Performance Indices Reference Booklet

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About Performance Indices

During materials selection, one needs to optimize the performance of the material based on the design requirements. When using the Ashby Selection methodology[1], these criteria are determined via the Objectives and are used during the Ranking stage.

We can determine the performance of the material by defining a performance equation. The general form of this equation can be found elsewhere. When focusing on the material properties segment of this performance equation, this can be called a material index or a performance index. These material indices help us determine how well a specific material that has passed the screening stage will perform during ranking[1].

As stated in our materials selection whitepaper[2] and Prof. Ashby's textbooks[1,3], the constraints defined during the translation step of the selection methodology set property limits. In some cases, the objectives are separate from the constraints, which leads to single material property performance indices (i.e. if the performance of a beam is measured by its stiffness, the performance equation contains only one property, the elastic modulus E). In other situations, the constraints and objectives are coupled, which leads to a group of multiple properties. Familiar examples are the specific stiffness, E/ρ, and the specific strength, σ_y/ρ, (where E is Young's modulus, σ_y is the yield strength or elastic limit, and ρ is the density), but there are many others. They are a key to the optimal selection of materials.

In this Booklet

This booklet provides pre-derived performance indices for a variety of conditions. A breakdown of the conditions can be found in the interactive table of contents on the next page.

By separating our performance equation into the function, geometry, and material elements, we can consider the material choice independently of other design factors[1]. This gives the indices found in this booklet great generality, which can be incredibly beneficial during the early stages of design. To truly consider all aspects of the performance, including function and geometry, one should turn to additional steps such as simulation or prototyping to ensure an optimal overall design.

References and Additional Texts

1. Ashby MF, "Materials Selection in Mechanical Design", 5th edition, Elsevier Butterworth-Heinemann, Oxford, UK, 2016.

2. Parnell, H, Tyler, K, "Granta EduPack White Paper: Material Selection", Ansys

3. Ashby MF, "Materials and the Environment", 2nd Edition, Elsevier Butterworth Heinemann, Oxford, UK, 2012.

4. Goedkoop, M.J., Demmers, M. and Collignon, M.X. "Eco-Indicator '95, Manual", Pré Consultants, and the Netherlands Agency for Energy and the Environment, Amersfort, Holland (1995), ISBN 90-72130-80-4.

Booklet Contents

Use the interactive table below to access the different performance indices by type. References shown in the tables can be found under the references section.

The symbols list can be found by clicking here.

	Mass	Cost	Embodied Energy	Carbon Footprint
Stiffness-limited Design	**kg**	**$**	**H_m**	**CO_2**
Strength-limited Design	**kg**	**$**	**H_m**	**CO_2**

Vibration-limited Design

Damage-tolerant Design

Abrasion-resistant Design

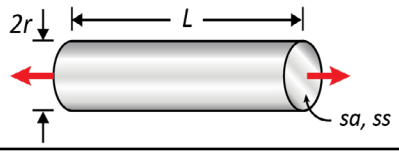
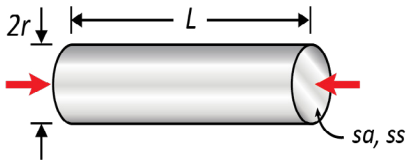
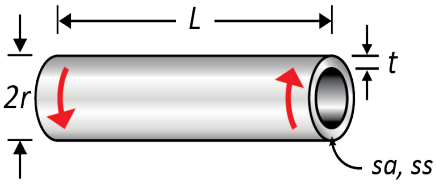
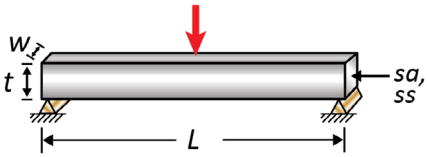
Thermo-mechanical Design

Electro-mechanical Design

Vapor barrier Design

Strength-limited design to optimize performance

Stiffness-limited design at minimum mass

Function and Constraints*			Maximize	Minimize
Tie in Tension		Length fixed; section area free	E/ρ	ρ/E
Column in compression		Length, section shape fixed; section area free	E/ρ	ρ/E
		Length fixed; section area and section shape free	$(E\phi)/\rho$	$\rho/(E\phi)$
		Length, section shape fixed; section area free; buckling stiffness limited	$E^{1/2}/\rho$	$\rho/E^{1/2}$
Shaft in torsion		Length, section shape fixed; section area free	$G^{1/2}/\rho$	$\rho/G^{1/2}$
		Length, wall-thickness fixed; outer radius free	$G^{1/3}/\rho$	$\rho/G^{1/3}$
		Length, outer radius fixed; wall-thickness free	G/ρ	ρ/G
Beam in bending		Length, shape fixed; section area free	$E_f^{1/2}/\rho$	$\rho/E_f^{1/2}$
		Length fixed; section area and section shape free	$(\phi E_f)^{1/2}/\rho$	$\rho/(\phi E_f)^{1/2}$
		Length, thickness, section shape fixed; width free	E_f/ρ	ρ/E_f
		Length, thickness fixed; width, section shape free	$(\phi E_f)/\rho$	$\rho/(\phi E_f)$
		Length, width, section shape fixed; thickness free	$E_f^{1/3}/\rho$	$\rho/E_f^{1/3}$
		Length, width, section shape fixed; thickness free	$(\phi E_f)^{1/3}/\rho$	$\rho/(\phi E_f)^{1/3}$

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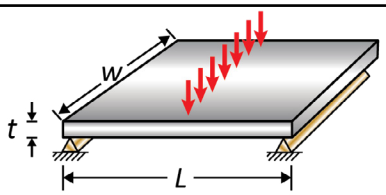
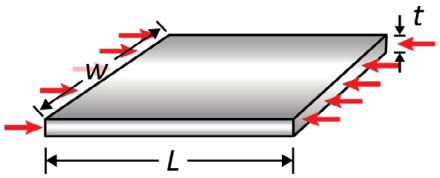
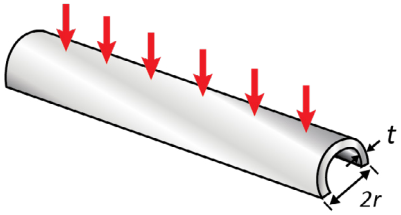
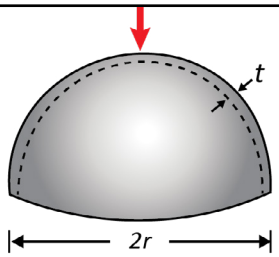
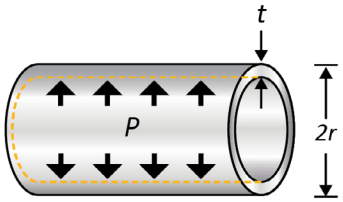
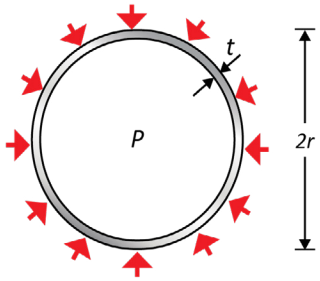
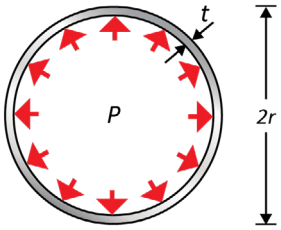
Function and Constraints*			Maximize	Minimize
Panel in bending		Length fixed, width fixed; thickness free	$E_f^{1/3}/\rho$	$\rho/E_f^{1/3}$
Panel in compression		Collapse load, length and width fixed; thickness free	E_f/ρ	ρ/E_f
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$E_f^{1/3}/\rho$	$\rho/E_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$E_f^{1/2}/\rho$	$\rho/E_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	E/ρ	ρ/E
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$E_f^{1/2}/\rho$	$\rho/E_f^{1/2}$
		Radius fixed; wall-thickness free; buoyancy limited	E/ρ	ρ/E
Sphere with internal pressure		Radius fixed; wall-thickness free	$E/(1-\upsilon)\rho$	$(1-\upsilon)\rho/E$

* to minimize ***volume***, replace density ρ by 1 (one). [1,2,3]

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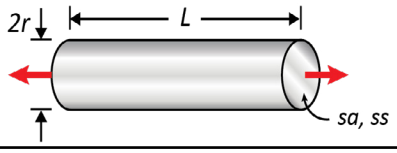
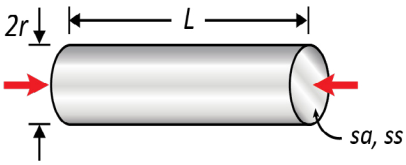
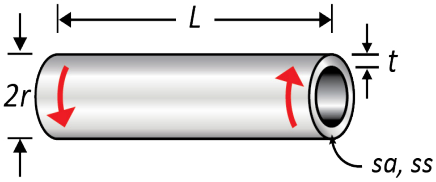
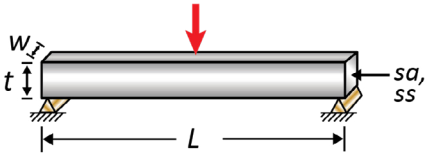
Stiffness-limited design at minimum cost

Function and Constraints			Maximize	Minimize
Tie in Tension		Length fixed; section area free	$E/C_m\rho$	$C_m\rho/E$
Column in compression		Length, section shape fixed; section area free	$E/C_m\rho$	$C_m\rho/E$
		Length fixed; section area and section shape free	$(E\phi)/C_m\rho$	$C_m\rho/(E\phi)$
		Length, section shape fixed; section area free; buckling stiffness limited	$E^{1/2}/C_m\rho$	$C_m\rho/E^{1/2}$
Shaft in torsion		Length, section shape fixed; section area free	$G^{1/2}/C_m\rho$	$C_m\rho/G^{1/2}$
		Length, wall-thickness fixed; outer radius free	$G^{1/3}/C_m\rho$	$C_m\rho/G^{1/3}$
		Length, outer radius fixed; wall-thickness free	$G/C_m\rho$	$C_m\rho/G$
Beam in bending		Length, shape fixed; section area free	$E_f^{1/2}/C_m\rho$	$C_m\rho/E_f^{1/2}$
		Length fixed; section area and section shape free	$(\phi E_f)^{1/2}/C_m\rho$	$C_m\rho/(\phi E_f)^{1/2}$
		Length, thickness, section shape fixed; width free	$E_f/C_m\rho$	$C_m\rho/E_f$
		Length, thickness fixed; width, section shape free	$(\phi E_f)/C_m\rho$	$C_m\rho/(\phi E_f)$
		Length, width, section shape fixed; thickness free	$E_f^{1/3}/C_m\rho$	$C_m\rho/E_f^{1/3}$
		Length, width, section shape fixed; thickness free	$(\phi E_f)^{1/3}/C_m\rho$	$C_m\rho/(\phi E_f)^{1/3}$

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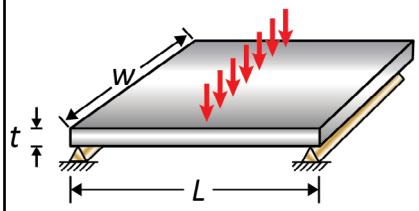
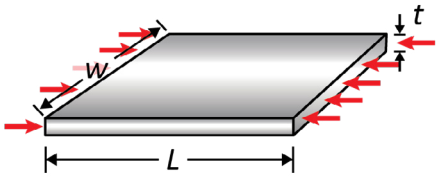
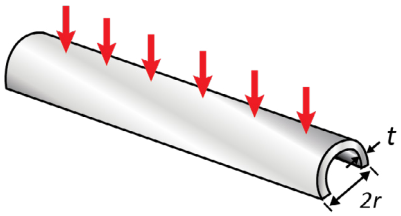
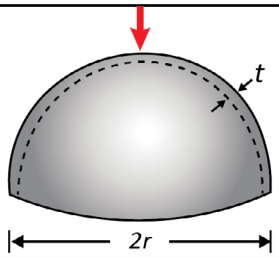
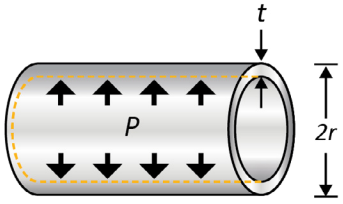
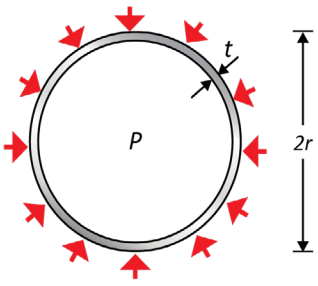
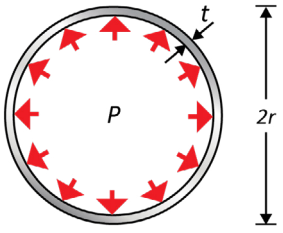
Function and Constraints			Maximize	Minimize
Panel in bending		Length fixed, width fixed; thickness free	$E_f^{1/3}/C_m\rho$	$C_m\rho/E_f^{1/3}$
Panel in compression		Collapse load, length and width fixed; thickness free	$E_f/C_m\rho$	$C_m\rho/E_f$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$E_f^{1/3}/C_m\rho$	$C_m\rho/E_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$E^{1/2}/C_m\rho$	$C_m\rho/E^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$E/C_m\rho$	$C_m\rho/E$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$E^{1/2}/C_m\rho$	$C_m\rho/E^{1/2}$
		Radius fixed; wall-thickness free; buoyancy limited	$E/C_m\rho$	$C_m\rho/E$
Sphere with internal pressure		Radius fixed; wall-thickness free	$E/(1-\upsilon)C_m\rho$	$(1-\upsilon)C_m\rho/E$

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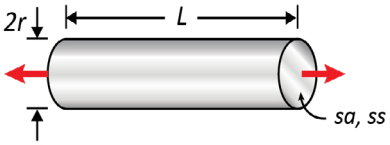
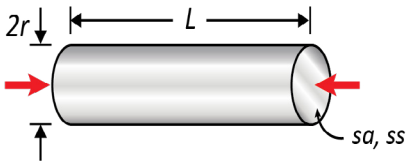
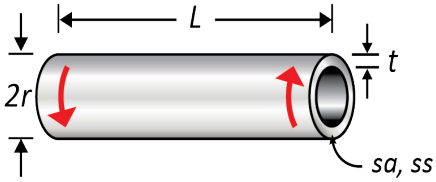
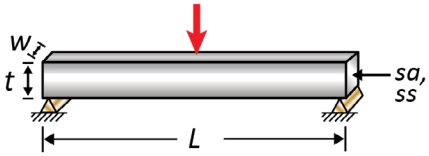
Stiffness-limited design at minimum energy

Function and Constraints[1]			Maximize[2]	Minimize[3]
Tie in Tension		Length fixed; section area free	$E/H_m\rho$	$H_m\rho/E$
Column in compression		Length, section shape fixed; section area free	$E/H_m\rho$	$H_m\rho/E$
		Length fixed; section area and section shape free	$(E\phi)/H_m\rho$	$H_m\rho/(E\phi)$
		Length, section shape fixed; section area free; buckling stiffness limited	$E^{1/2}/H_m\rho$	$H_m\rho/E^{1/2}$
Shaft in torsion		Length, section shape fixed; section area free	$G^{1/2}/H_m\rho$	$H_m\rho/G^{1/2}$
		Length, wall-thickness fixed; outer radius free	$G^{1/3}/H_m\rho$	$H_m\rho/G^{1/3}$
		Length, outer radius fixed; wall-thickness free	$G/H_m\rho$	$H_m\rho/G$
Beam in bending		Length, shape fixed; section area free	$E_f^{1/2}/H_m\rho$	$H_m\rho/E_f^{1/2}$
		Length fixed; section area and section shape free	$(\phi E_f)^{1/2}/H_m\rho$	$H_m\rho/(\phi E_f)^{1/2}$
		Length, thickness, section shape fixed; width free	$E_f/H_m\rho$	$H_m\rho/E_f$
		Length, thickness fixed; width, section shape free	$(\phi E_f)/H_m\rho$	$H_m\rho/(\phi E_f)$
		Length, width, section shape fixed; thickness free	$E_f^{1/3}/H_m\rho$	$H_m\rho/E_f^{1/3}$
		Length, width, section shape fixed; thickness free	$(\phi E_f)^{1/3}/H_m\rho$	$H_m\rho/(\phi E_f)^{1/3}$

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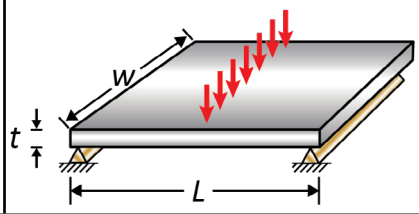
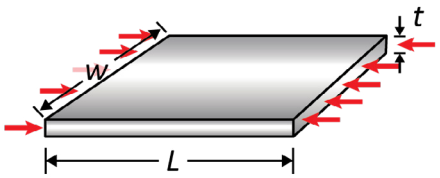
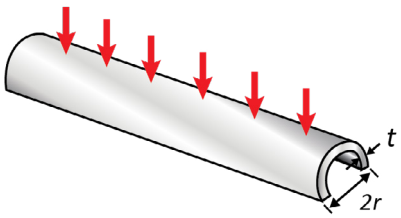
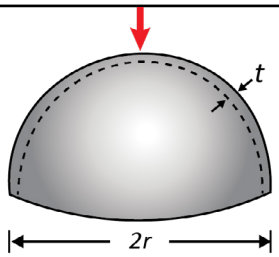
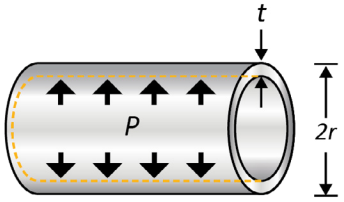
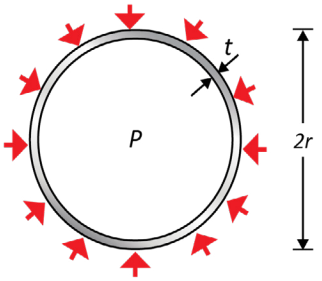
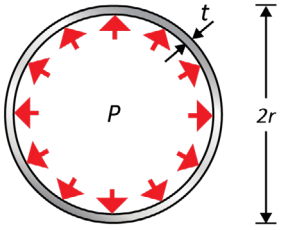
Function and Constraints			Maximize	Minimize
Panel in bending		Length fixed, width fixed; thickness free	$E_f^{1/3}/H_m\rho$	$H_m\rho/E_f^{1/3}$
Panel in compression		Collapse load, length and width fixed; thickness free	$E_f/H_m\rho$	$H_m\rho/E_f$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$E_f^{1/3}/H_m\rho$	$H_m\rho/E_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$E_f^{1/2}/H_m\rho$	$H_m\rho/E_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$E/H_m\rho$	$H_m\rho/E$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$E^{1/2}/H_m\rho$	$H_m\rho/E^{1/2}$
		Radius fixed; wall-thickness free; buoyancy limited	$E/H_m\rho$	$H_m\rho/E$
Sphere with internal pressure		Radius fixed; wall-thickness free	$E/(1-\upsilon)H_m\rho$	$(1-\upsilon)H_m\rho/E$

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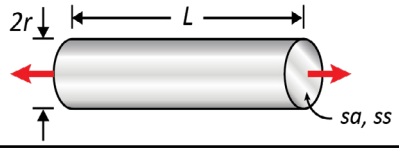
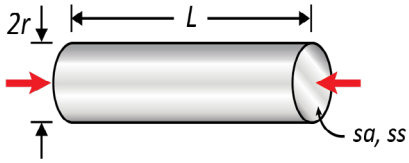
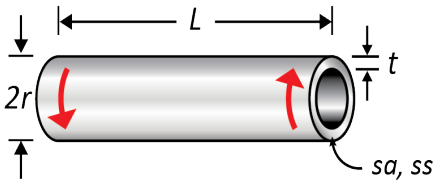
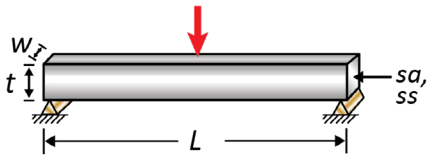
Stiffness-limited design at minimum environmental impact

Function and Constraints			Maximize	Minimize
Tie in Tension		Length fixed; section area free	$E/CO_2\rho$	$CO_2\rho/E$
Column in compression		Length, section shape fixed; section area free	$E/CO_2\rho$	$CO_2\rho/E$
		Length fixed; section area and section shape free	$(E\phi)/CO_2\rho$	$CO_2\rho/(E\phi)$
		Length, section shape fixed; section area free; buckling stiffness limited	$E^{1/2}/CO_2\rho$	$CO_2\rho/E^{1/2}$
Shaft in torsion		Length, section shape fixed; section area free	$G^{1/2}/CO_2\rho$	$CO_2\rho/G^{1/2}$
		Length, wall-thickness fixed; outer radius free	$G^{1/3}/CO_2\rho$	$CO_2\rho/G^{1/3}$
		Length, outer radius fixed; wall-thickness free	$G/CO_2\rho$	$CO_2\rho/G$
Beam in bending		Length, shape fixed; section area free	$E_f^{1/2}/CO_2\rho$	$CO_2\rho/E_f^{1/2}$
		Length fixed; section area and section shape free	$(\phi E_f)^{1/2}/_{CO_2\rho}$	$^{CO_2\rho}/_{(\phi E_f)^{1/2}}$
		Length, thickness, section shape fixed; width free	$E_f/CO_2\rho$	$CO_2\rho/E_f$
		Length, thickness fixed; width, section shape free	$(\phi E_f)/CO_2\rho$	$CO_2\rho/(\phi E_f)$
		Length, width, section shape fixed; thickness free	$E_f^{1/3}/CO_2\rho$	$CO_2\rho/E_f^{1/3}$
		Length, width, section shape fixed; thickness free	$(\phi E_f)^{1/3}/_{CO_2\rho}$	$^{CO_2\rho}/_{(\phi E_f)^{1/3}}$

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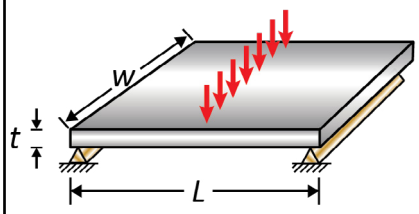
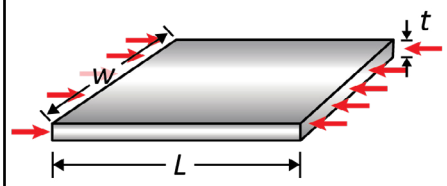
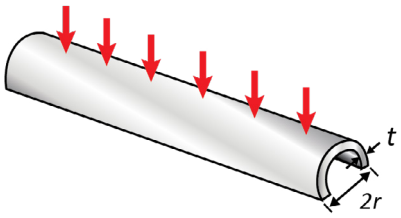
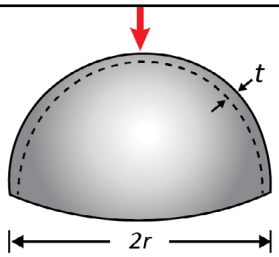
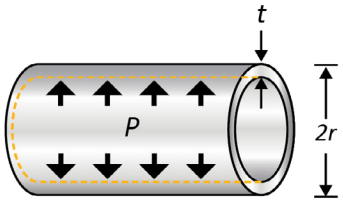
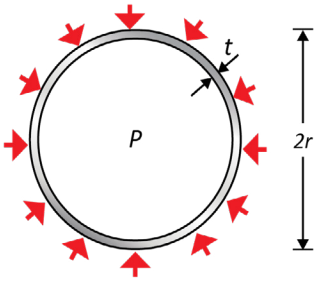
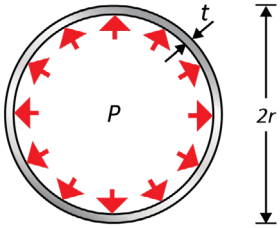
Function and Constraints			Maximize	Minimize
Panel in bending		Length fixed, width fixed; thickness free	$E_f^{1/3}/CO_2\rho$	$CO_2\rho/E_f^{1/3}$
Panel in compression		Collapse load, length and width fixed; thickness free	$E_f/CO_2\rho$	$CO_2\rho/E_f$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$E_f^{1/3}/CO_2\rho$	$CO_2\rho/E_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$E_f^{1/2}/CO_2\rho$	$CO_2\rho/E_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$E/CO_2\rho$	$CO_2\rho/E$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$E^{1/2}/CO_2\rho$	$CO_2\rho/E^{1/2}$
		Radius fixed; wall-thickness free; buoyancy limited	$E/CO_2\rho$	$CO_2\rho/E$
Sphere with internal pressure		Radius fixed; wall-thickness free	$E/(1-\upsilon)CO_2\rho$	$(1-\upsilon)CO_2\rho/E$

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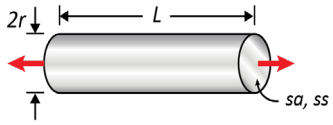
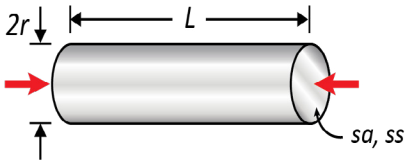
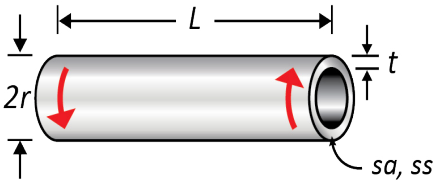
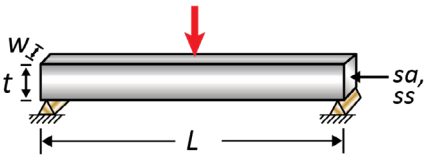
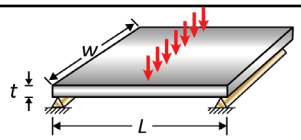
Strength-limited design at minimum mass

Function and Constraints*,†			Maximize	Minimize
Tie in Tension		Length fixed; section area free	σ_y/ρ	ρ/σ_y
Column in compression		Length, section shape fixed; section area free	σ_c/ρ	ρ/σ_c
		Length fixed; section area and section shape free	$(\phi^{1/2}\sigma_y)/\rho$	$\rho/(\phi^{1/2}\sigma_y)$
		Length, section shape fixed; section area free; buckling stiffness limited	$(\phi^{1/2}\sigma_y)^{2/3}/\rho$	$\rho/(\phi^{1/2}\sigma_y)^{2/3}$
Shaft in torsion		Length, section shape fixed; section area free	$\sigma_y^{2/3}/\rho$	$\rho/\sigma_y^{2/3}$
		Length, wall-thickness fixed; outer radius free	$\sigma_y^{1/2}/\rho$	$\rho/\sigma_y^{1/2}$
		Length, outer radius fixed; wall-thickness free	σ_y/ρ	ρ/σ_y
Beam in bending		Length, shape fixed; section area free	$\sigma_y^{2/3}/\rho$	$\rho/\sigma_y^{2/3}$
		Length fixed; section area and section shape free	$\left(\phi^{1/2}\sigma_f^{2/3}\right)/\rho$	$\rho/\left(\phi^{1/2}\sigma_f^{2/3}\right)$
		Length, thickness, section shape fixed; width free	σ_f/ρ	ρ/σ_f
		Length, thickness fixed; width, section shape free	$(\phi^{1/2}\sigma_f)/\rho$	$\rho/(\phi^{1/2}\sigma_f)$
		Length, width, section shape fixed; thickness free	$\sigma_f^{1/2}/\rho$	$\rho/\sigma_f^{1/2}$
		Length, width, section shape fixed; thickness free	$(\phi\sigma_f)^{1/2}/\rho$	$\rho/(\phi\sigma_f)^{1/2}$
Panel in bending		Length fixed, width fixed; thickness free	$\sigma_f^{1/2}/\rho$	$\rho/\sigma_f^{1/2}$

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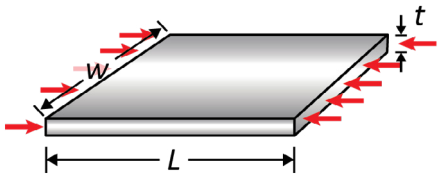
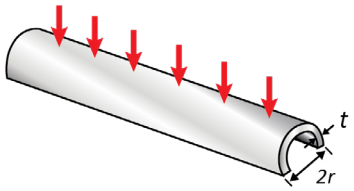
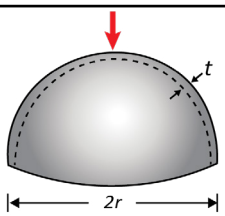
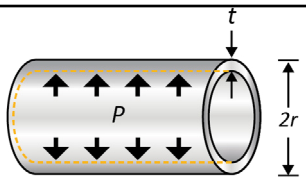
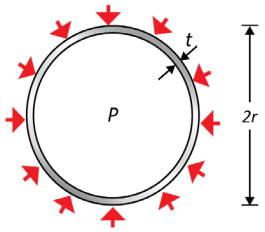
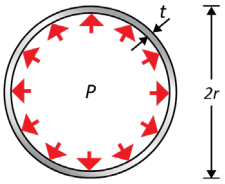
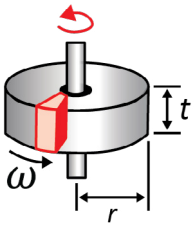
Function and Constraints*,†			Maximize	Minimize
Panel in compression		Length, width fixed; thickness free	$\sigma_c^{1/2}/\rho$	$\rho/\sigma_c^{1/2}$
		Length, width, thickness free; buckling strength fixed	$\sigma_y^{1/2}/\rho$	$\rho/\sigma_y^{1/2}$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$\sigma_f^{1/3}/\rho$	$\rho/\sigma_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$\sigma_f^{1/2}/\rho$	$\rho/\sigma_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	σ_y/ρ	ρ/σ_y
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	σ_c/ρ	ρ/σ_c
		Radius fixed; wall-thickness free; buoyancy limited	$\sigma_y^{2/3}/\rho$	$\rho/\sigma_y^{2/3}$
Sphere with internal pressure		Radius fixed; wall-thickness free	σ_y/ρ	ρ/σ_y
Flywheel/ rotating disk		Radius fixed; thickness free; angular velocity limited	ρ	$1/\rho$
		Thickness fixed; angular velocity, radius free	σ_y/ρ	ρ/σ_y

* to minimize ***volume***, replace density ρ by 1 (one). [1,2,3]

† For design for infinite fatigue life, replace σ_y by the fatigue strength (endurance limit) σ_E.

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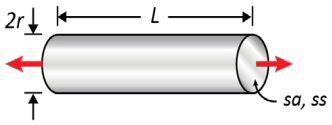
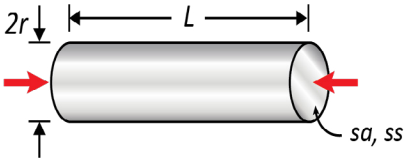
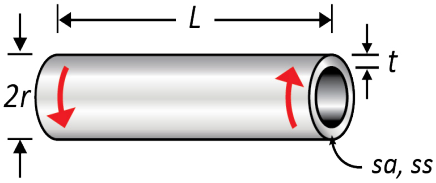
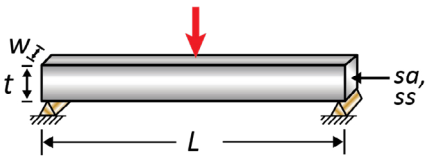
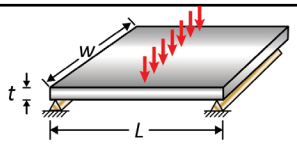
Strength-limited design at minimum cost

Function and Constraints†			Maximize	Minimize
Tie in Tension		Length fixed; section area free	$\sigma_y/C_m\rho$	$C_m\rho/\sigma_y$
Column in compression		Length, section shape fixed; section area free	$\sigma_c/C_m\rho$	$C_m\,\rho/\sigma_c$
		Length fixed; section area and section shape free	$(\phi^{1/2}\sigma_y)/C_m\rho$	$C_m\rho/(\phi^{1/2}\sigma_y)$
		Length, section shape fixed; section area free; buckling stiffness limited	$(\phi^{1/2}\sigma_y)^{2/3}/C_m\rho$	$C_m\rho/(\phi^{1/2}\sigma_y)^{2/3}$
Shaft in torsion		Length, section shape fixed; section area free	$\sigma_y^{2/3}/C_m\rho$	$C_m\rho/\sigma_y^{2/3}$
		Length, wall-thickness fixed; outer radius free	$\sigma_y^{1/2}/C_m\rho$	$C_m\rho/\sigma_y^{1/2}$
		Length, outer radius fixed; wall-thickness free	$\sigma_y/C_m\rho$	$C_m\rho/\sigma_y$
Beam in bending		Length, shape fixed; section area free	$\sigma_f^{2/3}/C_m\rho$	$C_m\rho/\sigma_f^{2/3}$
		Length fixed; section area and section shape free	$\left(\phi^{1/2}\sigma_f^{2/3}\right)/C_m\rho$	$C_m\rho/\left(\phi^{1/2}\sigma_f^{2/3}\right)$
		Length, thickness, section shape fixed; width free	$\sigma_f/C_m\rho$	$C_m\rho/\sigma_f$
		Length, thickness fixed; width, section shape free	$(\phi^{1/2}\sigma_f)/C_m\rho$	$C_m\rho/(\phi^{1/2}\sigma_f)$
		Length, width, section shape fixed; thickness free	$\sigma_f^{1/2}/C_m\rho$	$C_m\rho/\sigma_f^{1/2}$
		Length, width, section shape fixed; thickness free	$(\phi\sigma_f)^{1/2}/C_m\rho$	$C_m\rho/(\phi\sigma_f)^{1/2}$
Panel in bending		Length fixed, width fixed; thickness free	$\sigma_f^{1/2}/C_m\rho$	$C_m\rho/\sigma_f^{1/2}$

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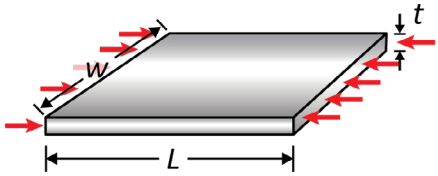
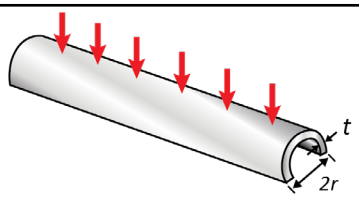
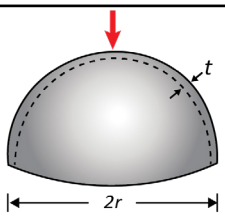
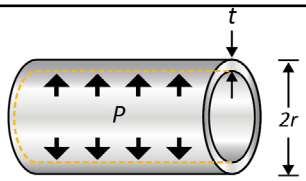
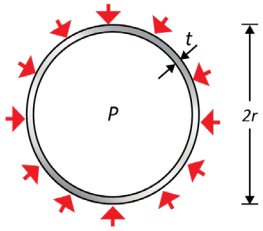
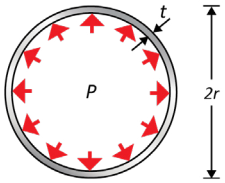
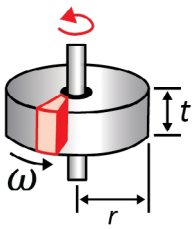
Function and Constraints†			Maximize	Minimize
Panel in compression		Length, width fixed; thickness free	$\sigma_c^{1/2}/C_m\rho$	$C_m\rho/\sigma_c^{1/2}$
		Length, width, thickness free; buckling strength fixed	$\sigma_y^{1/2}/C_m\rho$	$C_m\rho/\sigma_y^{1/2}$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$\sigma_f^{1/3}/C_m\rho$	$C_m\rho/\sigma_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$\sigma_f^{1/2}/C_m\rho$	$C_m\rho/\sigma_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/C_m\rho$	$C_m\rho/\sigma_y$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$\sigma_c/C_m\rho$	$\rho/C_m\sigma_c$
		Radius fixed; wall-thickness free; buoyancy limited	$\sigma_y^{2/3}/C_m\rho$	$C_m\rho/\sigma_y^{2/3}$
Sphere with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/C_m\rho$	$C_m\rho/\sigma_y$
Flywheel/ rotating disk		Radius fixed; thickness free; angular velocity limited	$C_m\rho$	$1/C_m\rho$
		Thickness fixed; angular velocity, radius free	$\sigma_y/C_m\rho$	$C_m\rho/\sigma_y$

† For design for infinite fatigue life, replace σ_y by the fatigue strength (endurance limit) σ_E.

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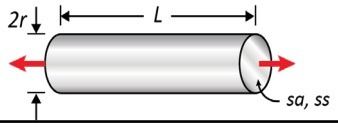
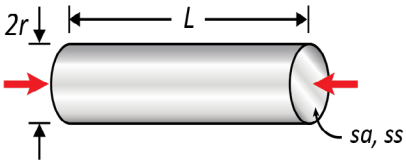
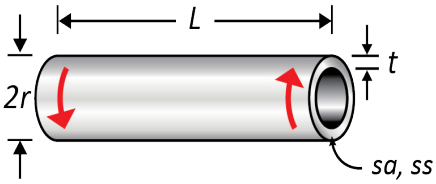
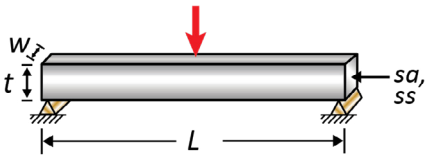
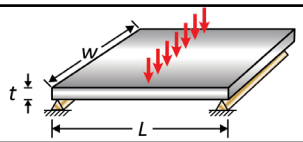
Strength-limited design at minimum energy

Function and Constraints†			Maximize	Minimize
Tie in Tension		Length fixed; section area free	$\sigma_y/H_m\rho$	$H_m\rho/\sigma_y$
Column in compression		Length, section shape fixed; section area free	$\sigma_c/H_m\rho$	$H_m\rho/\sigma_c$
		Length fixed; section area and section shape free	$(\phi^{1/2}\sigma_y)/H_m\rho$	$H_m\rho/(\phi^{1/2}\sigma_y)$
		Length, section shape fixed; section area free; buckling stiffness limited	$(\phi^{1/2}\sigma_y)^{2/3}/H_m\rho$	$H_m\rho/(\phi^{1/2}\sigma_y)^{2/3}$
Shaft in torsion		Length, section shape fixed; section area free	$\sigma_y^{2/3}/H_m\rho$	$H_m\rho/\sigma_y^{2/3}$
		Length, wall-thickness fixed; outer radius free	$\sigma_y^{1/2}/H_m\rho$	$H_m\rho/\sigma_y^{1/2}$
		Length, outer radius fixed; wall-thickness free	$\sigma_y/H_m\rho$	$H_m\rho/\sigma_y$
Beam in bending		Length, shape fixed; section area free	$\sigma_f^{2/3}/H_m\rho$	$H_m\rho/\sigma_f^{2/3}$
		Length fixed; section area and section shape free	$\left(\phi^{1/2}\sigma_f^{2/3}\right)/H_m\rho$	$H_m\rho/\left(\phi^{1/2}\sigma_f^{2/3}\right)$
		Length, thickness, section shape fixed; width free	$\sigma_f/H_m\rho$	$H_m\rho/\sigma_f$
		Length, thickness fixed; width, section shape free	$(\phi^{1/2}\sigma_f)/H_m\rho$	$H_m\rho/(\phi^{1/2}\sigma_f)$
		Length, width, section shape fixed; thickness free	$\sigma_f^{1/2}/H_m\rho$	$H_m\rho/\sigma_f^{1/2}$
		Length, width, section shape fixed; thickness free	$(\phi\sigma_f)^{1/2}/H_m\rho$	$H_m\rho/(\phi\sigma_f)^{1/2}$
Panel in bending		Length fixed, width fixed; thickness free	$\sigma_f^{1/2}/H_m\rho$	$H_m\rho/\sigma_f^{1/2}$

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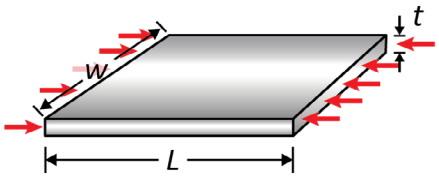
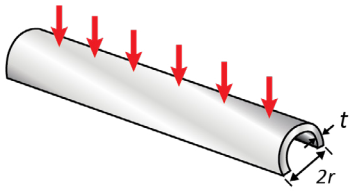
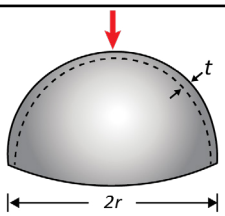
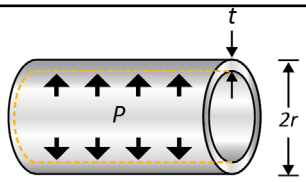
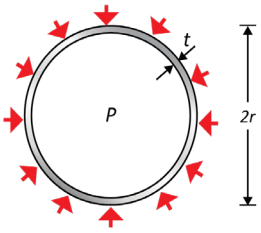
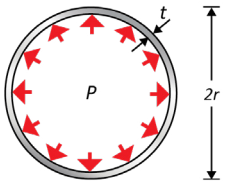
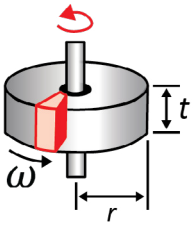
Function and Constraints†			Maximize	Minimize
Panel in compression		Length, width fixed; thickness free	$\sigma_c^{1/2}/H_m\rho$	$H_m\rho/\sigma_c^{1/2}$
		Length, width, thickness free; buckling strength fixed	$\sigma_y^{1/2}/H_m\rho$	$H_m\rho/\sigma_y^{1/2}$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$\sigma_f^{1/3}/H_m\rho$	$H_m\rho/\sigma_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$\sigma_f^{1/2}/H_m\rho$	$H_m\rho/\sigma_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/H_m\rho$	$H_m\rho/\sigma_y$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$\sigma_c/H_m\rho$	$\rho/H_m\sigma_c$
		Radius fixed; wall-thickness free; buoyancy limited	$\sigma_y^{2/3}/H_m\rho$	$H_m\rho/\sigma_y^{2/3}$
Sphere with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/H_m\rho$	$H_m\rho/\sigma_y$
Flywheel/ rotating disk		Radius fixed; thickness free; angular velocity limited	$H_m\rho$	$1/H_m\rho$
		Thickness fixed; angular velocity, radius free	$\sigma_y/H_m\rho$	$H_m\rho/\sigma_y$

† For design for infinite fatigue life, replace σ_y by the fatigue strength (endurance limit) σ_E.

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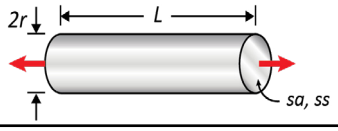
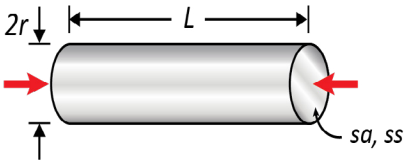
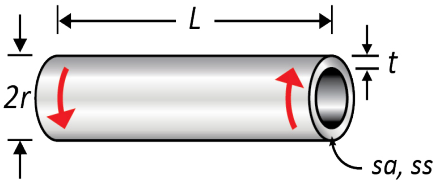
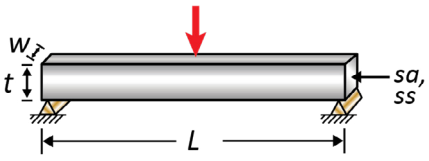
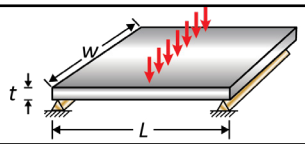
Strength-limited design at minimum environmental impact

Function and Constraints†			Maximize	Minimize
Tie in Tension		Length fixed; section area free	$\sigma_y/CO_2\rho$	$CO_2\rho/\sigma_y$
Column in compression		Length, section shape fixed; section area free	$\sigma_c/CO_2\rho$	$CO_2\rho/\sigma_c$
		Length fixed; section area and section shape free	$(\phi^{1/2}\sigma_y)/CO_2\rho$	$CO_2\rho/(\phi^{1/2}\sigma_y)$
		Length, section shape fixed; section area free; buckling stiffness limited	$(\phi^{1/2}\sigma_y)^{2/3}/CO_2\rho$	$CO_2\rho/(\phi^{1/2}\sigma_y)^{2/3}$
Shaft in torsion		Length, section shape fixed; section area free	$\sigma_y^{2/3}/CO_2\rho$	$CO_2\rho/\sigma_y^{2/3}$
		Length, wall-thickness fixed; outer radius free	$\sigma_y^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_y^{1/2}$
		Length, outer radius fixed; wall-thickness free	$\sigma_y/CO_2\rho$	$CO_2\rho/\sigma_y$
Beam in bending		Length, shape fixed; section area free	$\sigma_f^{2/3}/CO_2\rho$	$CO_2\rho/\sigma_f^{2/3}$
		Length fixed; section area and section shape free	$(\phi^{1/2}\sigma_f^{2/3})/CO_2\rho$	$CO_2\rho/(\phi^{1/2}\sigma_f^{2/3})$
		Length, thickness, section shape fixed; width free	$\sigma_f/CO_2\rho$	$CO_2\rho/\sigma_f$
		Length, thickness fixed; width, section shape free	$(\phi^{1/2}\sigma_f)/CO_2\rho$	$CO_2\rho/(\phi^{1/2}\sigma_f)$
		Length, width, section shape fixed; thickness free	$\sigma_f^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_f^{1/2}$
		Length, width, section shape fixed; thickness free	$(\phi\sigma_f)^{1/2}/CO_2\rho$	$CO_2\rho/(\phi\sigma_f)^{1/2}$
Panel in bending		Length fixed, width fixed; thickness free	$\sigma_f^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_f^{1/2}$

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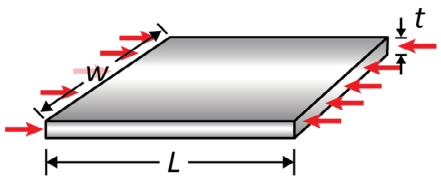
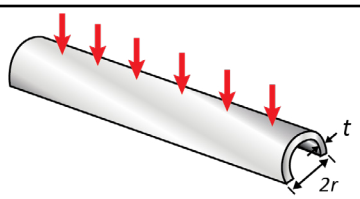
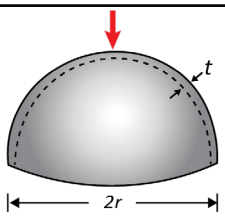
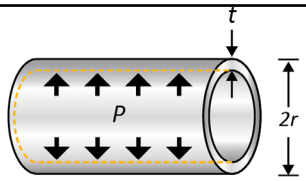
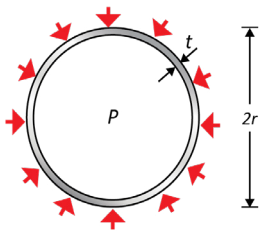
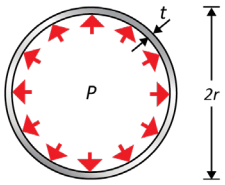
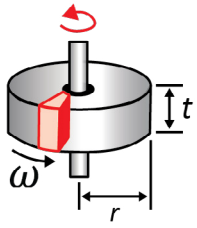
Function and Constraints†			Maximize	Minimize
Panel in compression		Length, width fixed; thickness free	$\sigma_c^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_c^{1/2}$
		Length, width, thickness free; buckling strength fixed	$\sigma_y^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_y^{1/2}$
Single-curvature shell under linear load		Radius fixed; wall-thickness free	$\sigma_f^{1/3}/CO_2\rho$	$CO_2\rho/\sigma_f^{1/3}$
Dome under central load		Radius fixed; wall-thickness free	$\sigma_f^{1/2}/CO_2\rho$	$CO_2\rho/\sigma_f^{1/2}$
Cylinder with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/CO_2\rho$	$CO_2\rho/\sigma_y$
Sphere with external pressure		Radius fixed; wall-thickness free; buckling stiffness limited	$\sigma_c/CO_2\rho$	$CO_2\rho/\sigma_c$
		Radius fixed; wall-thickness free; buoyancy limited	$\sigma_f^{2/3}/CO_2\rho$	$CO_2\rho/\sigma_f^{2/3}$
Sphere with internal pressure		Radius fixed; wall-thickness free	$\sigma_y/CO_2\rho$	$CO_2\rho/\sigma_y$
Flywheel/ rotating disk		Radius fixed; thickness free; angular velocity limited	$CO_2\rho$	$1/CO_2\rho$
		Thickness fixed; angular velocity, radius free	$\sigma_y/CO_2\rho$	$CO_2\rho/\sigma_y$

† For design for infinite fatigue life, replace σ_y by the fatigue strength (endurance limit) σ_E.

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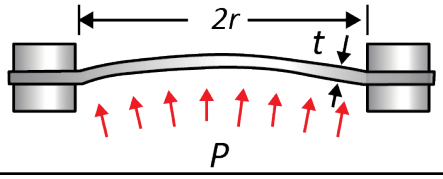
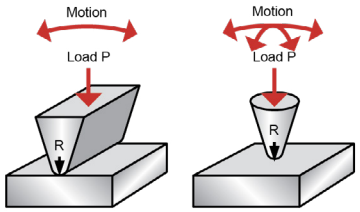
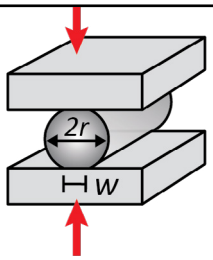
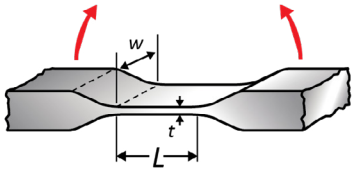
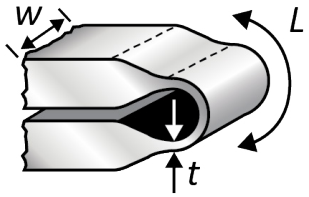
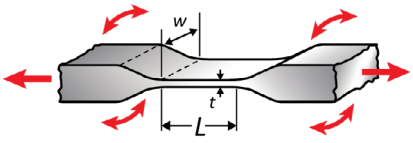
Strength-limited design for maximum performance springs, hinges, etc.

Function and Constraints†,¥			Maximize	Minimize
Diaphragm with pressure difference		Maximum deflection under specified pressure or force	$\sigma_y^{3/2}/E$	$E/\sigma_y^{3/2}$
Knife edge/ pivot		Minimum contact area, maximum bearing load	σ_y^3/E^2 and ***H***	E^2/σ_y^3 and 1/***H***
Static seal		Maximum conformability; limit on contact pressure	σ_y/E and 1/***E***	E/σ_y and ***E***
Elastic hinge with small deformation		Optimize flexibility; thickness fixed; length, width free	σ_y/E_f	E_f/σ_y
Elastic hinge with large deformation		Optimize flexibility; thickness fixed; length, width free	σ_y^3/E_f^2	E_f^2/σ_y^3
Elastic hinge with axial load		Optimize flexibility; thickness fixed; length, width free	σ_y^2/E_f	E_f/σ_y^2

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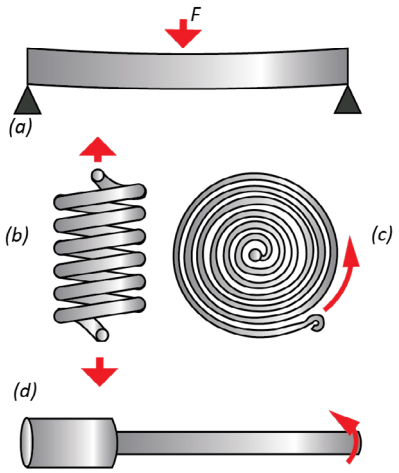
Function and Constraints†,¥			Maximize	Minimize
Spring		Optimize volume; maximum stored elastic energy per unit	σ_y^2/E	E/σ_y^2
		Optimize mass; all dimensions free; maximum stored elastic energy per unit mass	$\sigma_y^2/E\rho$	$E\rho/\sigma_y^2$

† For design for infinite fatigue life, replace σ_y by the fatigue strength (endurance limit) σ_E.
¥ To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C_m\rho$, where C_m is the material cost per unit mass
To minimize embodied energy or CO_2 footprint, use the above criteria for minimum mass, replacing ρ by $H_m\rho$ or $CO_2\rho$, where H_m is the embodied energy content per unit mass and CO_2 is the CO_2 footprint per unit mass
References[1,2,3]

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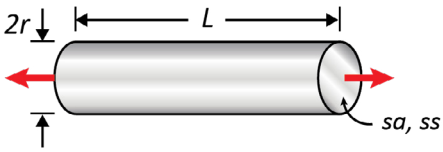
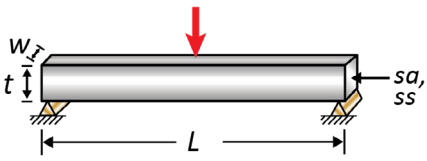
Vibration-limited design

Function and Constraints			Maximize	Minimize
Tie in Tension		Optimize for resonant frequency; length fixed; section area and section shape free	E/ρ	ρ/E
		Optimize for vibration amplitude; length fixed; section area and section shape free	$\eta E/\rho$	$\rho/\eta E$
Beam in bending		Optimize for resonant frequency; length, section shape fixed; section area free	$E_f^{1/2}/\rho$	$\rho/E_f^{1/2}$
		Optimize for resonant frequency; length fixed; section area, section shape free	$(\phi E_f)^{1/2}/\rho$	$\rho/(\phi E_f)^{1/2}$
		Optimize for resonant frequency; length, thickness, section shape fixed; width free	E_f/ρ	ρ/E_f
		Optimize for resonant frequency; length, thickness, fixed; width, section shape free	$\phi E_f/\rho$	$\phi E_f/\rho$
		Optimize for resonant frequency; length, width, section shape fixed; thickness free	$E_f^{1/3}/\rho$	$\rho/E_f^{1/3}$
		Optimize for resonant frequency; length, width fixed; thickness, section shape free	$(\phi E_f)^{1/3}/\rho$	$\rho/(\phi E_f)^{1/3}$

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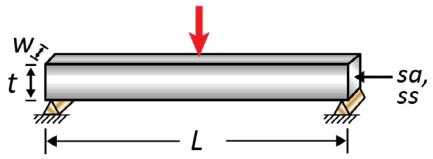
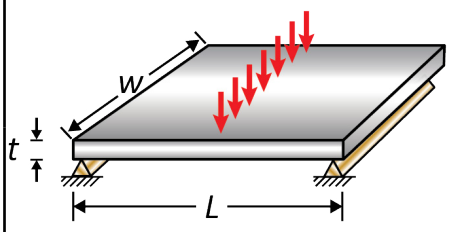
Function and Constraints			Maximize	Minimize
Beam in bending		Optimize for vibration amplitude; length, section shape fixed; section area free	$\eta E_f^{1/2}/\rho$	$\rho/\eta E_f^{1/2}$
		Optimize for vibration amplitude; length fixed; section area, section shape free	$\eta(\phi E_f)^{1/2}/\rho$	$\rho/\eta(\phi E_f)^{1/2}$
		Optimize for vibration amplitude; length, thickness, section shape fixed; width free	$\eta E_f/\rho$	$\rho/\eta E_f$
		Optimize for vibration amplitude; length, thickness fixed; width, section shape free	$\eta\phi E_f/\rho$	$\rho/\eta\phi E_f$
		Optimize for vibration amplitude; length, width, section shape fixed; thickness free	$\eta E_f^{1/3}/\rho$	$\rho/\eta E_f^{1/3}$
		Optimize for vibration amplitude; length, width fixed; thickness, section shape free	$\eta(\phi E_f)^{1/3}/\rho$	$\rho/\eta(\phi E_f)^{1/3}$
Panel in bending		Optimize for resonant frequency; length, width fixed; thickness free	$\eta E_f/\rho$	$\rho/\eta E_f$
		Optimize for vibration amplitude; length, width fixed; thickness free	$\eta E_f^{1/3}/\rho$	$\rho/\eta E_f^{1/3}$

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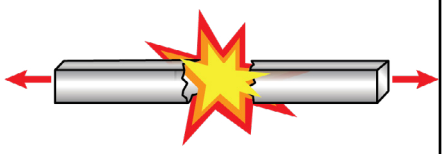
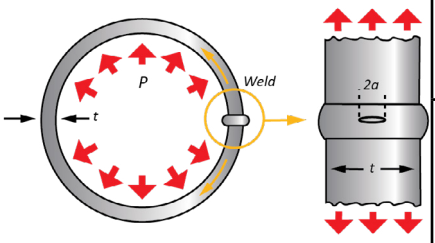
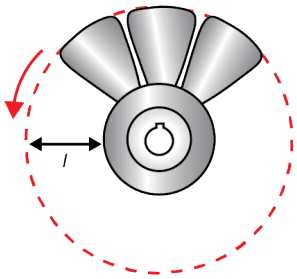
Damage-tolerant design

Function and Constraints*,¥			Maximize	Minimize
Damage tolerance (for ties, columns, shafts, beams, panels, springs, etc.)		Maximize flaw tolerance and strength; load limited design	K_{1c}/ρ and σ_y/ρ	ρ/K_{1c} and ρ/σ_y
		Maximize flaw tolerance and strength; displacement limited design	$K_{1c}/E\rho$ and σ_y/ρ	$E\rho/K_{1c}$ and ρ/σ_y
		Maximize flaw tolerance and strength; energy limited design	K_{1c}^2/E and σ_y/ρ	E/K_{1c}^2 and ρ/σ_y
Pressure Vessel		Yield-before-break limited	K_{1c}/σ_y	σ_y/K_{1c}
		Leak-before-break limited	K_{1c}^2/σ_y	σ_y/K_{1c}^2
Rotating Blade		Resistance to fast fracture; blade length, defect size fixed	K_{1c}/ρ	ρ/K_{1c}
		Resistance to centrifugal loading; blade length, defect size fixed	σ_y/ρ	ρ/σ_y

*** to minimize *volume*, replace density ρ by 1 (one).** [1,2,3]

¥ To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C_m\rho$, where C_m is the material cost per unit mass

To minimize embodied energy or CO_2 footprint, use the above criteria for minimum mass, replacing ρ by $H_m\rho$ or $CO_2\rho$, where H_m is the embodied energy content per unit mass and CO_2 is the CO_2 footprint per unit mass

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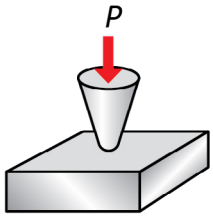
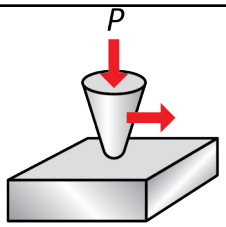
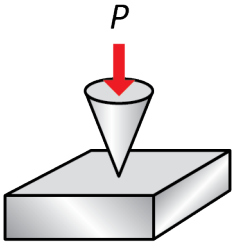
Abrasion resistant design

Function and Constraints			Maximize	Minimize
Blunt contact, static load		Optimizing resistance to yielding	H^3/E^2	E^2/H^3
		Optimizing resistance to cracking	$K_{1c}^2(1-\upsilon^2)/E$	$E/K_{1c}^2(1-\upsilon^2)$
Blunt contact, sliding load		Optimizing resistance to yielding	H^3/E^2	E^2/H^3
		Optimizing resistance to cracking	$K_{1c}^3/E^2(1-2\upsilon)^3$	$E^2(1-2\upsilon)^3/K_{1c}^3$
Sharp contact, static load		Optimizing resistance to yielding	H	$1/H$
		Optimizing resistance to cracking	K_{1c}^4/H^3	H^3/K_{1c}^4

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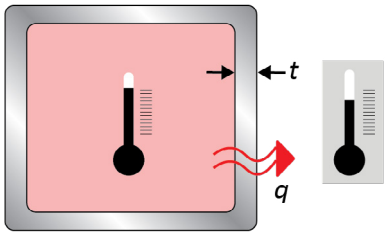
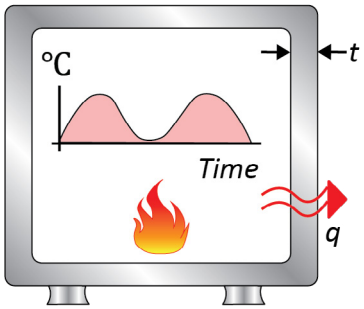
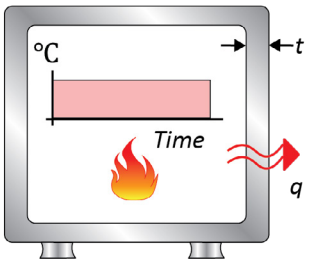
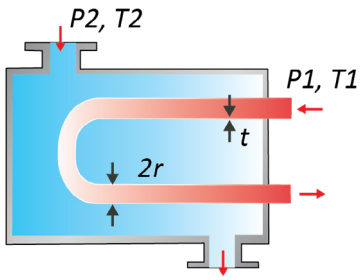
Thermal and Thermo-mechanical design

Function and Constraints			Maximize	Minimize
Thermal insulation, transitional		Optimize thermal stability; temperature difference, time fixed; thickness free	$1/a = \rho C_p/\lambda$	$a = \lambda/pC_p$
Thermal insulation, cyclic heating		Optimize energy consumption per cycle; temperature rise, cycle time fixed; wall thickness free	$(\sqrt{a})/\lambda = (\lambda\rho C_p)^{-1/2}$	$\lambda/(\sqrt{a}) = (\lambda\rho C_p)^{1/2}$
		Optimize mass; temperature rise, cycle time, wall thickness fixed	$(\sqrt{a})/\lambda = \left((\rho C_p)/\lambda\right)^{1/2}$	$\lambda/(\sqrt{a}) = \left(\lambda/(\rho C_p)\right)^{1/2}$
Thermal insulation, steady state		Optimize mass; minimum heat flux at steady state; thickness specified	ρ/λ	λ/ρ
Heat exchanger tubes		Maximum heat flux per unit area; no failure under Δp	$\lambda\sigma_y$	$1/\lambda\sigma_y$
		Optimize mass; maximum heat flux per unit mass; pressure and temperature difference, tube radius fixed; wall thickness free	$\sigma_y^2\lambda/\rho$	$\rho/\sigma_y^2\lambda$

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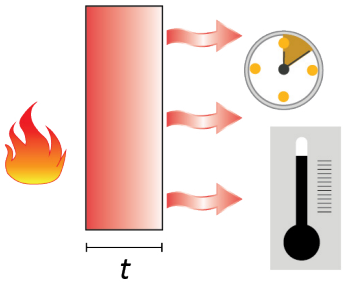
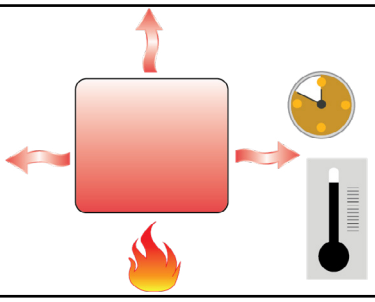
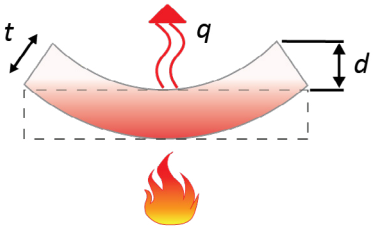
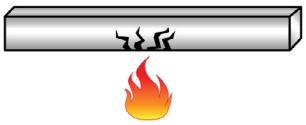
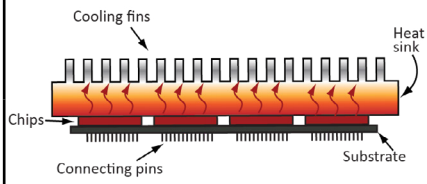
Function and Constraints			Maximize	Minimize
Short-term thermal energy storage		Optimize energy stored for given temperature rise and time	$\lambda/(\sqrt{a}) = (\lambda\rho C_p)^{1/2}$	$(\sqrt{a})/\lambda = (\lambda\rho C_p)^{-1/2}$
		Maximize energy stored for given temperature rise and time	$1/(\rho\sqrt{a}) = \left(C_p/\lambda\rho\right)^{1/2}$	$\rho\sqrt{a} = \left(\lambda\rho/C_p\right)^{1/2}$
Long-term thermal energy storage		Maximum energy stored / unit material cost (storage heaters)	C_p/C_m	C_m/C_p
Thermal stability		Minimize thermal distortion for given heat flux	λ/α	α/λ
Thermal shock resistance		Maximum change in surface temperature; no failure	$\sigma_y/E\alpha$	$E\alpha/\sigma_y$
Heat Sinks		Maximum heat flux per unit volume; expansion limited	$\lambda/\Delta\alpha$	$\Delta\alpha/\lambda$
		Maximum heat flux per unit mass; expansion limited	$\lambda/\rho\Delta\alpha$	$\rho\Delta\alpha/\lambda$

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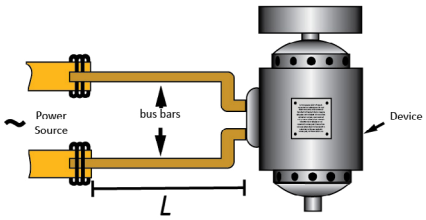
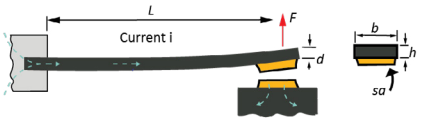
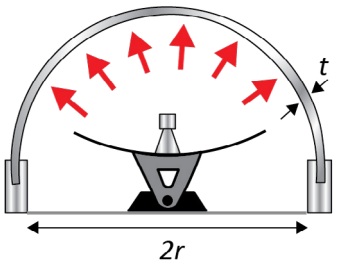
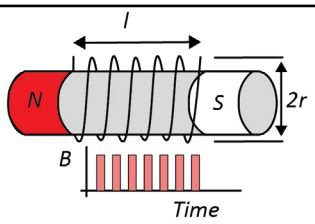
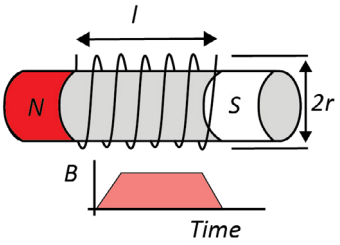
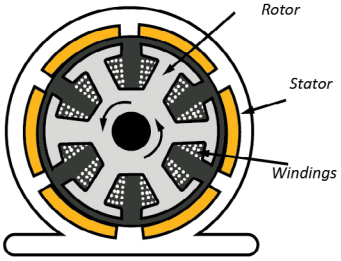
Electro-mechanical design

Function and Constraints			Maximize	Minimize
Bus-bars		Minimum life-cost; high current conductor	$1/\rho_e \rho C_m$	$\rho_e \rho C_m$
Relay arms		Minimum response time; no fatigue failure	$\sigma_e/E\rho_e$	$E\rho_e/\sigma_e$
		Minimum ohmic losses; no fatigue failure	$\sigma_e^2/E\rho_e$	$E\rho_e/\sigma_e^2$
Radome		Optimize electromagnetic absorption; pressure difference, radius fixed; thickness free	$\sigma_y/\varepsilon_t \tan[\delta]$	$\varepsilon_t \tan[\delta]/\sigma_y$
Electro-magnet windings, short pulse length		Maximum short-pulse field; no mechanical failure	σ_y	$1/\sigma_y$
Electro-magnet windings, long pulse length		Maximize field and pulse-length, limit on temperature rise	$C_p\rho/\rho_e$	$\rho_e/C_p\rho$
High speed motor windings		Maximum rotational speed; no fatigue failure	σ_e/ρ_e	ρ_e/σ_e
		Minimum ohmic losses; no fatigue failure	$1/\rho_e$	ρ_e

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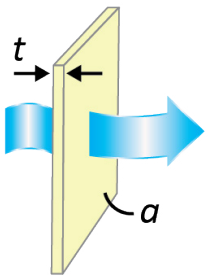
Vapor Barrier Design

Vapor barrier design at minimum mass

Function and Constraints			Maximize*,ɣ	Minimize*,ɣ
GAS/VAPOR BARRIER (not subject to significant loads)	*Gas/ Vapor* 	Permeability resistance (O2), area fixed, thickness free	$1/(P_{O_2}\rho)$	$P_{O_2}\rho$
		Permeability resistance (H2O vapor), area fixed, thickness free	$1/(VTR * \rho)$	$VTR * \rho$

* to minimize ***volume***, replace density ρ by 1 (one). [1,2,3]

ɣ To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C_m\rho$, where C_m is the material cost per unit mass

To minimize embodied energy or CO_2 footprint, use the above criteria for minimum mass, replacing ρ by $H_m\rho$ or $CO_2\rho$, where H_m is the embodied energy content per unit mass and CO_2 is the CO_2 footprint per unit mass

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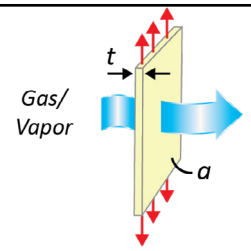
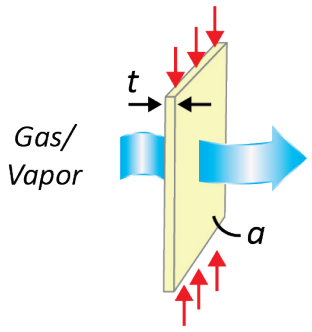
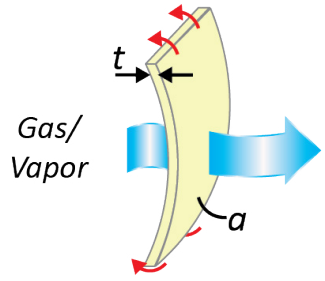
Vapor barrier design at minimum permeability (O_2)

Function and Constraints			Maximize⁺	Minimize⁺
GAS/VAPOR BARRIER (loaded in tension)		Stiffness limited, area fixed, thickness free	E/P_{O_2}	P_{O_2}/E
		Strength limited, area fixed, thickness free	σ_y/P_{O_2}	P_{O_2}/σ_y
GAS/VAPOR BARRIER (loaded in compression)		Stiffness limited, area fixed, thickness free	E/P_{O_2}	P_{O_2}/E
		Strength limited, area fixed, thickness free	σ_c/P_{O_2}	P_{O_2}/σ_c
		Buckling stiffness limited, area fixed, thickness free	$E^{1/3}/P_{O_2}$	$P_{O_2}/E^{1/3}$
		Buckling strength limited, area fixed, thickness free	$\left(\sigma_y^{1/2}\right)/P_{O_2}$	$P_{O_2}/\left(\sigma_y^{1/2}\right)$
GAS/VAPOR BARRIER (loaded in bending)		Stiffness limited, area fixed, thickness free	$E^{1/3}/P_{O_2}$	$P_{O_2}/E^{1/3}$
		Strength limited, area fixed, thickness free	$\left(\sigma_y^{1/2}\right)/P_{O_2}$	$P_{O_2}/\left(\sigma_y^{1/2}\right)$
		Elastic flexibility limited, area fixed, thickness free	$\sigma_y/(P_{O_2} * E)$	$(P_{O_2} * E)/\sigma_y$

⁺ To minimize permeability (H_2O vapor), use the above criteria for minimum permeability (O_2), replacing Oxygen permeability P_{O2} by VTR, where VTR is the water vapor transmission rate

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Symbols used in performance indices for materials

Category	Property	Symbol	Units (Metric)	Units (US Customary)
General	Density	ρ	kg/m^3	lb/in^3
	Price	C_m	currency/kg	currency/lb.
	Shape Factor	ϕ	*dimensionless*	*dimensionless*
Mechanical	Young's modulus	E	GPa	10^6 psi
	Shear modulus	G	GPa	10^6 psi
	Bulk modulus	K	GPa	10^6 psi
	Flexural modulus	E_f	GPa	10^6 psi
	Poisson's ratio	v	*dimensionless*	*dimensionless*
	Failure strength (Yield, fracture)	σ_y	MPa	ksi
	Fatigue strength	σ_e	MPa	ksi
	Compression strength	σ_c	MPa	ksi
	Flexural strength (modulus of rupture)	σ_f	MPa	ksi
	Hardness	H	Vickers	Vickers
	Fracture toughness	K_{1c}	$MPa.m^{1/2}$	$ksi.in^{1/2}$
	Loss coefficient (damping capacity)	η	*dimensionless*	*dimensionless*
Thermal	Thermal conductivity	λ	W/m.K	$BTU.ft/h.ft^2$
	Thermal diffusivity	a	m^2/s	ft^2/s
	Specific heat	C_p	J/kg.K	BTU/lb.F
	Thermal expansion coefficient	α	K^{-1}	$°F^{-1}$
	Difference in thermal conductivity	$\Delta\alpha$	K^{-1}	$°F^{-1}$

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Category	Property	Symbol	Units (Metric)	Units (US Customary)
Electrical	Electrical resistivity	ρ_e	μΩ.cm	μΩ.cm
	Dielectric constant (relative permittivity)	ε_r	*dimensionless*	*dimensionless*
	Dissipation factor (dielectric loss tangent)	tanδ	*dimensionless*	*dimensionless*
Eco-properties	Energy required per unit mass to produce material (embodied energy)	H_m	MJ/kg	kcal/lb
	CO_2 footprint (CO_2 mass produced per unit mass of material produced)	CO_2	kg/kg	lb/lb
Diffusion	Oxygen permeability	P_{O2}	$cm^3.mm/(m^2.day.atm)$	$cm^3.mm/(m^2.day.atm)$
	Water vapor transmission rate	*VTR*	$g.mm/(m^2.day)$	$g.mm/(m^2.day)$

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