# CONCORDIA UNIVERSITY
# ENGR 244 – Mechanics of Materials

## Experiment 3: Torsion Test on Metals


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## Objective:

The torsion test's is used to analyze the behaviour of materials under specific type of load called torsion. The torsion test reveals important mechanical properties of the material and their applicability to various designs.

## Introduction:

In this experiment, we've conducted a torsion test on three different metal samples, steel, aluminum, and brass. The test consists of subjecting the specimen to a controlled torque using a torsion apparatus. Torsion is a form of load that materials undergo while being twisted about their longitudinal axes. The torsion test machine then measures and records the angle of twist of the specimen under different loading. The torsion test informs the designer about the behaviour of materials under a controlled torque which is a critical step in the design process to ensure the safety and reliability of a material in its application [1].

The torsion test has been historically part of the study of materials strength, along with different experimenting techniques. First experiments were conducted in the early 19$^{th}$ century by engineers such as Thomas Young and Augustin-Louis Cauchy who laid the foundation for the study of stress and strain in materials, along with French engineer Jean-Victor Poncelet who conducted different experiments on the strength of materials including torsion tests [2].

There exist several types of torsional testing methods depending on the application of interest. Aside from the standard torsion test we used, there is torsional impact testing which evaluates the behaviours of materials under sudden dynamic torsion, and torsion fatigue testing that involve studying the behaviour of materials under cyclic torsion [1].

The selection of the standard torsion test was based on its verifiable reliability in providing accurate information for our analytical experiment, as well as the availability of the testing apparatus.

Prior to the experiment, certain assumptions are to be noted:

- The machine used has been properly calibrated and follows ASTM standards.
- Based on our measurements, the samples have been machined to have a uniform thickness along their gauge length.
- The samples tested are not ASTM certified.
- The testing samples are uniformly made of steel for the first, aluminum for the second, and brass for the third.

Torsion testing has practical applications through the information it provides the designer. From design, including material selection, quality control and research, torsion testing evaluates the strength, ductility, life cycle of materials, as well as some key mechanical properties like the shear modulus, the yield and ultimate shear strength. All this valuable information is used by the designer to determine the capacity of a material, use them appropriately depending on the requirements of the application, and lastly predict and prevent their failure. Torsion testing is a reliable experiment in research as well as design, the procedure has potential to be used in the development of new materials or simply testing the behaviour of existing material under different conditions and applications.

## Procedure:

In this experiment we used a torsion testing apparatus by TestResources to test three metal samples under a controlled torque.
The testing machine is composed of a base holding the lower platform that supports one side of a circular rotating mechanism, and an upper platform that supports the second part of the rotating mechanism. The adapters on the upper and lower platforms are effectively the rotational driving system, equipped with clamps that hold the test sample on each end, once the specimen is set in place and tightened, the operator can then proceed to the test by using the digital controls, see figure 1.
The initial gauge lengths of each sample are as follow: 76mm for steel, 100mm for aluminum, and 76mm for brass.


*Figure 1: Torsion testing fixture*

Prior to the test, the diameter of the samples has been measured in three locations along their longitudinal axes, the three results were used to calculate an average as follows:

- Diameter of the steel specimen: $d_i = \frac{6.008+6.047+6.026}{3} = 6.027mm$
- Diameter of the aluminum specimen: $d_i = \frac{4.965+4.956+4.947}{3} = 4.956mm$
- Diameter of the brass specimen: $d_i = \frac{5.960+5.985+5.978}{3} = 5.974mm$

Once the test starts the machine applies a controlled counterclockwise torque to the sample, therefore twisting it. As soon as the torque is applied, an angular displacement sensor detects and records the angle of twist for consecutive load intervals and compiles then into an excel document that is later retrieved by the team. The displacement sensor records the angular displacement and the corresponding load at every 0.1s for the programmed duration of the experiment.

## Results:

The full results collected during the test have been assembled in table 2 at the end of the document.
To calculate the shear modulus G, we can use the following equation:

$$\mathbf{G} = \frac{\mathbf{TL}}{\boldsymbol{\theta}\mathbf{J}}$$

**T**: torque (N.m)

**L**: gauge length (mm)
**θ**: angle of twist (radians)
**J**: polar moment of inertia: **J** $= \frac{(\pi D^4)}{32}$ (mm²)

The **polar moment of inertia** for each of the three samples are as follows:

- Polar moment of inertia of the steel specimen: $J = \frac{(\pi \times 6.027^4)}{32} = 129.54mm^2$
- Polar moment of inertia of the aluminum specimen: $J = \frac{(\pi \times 4.956^4)}{32} = 59.22mm^2$
- Polar moment of inertia of the brass specimen: $J = \frac{(\pi \times 5.974^4)}{32} = 125.04mm^2$

The three following tables include results of the test, and the resulting shear modulus.

| **STEEL** | | | | |
|---|---|---|---|---|
| **T (N.m)** | **θ (Deg.)** | **θ (Rad.)** | **G (GPa)** | **$G_{av}$ (GPa)** |
| **1.50** | 0.72 | 0.0125 | 70.40 | **70.57** |
| **3.00** | 1.43 | 0.0249 | 70.68 | |
| **4.50** | 2.14 | 0.0373 | 70.78 | |
| **6.00** | 2.85 | 0.0497 | 70.82 | |
| **7.40** | 3.50 | 0.0610 | 71.71 | |

*Table 1: Steel experimental values*

| **ALUMINUM** | | | | |
|---|---|---|---|---|
| **T (N.m)** | **θ (Deg.)** | **θ (Rad.)** | **G (GPa)** | **$G_{av}$ (GPa)** |
| **0.10** | 0.84 | 0.0146 | 11.566 | **18.32** |
| **0.20** | 1.19 | 0.0207 | 16.315 | |
| **0.30** | 1.55 | 0.0270 | 18.762 | |
| **0.40** | 1.95 | 0.0340 | 19.866 | |
| **0.50** | 2.28 | 0.0397 | 21.267 | |
| **0.60** | 2.62 | 0.0457 | 22.170 | |

*Table 2: Aluminum experimental values*

| **BRASS** | | | | |
|---|---|---|---|---|
| **T (N.m)** | **θ (Deg.)** | **θ (Rad.)** | **G (GPa)** | **$G_{av}$ (GPa)** |
| **1.00** | 0.73 | 0.0127 | 47.85 | **47.77** |
| **2.00** | 1.47 | 0.0256 | 47.48 | |
| **3.00** | 2.18 | 0.0380 | 47.98 | |
| **4.00** | 2.91 | 0.0507 | 47.95 | |
| **5.00** | 3.67 | 0.0640 | 47.48 | |

*Table 3: Brass experimental values*

We used the results recorded by the sensors, the load at every angle of twist, and plotted a torque-rotation diagram, the graphs will allow us to clearly see the behaviour of the specimen as the machine increases its torsional load.

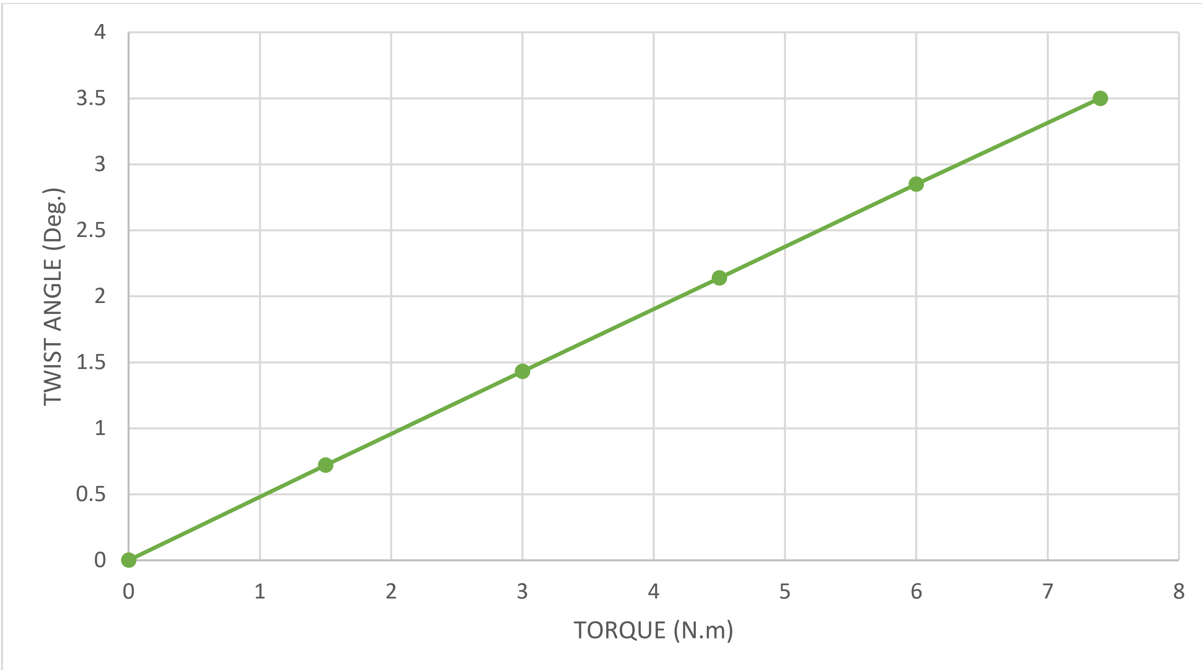


*Figure 2: Torque - Rotation diagram for STEEL*

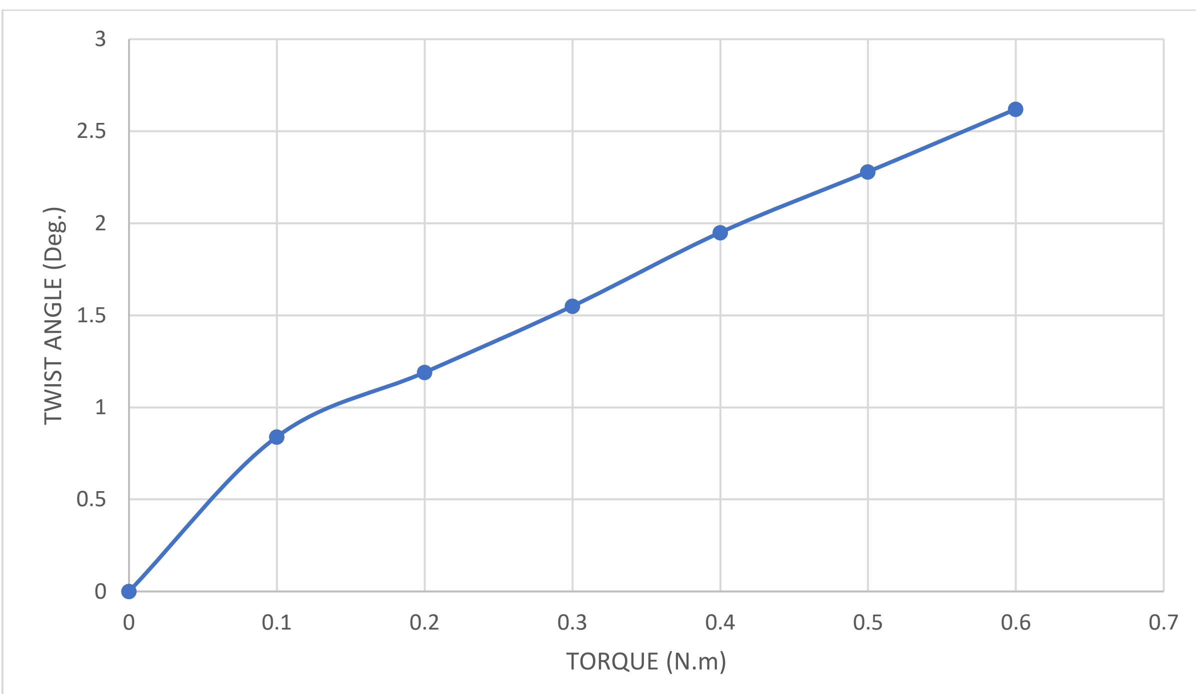


*Figure 3: Torque - Rotation diagram for ALUMINUM*

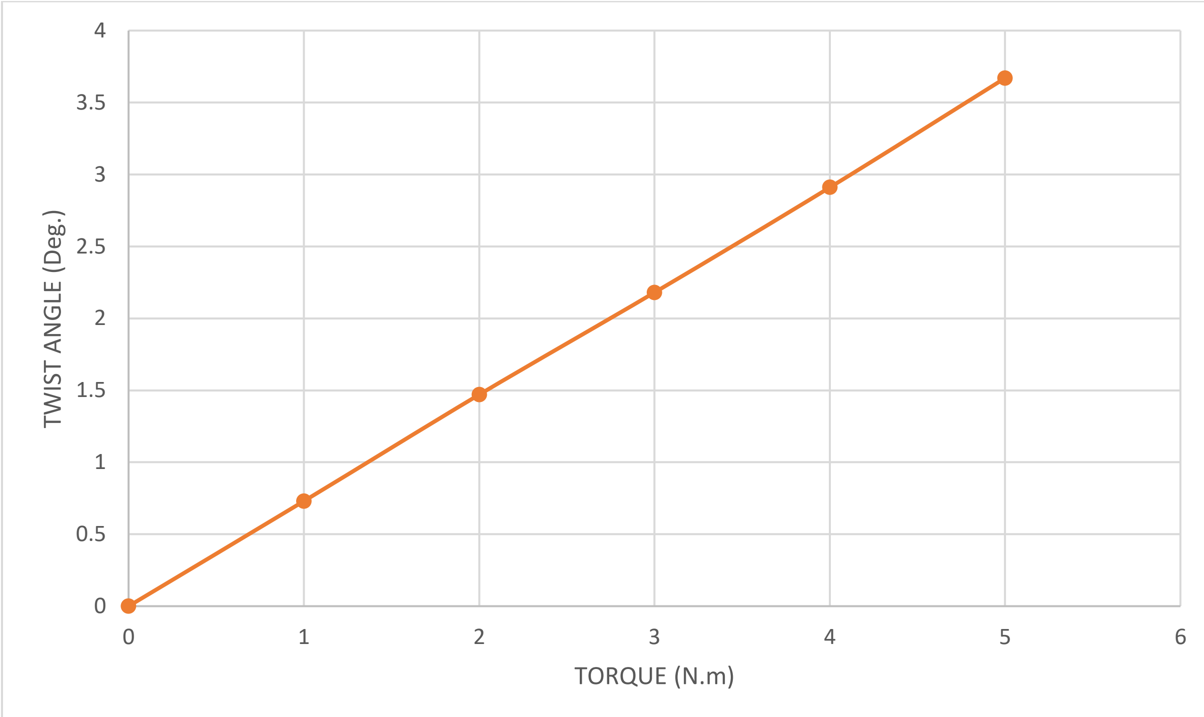

*Figure 4: Torque - Rotation diagram for BRASS*

| Material | Max torque (N.m) | Shear modulus (GPA) |
|---|---|---|
| **Steel** | 10.5 | 77 |
| **Aluminum** | 6 | 26 |
| **Brass** | 6 | 39 |

*Table 4: Approx. values of maximum torque and shear modulus*

An important step in our analysis is comparing the experimental values that we calculated with preexisting expected values. The shear modulus for steel is slightly lower than the expected value. As for aluminum we have a difference of almost 8GPa in the shear modulus compared to the expected value. And lastly the brass sample which shows a modulus of rigidity much higher than the expected value.

There are many factors that may contribute to these discrepancies. Firstly, the loading history of the sample, if the sample has been tested more than once, that might result in incremental plastic deformation overtime. Furthermore, human factor can also contribute to faulty results, for example a misalignment of the sample that can cause slippage or improper gripping during the test. It is also important to note that the sample are not ASTM standardized, even if metals generally have an isotropic profile, the materials could exhibit some anisotropic behaviour that results in higher or lower values depending on the orientation of their crystalline structures. In addition to this, the test might be affected by technical noise, if the machine or any of the measuring elements is not properly calibrated or fail to output accurate data.

## Discussion:

In our torsion test, we used solid cylindrical specimen, which present some advantages as opposed to other geometries, firstly because of the cylindricity. The geometry of the specimen plays an important factor in the feasibility and reliability of the test, this is related to the uniform stress distribution that circular cross sections exhibit. With a null shear stress at the center, the stress increases linearly as the radius is increased, therefore the distribution is uniform on any point of the same radius of the cross section, this is not applicable to noncircular samples. Another result of this distribution is that the circular sample's cross section, whether solid or hollow, remains plane and undistorted when subjected to torsion, since the cross section is axisymmetric. In addition, as opposed to circular samples, other geometries will induce undesired concentrated stresses on edges and corners of the samples, leading to failure that do not represent the material's overall properties. Furthermore, the analytical process is much simpler to process for circular samples since the equations are straightforward and the parameters well defined.

It is important to note that circular samples have their limitations in torsion testing, especially hollow samples, since they present a higher chance of experiencing bulking, which might introduce undesired types of stress in the test.

The torsion test that we've conducted is not of a destructive nature, but it is important to understand the failure of brittle versus ductile materials, figure 5 shows an example of both. Small elements on the face of the sample, parallel and perpendicular to the longitudinal axes are in pure shear stress. But elements at any other orientation experience both normal and shear stress. Those elements at 45˚ from the longitudinal axes experience pure tension. Since brittle materials, like cast iron, are weaker in tension than shear, they generally fail along surfaces 45˚ to the longitudinal axes, which experience maximum tension. As for ductile material, like aluminum, they fail in planes of maximum shear, planes perpendicular to the longitudinal axes.

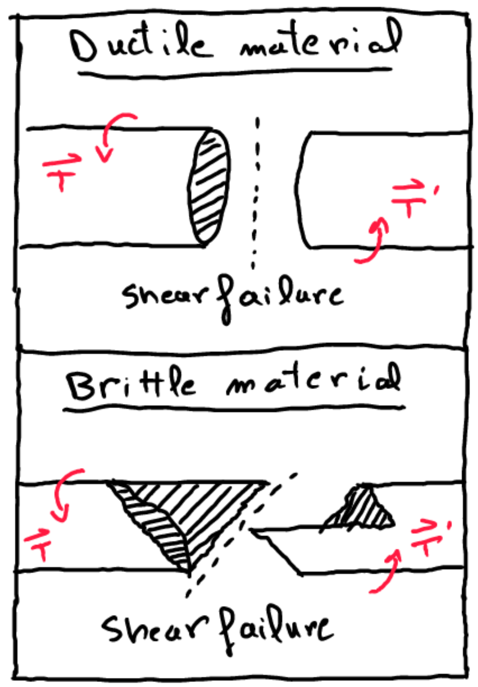


*Figure 5: Failure of ductile and brittle materials*

## Conclusions:

In this experiment, we conducted a torsion test on a steel, brass, and aluminum samples in order to observe their behaviour, determine their shear modulus, and deduce their mechanical behaviour under torsion. The experimental values for the shear modulus of the samples were relatively consistent with the literature with some variations due to factors such as loading history, human factor and technical issues. A comparison of the three samples shows steel followed by brass have higher shear modulus values than aluminum, therefore better resist deformation due to torsion. These conclusions relatively align with literature from our theory, asserting the reliability of torsion testing in collecting material's valuable mechanical properties. These results have direct implications in informing engineers and researchers about the behaviour of materials, particularly where torsion would be a primary source of stress. The analysis of shafts subjected to torque for example, requires the type of data that we deduced, allowing the designer to define the limitations of the material and evaluate their applicability to their design.

## References:


[1] M. F. Ashby and D. R. H. Jones 1945-, *Engineering materials. 1 : an introduction to properties, applications and design*, Fifth edition., 1 online resource (1 volume) vols. Amsterdam: Butterworth-Heinemann, 2018. [Online]. Available: https://www.sciencedirect.com/science/book/9780081020517

[2] S. Timoshenko 1878-1972., *History of strength of materials : with a brief account of the history of theory of elasticity and theory of structures*, 1 online resource (x, 452 pages) : illustrations vols. New York: Dover Publications, 1983. [Online]. Available: http://app.knovel.com/hotlink/toc/id:kpHSMWBAH3/history-of-strength

*Table 5: Experimental torsion test results*

| | STEEL | | ALUMINUM | | BRASS | |
|---|---|---|---|---|---|---|
| **Time (sec)** | **Torque (N.m)** | **Angle (deg)** | **Torque (N.m)** | **Angle (deg)** | **Torque (N.m)** | **Angle (deg)** |
| 0 | 0.06 | 0 | 0.03 | 0.57 | 0.07 | 0.04 |
| 0.1 | 0.05 | 0 | 0.04 | 0.59 | 0.09 | 0.05 |
| 0.2 | 0.05 | 0.02 | 0.04 | 0.61 | 0.09 | 0.05 |
| 0.3 | 0.08 | 0.06 | 0.06 | 0.68 | 0.13 | 0.08 |
| 0.4 | 0.16 | 0.1 | 0.08 | 0.75 | 0.2 | 0.13 |
| 0.5 | 0.21 | 0.12 | 0.08 | 0.8 | 0.25 | 0.16 |
| 0.6 | 0.27 | 0.15 | 0.09 | 0.82 | 0.29 | 0.19 |
| 0.7 | 0.34 | 0.19 | 0.1 | 0.84 | 0.33 | 0.22 |
| 0.8 | 0.42 | 0.22 | 0.1 | 0.86 | 0.35 | 0.24 |
| 0.9 | 0.48 | 0.25 | 0.12 | 0.89 | 0.37 | 0.25 |
| 1 | 0.56 | 0.29 | 0.13 | 0.92 | 0.39 | 0.27 |
| 1.1 | 0.64 | 0.33 | 0.14 | 0.96 | 0.41 | 0.29 |
| 1.2 | 0.7 | 0.36 | 0.14 | 1 | 0.44 | 0.31 |
| 1.3 | 0.77 | 0.39 | 0.16 | 1.03 | 0.48 | 0.33 |
| 1.4 | 0.86 | 0.43 | 0.16 | 1.06 | 0.5 | 0.35 |
| 1.5 | 0.92 | 0.46 | 0.17 | 1.09 | 0.52 | 0.36 |
| 1.6 | 0.98 | 0.49 | 0.17 | 1.12 | 0.55 | 0.39 |
| 1.7 | 1.06 | 0.52 | 0.19 | 1.15 | 0.6 | 0.42 |
| 1.8 | 1.13 | 0.56 | 0.19 | 1.18 | 0.65 | 0.46 |
| 1.9 | 1.2 | 0.58 | 0.2 | 1.19 | 0.7 | 0.49 |
| 2 | 1.29 | 0.63 | 0.21 | 1.22 | 0.72 | 0.51 |
| 2.1 | 1.4 | 0.68 | 0.22 | 1.29 | 0.73 | 0.51 |
| 2.2 | 1.49 | 0.72 | 0.24 | 1.34 | 0.73 | 0.52 |
| 2.3 | 1.57 | 0.76 | 0.25 | 1.39 | 0.77 | 0.55 |
| 2.4 | 1.65 | 0.79 | 0.27 | 1.42 | 0.88 | 0.63 |
| 2.5 | 1.71 | 0.83 | 0.27 | 1.45 | 0.95 | 0.68 |
| 2.6 | 1.81 | 0.86 | 0.28 | 1.48 | 1.02 | 0.73 |
| 2.7 | 1.88 | 0.9 | 0.28 | 1.51 | 1.04 | 0.74 |
| 2.8 | 1.93 | 0.93 | 0.3 | 1.55 | 1.04 | 0.74 |
| 2.9 | 2 | 0.96 | 0.3 | 1.58 | 1.05 | 0.74 |
| 3 | 2.07 | 0.99 | 0.31 | 1.62 | 1.05 | 0.74 |
| 3.1 | 2.15 | 1.03 | 0.32 | 1.65 | 1.06 | 0.75 |
| 3.2 | 2.21 | 1.05 | 0.33 | 1.69 | 1.11 | 0.79 |
| 3.3 | 2.27 | 1.09 | 0.34 | 1.72 | 1.17 | 0.84 |
| 3.4 | 2.35 | 1.12 | 0.35 | 1.75 | 1.21 | 0.87 |
| 3.5 | 2.4 | 1.15 | 0.36 | 1.78 | 1.26 | 0.9 |
| 3.6 | 2.45 | 1.17 | 0.36 | 1.79 | 1.28 | 0.92 |
| 3.7 | 2.51 | 1.2 | 0.37 | 1.8 | 1.32 | 0.94 |
| 3.8 | 2.59 | 1.24 | 0.36 | 1.83 | 1.34 | 0.96 |
| 3.9 | 2.66 | 1.27 | 0.39 | 1.9 | 1.35 | 0.97 |
| 4 | 2.74 | 1.3 | 0.41 | 1.95 | 1.38 | 1 |
| 4.1 | 2.81 | 1.34 | 0.41 | 1.99 | 1.43 | 1.03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4.2 | 2.87 | 1.37 | 0.43 | 2.02 | 1.48 | 1.07 |
| 4.3 | 2.93 | 1.4 | 0.44 | 2.05 | 1.53 | 1.1 |
| 4.4 | 3.01 | 1.43 | 0.45 | 2.08 | 1.56 | 1.12 |
| 4.5 | 3.09 | 1.47 | 0.45 | 2.11 | 1.56 | 1.12 |
| 4.6 | 3.15 | 1.5 | 0.46 | 2.15 | 1.57 | 1.12 |
| 4.7 | 3.21 | 1.53 | 0.48 | 2.19 | 1.58 | 1.15 |
| 4.8 | 3.28 | 1.57 | 0.49 | 2.22 | 1.69 | 1.23 |
| 4.9 | 3.36 | 1.6 | 0.49 | 2.25 | 1.76 | 1.27 |
| 5 | 3.42 | 1.63 | 0.5 | 2.28 | 1.82 | 1.32 |
| 5.1 | 3.5 | 1.66 | 0.51 | 2.32 | 1.86 | 1.34 |
| 5.2 | 3.56 | 1.7 | 0.52 | 2.35 | 1.86 | 1.34 |
| 5.3 | 3.62 | 1.72 | 0.54 | 2.38 | 1.87 | 1.35 |
| 5.4 | 3.69 | 1.75 | 0.53 | 2.4 | 1.87 | 1.35 |
| 5.5 | 3.77 | 1.79 | 0.54 | 2.4 | 1.89 | 1.36 |
| 5.6 | 3.85 | 1.83 | 0.55 | 2.44 | 1.9 | 1.38 |
| 5.7 | 3.93 | 1.87 | 0.56 | 2.49 | 1.96 | 1.42 |
| 5.8 | 4.02 | 1.91 | 0.58 | 2.54 | 2.02 | 1.47 |
| 5.9 | 4.09 | 1.94 | 0.58 | 2.58 | 2.07 | 1.5 |
| 6 | 4.15 | 1.97 | 0.6 | 2.62 | 2.1 | 1.52 |
| 6.1 | 4.22 | 2.01 | 0.6 | 2.65 | 2.13 | 1.54 |
| 6.2 | 4.31 | 2.04 | 0.61 | 2.68 | 2.16 | 1.57 |
| 6.3 | 4.37 | 2.07 | 0.62 | 2.71 | 2.18 | 1.58 |
| 6.4 | 4.44 | 2.11 | 0.63 | 2.75 | 2.19 | 1.59 |
| 6.5 | 4.52 | 2.14 | 0.64 | 2.78 | 2.25 | 1.63 |
| 6.6 | 4.58 | 2.17 | 0.65 | 2.82 | 2.3 | 1.67 |
| 6.7 | 4.63 | 2.2 | 0.66 | 2.85 | 2.35 | 1.71 |
| 6.8 | 4.71 | 2.23 | 0.67 | 2.88 | 2.38 | 1.72 |
| 6.9 | 4.79 | 2.27 | 0.67 | 2.91 | 2.39 | 1.73 |
| 7 | 4.85 | 2.3 | 0.68 | 2.94 | 2.4 | 1.74 |
| 7.1 | 4.91 | 2.33 | 0.7 | 2.98 | 2.42 | 1.76 |
| 7.2 | 4.98 | 2.36 | 0.7 | 2.99 | 2.49 | 1.81 |
| 7.3 | 5.04 | 2.39 | 0.7 | 3 | 2.53 | 1.84 |
| 7.4 | 5.1 | 2.42 | 0.71 | 3.02 | 2.57 | 1.87 |
| 7.5 | 5.2 | 2.47 | 0.73 | 3.09 | 2.64 | 1.92 |
| 7.6 | 5.31 | 2.51 | 0.75 | 3.15 | 2.69 | 1.95 |
| 7.7 | 5.36 | 2.54 | 0.75 | 3.2 | 2.71 | 1.97 |
| 7.8 | 5.44 | 2.58 | 0.76 | 3.22 | 2.73 | 1.98 |
| 7.9 | 5.52 | 2.62 | 0.77 | 3.24 | 2.75 | 1.99 |
| 8 | 5.58 | 2.64 | 0.78 | 3.25 | 2.77 | 2.01 |
| 8.1 | 5.65 | 2.68 | 0.78 | 3.29 | 2.82 | 2.04 |
| 8.2 | 5.73 | 2.72 | 0.79 | 3.32 | 2.85 | 2.07 |
| 8.3 | 5.79 | 2.75 | 0.8 | 3.35 | 2.87 | 2.08 |
| 8.4 | 5.86 | 2.78 | 0.81 | 3.39 | 2.89 | 2.1 |
| 8.5 | 5.94 | 2.82 | 0.82 | 3.43 | 2.92 | 2.12 |
| 8.6 | 6.01 | 2.85 | 0.83 | 3.46 | 2.96 | 2.15 |
| 8.7 | 6.07 | 2.87 | 0.83 | 3.48 | 2.99 | 2.17 |
| 8.8 | 6.12 | 2.9 | 0.84 | 3.5 | 3.01 | 2.18 |
| 8.9 | 6.2 | 2.94 | | | 3.05 | 2.22 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 9 | 6.27 | 2.97 | | | 3.11 | 2.26 |
| 9.1 | 6.31 | 2.99 | | | 3.16 | 2.3 |
| 9.2 | 6.38 | 3.02 | | | 3.18 | 2.31 |
| 9.3 | 6.49 | 3.07 | | | 3.2 | 2.32 |
| 9.4 | 6.57 | 3.11 | | | 3.22 | 2.34 |
| 9.5 | 6.65 | 3.15 | | | 3.23 | 2.35 |
| 9.6 | 6.73 | 3.19 | | | 3.29 | 2.4 |
| 9.7 | 6.79 | 3.22 | | | 3.36 | 2.45 |
| 9.8 | 6.87 | 3.25 | | | 3.4 | 2.47 |
| 9.9 | 6.95 | 3.29 | | | 3.48 | 2.53 |
| 10 | 7.01 | 3.32 | | | 3.52 | 2.56 |
| 10.1 | 7.06 | 3.34 | | | 3.53 | 2.57 |
| 10.2 | 7.14 | 3.38 | | | 3.54 | 2.57 |
| 10.3 | 7.22 | 3.42 | | | 3.56 | 2.59 |
| 10.4 | 7.28 | 3.45 | | | 3.6 | 2.62 |
| 10.5 | 7.35 | 3.48 | | | 3.62 | 2.64 |
| 10.6 | 7.4 | 3.5 | | | 3.65 | 2.66 |
| 10.7 | | | | | 3.68 | 2.68 |
| 10.8 | | | | | 3.7 | 2.69 |
| 10.9 | | | | | 3.72 | 2.71 |
| 11 | | | | | 3.76 | 2.74 |
| 11.1 | | | | | 3.8 | 2.77 |
| 11.2 | | | | | 3.83 | 2.79 |
| 11.3 | | | | | 3.88 | 2.83 |
| 11.4 | | | | | 3.93 | 2.87 |
| 11.5 | | | | | 3.98 | 2.9 |
| 11.6 | | | | | 4 | 2.91 |
| 11.7 | | | | | 4 | 2.92 |
| 11.8 | | | | | 4 | 2.92 |
| 11.9 | | | | | 4.04 | 2.95 |
| 12 | | | | | 4.14 | 3.03 |
| 12.1 | | | | | 4.21 | 3.07 |
| 12.2 | | | | | 4.29 | 3.13 |
| 12.3 | | | | | 4.31 | 3.14 |
| 12.4 | | | | | 4.31 | 3.14 |
| 12.5 | | | | | 4.31 | 3.14 |
| 12.6 | | | | | 4.31 | 3.15 |
| 12.7 | | | | | 4.33 | 3.15 |
| 12.8 | | | | | 4.36 | 3.19 |
| 12.9 | | | | | 4.43 | 3.23 |
| 13 | | | | | 4.47 | 3.27 |
| 13.1 | | | | | 4.51 | 3.29 |
| 13.2 | | | | | 4.54 | 3.32 |
| 13.3 | | | | | 4.57 | 3.34 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 13.4 | | | | | 4.6 | 3.36 |
| 13.5 | | | | | 4.61 | 3.37 |
| 13.6 | | | | | 4.63 | 3.39 |
| 13.7 | | | | | 4.69 | 3.43 |
| 13.8 | | | | | 4.74 | 3.47 |
| 13.9 | | | | | 4.79 | 3.5 |
| 14 | | | | | 4.82 | 3.52 |
| 14.1 | | | | | 4.83 | 3.52 |
| 14.2 | | | | | 4.83 | 3.53 |
| 14.3 | | | | | 4.83 | 3.53 |
| 14.4 | | | | | 4.92 | 3.6 |
| 14.5 | | | | | 5.02 | 3.67 |
| 14.6 | | | | | 5.11 | 3.74 |
| 14.7 | | | | | 5.14 | 3.76 |
| 14.8 | | | | | 5.14 | 3.76 |
| 14.9 | | | | | 5.14 | 3.76 |
| 15 | | | | | 5.15 | 3.76 |
| 15.1 | | | | | 5.14 | 3.76 |
| 15.2 | | | | | 5.16 | 3.77 |
| 15.3 | | | | | 5.2 | 3.81 |
| 15.4 | | | | | 5.27 | 3.86 |
| 15.5 | | | | | 5.32 | 3.9 |
| 15.6 | | | | | 5.36 | 3.92 |
| 15.7 | | | | | 5.39 | 3.94 |
| 15.8 | | | | | 5.43 | 3.97 |
| 15.9 | | | | | 5.44 | 3.98 |
| 16 | | | | | 5.45 | 3.99 |
| 16.1 | | | | | 5.46 | 4 |