermal stresses were concentrated around the area of the plate. However, the stresses were still not below the target yields. Therefore further investigation of this issue is needed. The possibility of using an alternative heat-resistant material for the base or making the base thicker still could also be explored further.

The manufacturability of the vessel was also considered, with deep-drawing of the stainless steel deemed to be the best method of construction.

As outlined in the V-diagrams below, the next phase of the product development would involve physical construction and testing of the part for performance in real-life pressure simulations, heat exposure and aesthetic design. The design requirements and specifications could then be quantified and the product could be deemed ready for production, in which case the production work streams and part tolerances could be created, or the design could be reviewed and the iterative process of improvement would start again.

6.1 V-diagrams

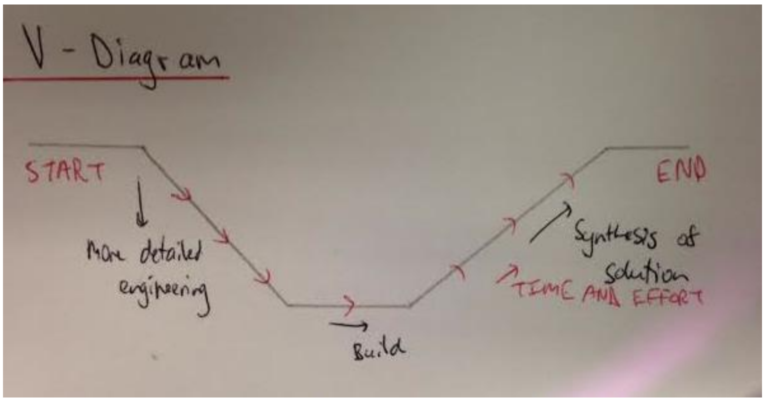

Figure 15: Basic V-diagram

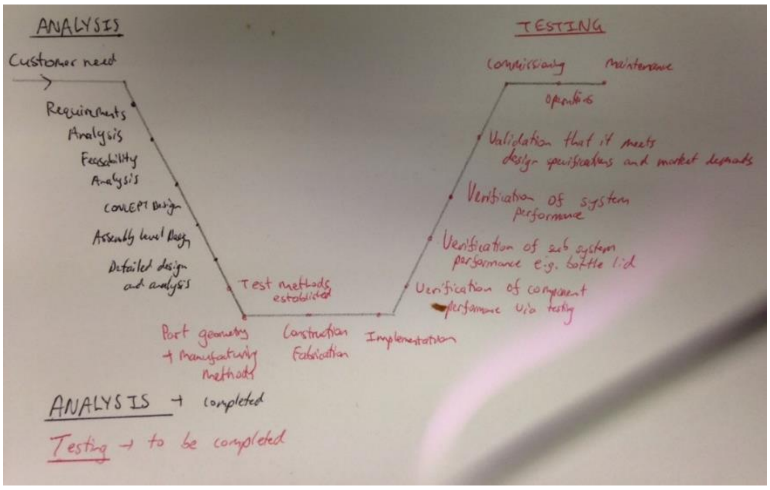

Figure 16: Analysis (completed) and testing (to be completed) V-Diagram

7. Supporting documents and appendices

Reference 1: Rocket bottle design: https://www.google.co.nz/search?q=stainless+steel+water+bottles&biw=1920&bih=969&source=lnms&tbm=isch&sa=X&sqi=2&ved=0ahUKEwj2ppfXzNDLAhWkG6YKHYwKCP0Q_AUIBigB#tbm=isch&tbs=rimg%3ACRkoISbfd88lIjg3hCikI7wM2wyL3O-uXQiRMulec5Yx19Zuy0rxVSWhrl-lk77OwYqx5sxumbVvVx-WxvvPuw02KioSCTeEKKQjvAzbEfE6TsouNTn4KhIJDIvc765dCJERKVe8GUYTRAgqEgky6V5zljHX1hEzQrj6w8R-hyoSCW7LSvFVJaGuEciNL3v1kYw-KhIJX6WTvs7BirER-Ti-hu5rw2oqEgnmzG6ZtW9XHxGACmzDe_1RlVSoSCZbG-8-7DTYqEfKZPI18GEn2&q=stainless%20steel%20water%20bottles%20cool%20shape&imgrc=GSghJt93zyUpXM%3A
(retrieved 21/03/2016)

8. Appendix (Original CAD files, FEA files and MathCAD documents)