

Suggested Answers Exercise set 1

General Comment: These are suggested example answers to the exercises. There are other ways to think about and tackle the different problems and there is always space for discussion on how different aspects are weighed or sorted.

Suggested Answers 1.1: An Alternative to Teflon in Non-Stick Cookware

Providing references or calculations for your specifications is very important. Numerical estimations/quantifications are imperative for the specifications.

- (i) The needs:
 - a. Essential needs:
 - i. Has to be “non-stick”
 - ii. Has to be resistant to high temperatures
 - iii. Has to be non-flammable
 - iv. Has to adhere well to lower metal layers of the pan
 - v. Has to be non-toxic (also if damaged)
 - vi. Has to conduct heat well
 - b. Desirable needs:
 - i. Easy to manufacture
 - ii. Inexpensive
 - iii. Hard/resistant to scratching
 - iv. Durable
 - v. Odorless (also when heated)
 - vi. Compatible with all stove-tops (gas, electrical, induction)
 - c. Useful needs:
 - i. Easy to clean/dishwasher safe
 - ii. Recyclable
 - iii. Lightweight
 - iv. Esthetically pleasing
 - v. Produced from environmentally friendly chemicals/materials

(ii) The specifications:

i. Has to be “non-stick”

The first essential need for our non-stick cookware is that it is non-stick, meaning that any kind of food/aliment prepared in it does not adhere strongly to the surface. It must therefore be inert to react with other molecules to hinder bond formation with the surface.^[1] A value to describe the possibility and rate of reactions of adhesion to occur on the surface is the surface energy.^[2] The coating material should have a low surface energy, similar to or smaller than that of Teflon, which is 18 mN/m.^[2] This surface energy should not change significantly over the temperature range from 0-250°C. The roughness of the coating surface should be as small as possible to reduce friction, which also contributes to non-stickiness. This roughness can be described by the arithmetic mean roughness R_a , which indicates the average height of peaks and valleys with respect to a central line a specific evaluation length, and the total height mean roughness R_z , which provides information on the difference between the highest (peaks) and lowest (valleys) deviations.^[3] For Teflon coatings, these values are typically 1.7 μm and 22.7 μm , respectively.^[3] The coating material should have a low friction coefficient so that food does not stick but rather slides over the surface. Teflon has a very low friction coefficient of 0.05 to 0.2.^[4,5] The aim for the new material should therefore be to have a friction coefficient that is similarly small. One last aspect to look at is the hydrophobicity of the coating. This can be measured by water contact angle measurements, where for a contact angle $\theta < 90^\circ$ the surface is considered hydrophilic, for $\theta > 90^\circ$ the surface is considered hydrophobic, and for $\theta > 150^\circ$ the surface is considered superhydrophobic.^[6] The contact angle of water on Teflon coatings is higher than 120° ,^[7] so the new coating material should show a water contact angle that is similar to or higher than this.

For testing the food stickiness properties of coatings, two qualitative standard tests are used in industry: The egg test (BS 7069:1988) and the milk test (AFNOR NF D 21-511).^[8] In the egg test, a medium egg is cooked for 8-9 minutes at 150-170°C in the middle of a pan without oil.^[9] Then, the ease of detachment of the cooked egg from the pan is measured using a spatula. For the milk test milk is put onto the whole coating at heated with a 2-kW stove until the milk is carbonized and there is emission of smoke. After cooling the pan with water, the ease of cleaning is measured.^[9] Since both tests are used as standard characterization tests in industry, the new coating should perform similarly or better than Teflon to be considered a good alternative.

ii. Has to be resistant to high temperatures

The coating will of course be subjected to high temperatures needed for cooking food. It therefore of course has to be resistant to these cooking temperatures. Typical temperatures that are being reached depend on what is being cooked and how. They reach from boiling water at 100 °C, over pan-frying meat at 200-245 °C, up to 290 °C when broiling.^[10] However, if a pan is heated for a while being empty the temperature can reach up to almost 350 °C.^[10] Teflon can deteriorate at temperatures above 260 °C.^[11] Since we are looking for an alternative that is more safe, especially at higher

tempeatures, the new coating should withstand at least the 300 °C that can be reached during normal cooking conditions including broiling.

iii. Has to be non-flammable

For a pan it is crucial that the coating material is non-flammable, since it is possible for it to come directly in contact with fire, e.g. when using a gas stove. A standard industry test widely used for testing the flammability characteristics of materials, such as plastics and coatings, is the UL 94.^[12] A material used for a pan material would need to achieve the rating V-0, which means that any flame extinguishes within 10 seconds without any dripping of material.^[12,13] Another standard test that can be considered is the ISO 1182:2020 non-combustibility test.^[14]

iv. Has to adhere well to lower metal layers of the pan

One standard that could be taken into consideration for characterizing this property is the ASTM D3359-92a procedure, where an X-cut is made through the film to the substrate. Then pressure-sensitive tape is applied over the cut and subsequently removed. With this, the adhesion is assessed qualitatively on a 0 to 5 scale, with 5 corresponding to no peeling or removal of the product.^[15] One parameter that influences the adhesion of coating materials is their melting temperature. Since coatings are usually applied with the material in liquid form followed by solidification, lower melting temperatures can ensure that the substance can flow and penetrate more easily into small surface irregularities of the underlying metal layer to create a stronger binding to the metal surface.^[16] In addition to the initial adhesion, a second factor will be quite important for a long-lasting adhesion: the difference in the thermal expansion coefficient of the coating layer and the underlying metal layer. Since the pan might be heated quite quickly, or cooled down very fast after cooking, for example under running water for cleaning, it is important that these thermal swings do not cause the material to delaminate. The linear thermal expansion coefficient of stainless steels can range from $10.1\text{-}17.3 \times 10^{-6} \text{ m}/(\text{m } ^\circ\text{C})$, for aluminum it is $21\text{-}24 \times 10^{-6} \text{ m}/(\text{m } ^\circ\text{C})$, and for PTFE it goes up to $112\text{-}135 \times 10^{-6} \text{ m}/(\text{m } ^\circ\text{C})$.^[17] For the new material, we should aim to reduce the thermal expansion coefficient to be as close to the underlying metal, most likely stainless steel, to minimize potential issues arising from this.

i. Has to be non-toxic (also if damaged)

The coating has to be non-toxic to humans when being used. Additionally, there should be no possible transfer of toxic or unhealthy materials to food prepared in the pan. The coating should therefore not contain any substances classified as toxic, poisonous, carcinogenic, or dangerous. If the production stage involves any hazardous materials or chemicals these also need to be either completely removed by washing steps or neutralized to be safe for the user. One big issue for Teflon, as discussed in the exercise, is that Teflon coatings, especially those made using specific chemicals, can emit toxic fumes at high temperatures ($\sim 260 \text{ } ^\circ\text{C}$).^[18] As discussed for the essential need of high-temperature stability (ii.), the new coating has to be stable at these high temperatures without emission of any fumes. Generally, in countries that are part of the EU, any coatings that are intended to come in contact with food need to meet

specific norms and directives concerning the safety of food contact materials as stated in Regulation (EC) No 1935/2004,^[19] which includes the testing of these materials by specialized laboratories as described in Regulation (EC) No 882/2004.^[20]

ii. Has to conduct heat well

This last essential need comes with a somewhat limited necessity. In general, the coating applied on top of the pan of course needs to conduct heat from the stove and underlying layers to the food being cooked in the pan. A material is considered heat-conductive when the thermal conductivity is higher than $0.1 \text{ W m}^{-1} \text{ K}^{-1}$.^[21] How high this heat conductivity needs to be highly depends on the thickness of the coating, however, as this is another crucial parameter for heat transfer. Teflon coatings in non-stick pans are extremely thin. Because of this the coated pans still function well even though Teflon has a very low heat conductivity of just $0.25 \text{ W m}^{-1} \text{ K}^{-1}$.^[22] In comparison, the heat conductivities of aluminum, stainless steel, and cast iron are $236 \text{ W m}^{-1} \text{ K}^{-1}$, $15 \text{ W m}^{-1} \text{ K}^{-1}$, $52 \text{ W m}^{-1} \text{ K}^{-1}$, respectively.^[23] If a material is chosen for the final coating that needs to be deposited as a thicker film, the heat conductivity should be higher than that of Teflon, and close to those of cast iron, stainless steel, or aluminum, depending on the underlayers.

Suggested Answers 1.2: A specification for artificial blood

Providing references or calculations for your specifications is very important. Numerical estimations/quantifications are imperative for the specifications.

Oxygen has poor solubility in blood plasma. This is why only 2% of oxygen carried by the blood in our bodies is actually dissolved in the plasma. The other 98% percent are bound to hemoglobin.^[24] The solubility of oxygen in the blood plasma depends on the partial pressure of oxygen and is around 0.003 mL of O_2 per mmHg oxygen partial pressure and 100 mL of blood.^[25] In the lungs, where the partial pressure is high (around 100 mm Hg) this means about 0.3 mL of oxygen are dissolved in 100 mL of blood.^[25] Hemoglobin on the other hand binds about 20 mL of oxygen per 100 mL of blood in these arterial blood conditions.^[26] To carry a similar amount of oxygen, the artificial blood would therefore need to dissolve about 20 mL of oxygen per 100 mL of artificial blood.

One aspect that is even more important than the overall oxygen content of the artificial blood is however its capability to release oxygen in the tissues where it is needed. This is actually the key parameter for the artificial blood to function. What this means is that the solubility of oxygen has to show a similar dependence on the partial pressure of oxygen as is the case for real blood. This means that the product has to catch oxygen in the lungs, where the partial pressure of O_2 is high (around 100 mmHg), and release it where the oxygen partial pressure is low, in the tissue (around 40 mmHg).^[27] The graph in Figure 1 shows the concentration of O_2 vs. the partial pressure of O_2 for human blood.

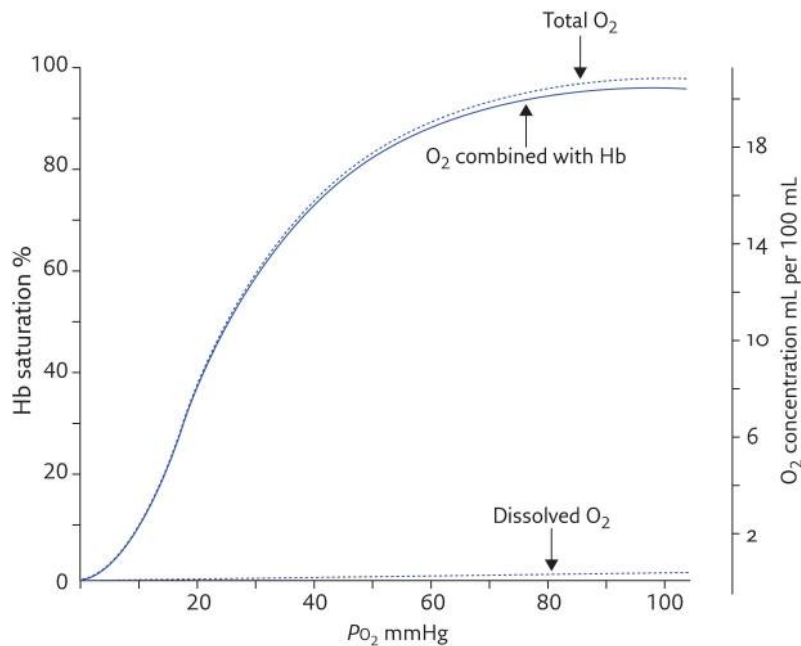


Figure 1. Oxygen concentration in blood vs. oxygen partial pressure.^[28]

As we can see on this graph, human blood can release around 5 mL O₂ per 100 mL blood into the tissues. Our product should deliver the same amount of oxygen. Obtaining a curve with a similar shape is therefore one of the primary needs for the product. This would ensure sufficient oxygen delivery and make the design fulfill the requirements concerning O₂ transport.

Suggested Answers 1.3: Ocean Plastics Pollution

1.	Filter the ocean using fishing nets.
2.	Impose taxes on manufacturers that don't dispose of plastic correctly.
3.	Stop using plastic bags for trash.
4.	Use drones with built-in vacuums to suck up plastic.
5.	Ban plastic packaging in shops.
6.	Start teaching children in kindergarten about the dangers of plastic to increase global awareness.
7.	Reward people who dispose of plastic properly
8.	Reward companies that promote a plastic-free environment
9.	Ban single-use containers
10.	Increase the budget for research laboratories into alternatives to plastic
11.	Develop plastics that can be eaten by humans and aquatic life
12.	Develop biodegradable plastics
13.	Develop bacteria that eat plastics
14.	Ban all use of plastic
15.	Replace all plastic products by reusable ones made of robust and recyclable materials
16.	Tax companies and people according to their use of plastics
17.	Reward people/companies that reduce their use of plastic
18.	Develop a chemical that transforms plastic into a non-toxic soluble material

19.	Ban the practice of shipping a country's garbage to another country
20.	Increase taxes on plastics to make them less attractive
21.	Develop robust recycling processes
22.	Burn plastics at home
23.	Limit the production of plastics
24.	Sanction countries that do not recycle enough plastic
25.	Increase the number of trash cans
26.	Increase funding to ocean clean up initiatives
27.	Put nets on rivers to stop plastic before it reaches the oceans
28.	Develop filters to be put on the bottom of the ocean that filter out microplastics from water
29.	Ban single use plastics
30.	Send plastic into space
31.	Genetically modify a fish species so that they can consume the plastic
32.	Develop ocean clean up technologies, such as large boats dragging plastic barriers to gather the waste
33.	Develop water- soluble plastics
34.	Develop diving robots that collect plastic from the ocean
35.	Add a deposit to plastic packaging to increase recycling
36.	Make prisoners collect waste
37.	Recycle plastic waste into fuel for cars
38.	Reward people for collecting plastics in nature
39.	Improve waste sorting and create lower-value products from plastic wastes, such as insulation and construction materials
40.	Design plastic products using a single type of polymer to simplify recycling

- [1] Brunning, A. Chemistry History: Teflon & Non-Stick Pans, Compound Interest <https://www.compoundchem.com/2016/02/04/teflon/>.
- [2] A. Author and B. Author, "Adhesion of food on surfaces: Theory, measurements, and main trends to reduce it prior to industrial drying."
- [3] G. Guerrero-Vacas, F. Comino, and O. Rodríguez-Alabanda, "Evaluation of the effectiveness and durability of commercial non-stick coatings," *Journal of Food Engineering*, vol. 370, p. 111959, June 2024.
- [4] Eriks Propriétés du PTFE <https://static.eriksgroup.com/fr/plastics/datasheets/fluores/ptfe/eriks%20-%20proprietes%20du%20ptfe.pdf>.
- [5] "Overview of materials for Polytetrafluoroethylene (PTFE), Extruded."
- [6] *J. Phys. Chem. Lett.* 2014, 5, 686–688.
- [7] *Langmuir* 2022, 38, 1631–1637.
- [8] FIT FOR USE - Industrielack AG <https://www.ilag.ch/en/fit-for-use.html>.
- [9] Rossi, S.; Valdrè, F.; Calovi, M. Validation of adhesion characterization methods for antistick coatings applied in cooking systems <https://doi.org/10.1007/s11998-022-00611-3> (accessed 09/12/2024).
- [10] Safety of Teflon™ Nonstick Coatings. url: <https://www.teflon.com/en/consumers/tefloncoatings-cookware-bakeware/safety#:~:text=Do%20not%20use%20nonstick%20cookware,some%20of%20its%20nonstick%20properties..> [11] <https://www.fda.gov/news-events/press-announcements/fdaadvances-new-proposed-regulation-make-sure-sunscreensare-safe-and-effective#:~:text=Proposes%20to%20require%20sunscreens%20with,against%20UVA%20radiation%20also%20increases.>
- [11] Teflon - <https://www.teflon.com/fr/industries-and-solutions/solutions/chemicalthermalresistance#:~:text=Avec%20leur%20inertie%20chimique%20et,sur%20l'ensemble%20des%20applications.>

- [12] "UL94 Coating Material - Testing Method, Material Selection."
- [13] T. Zedníček, "Flammability UL94 and What It Means," Nov. 2019.
- [14] <https://www.iso.org/standard/70178.html>.
- [15] D01 Committee, "Test Methods for Measuring Adhesion by Tape Test."
- [16] P. Thomas, "The use of fluoropolymers for non-stick cooking utensils," *Surface Coatings International*, vol. 81, pp. 604–609, Dec. 1998.
- [17] https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html.
- [18] Sajid, M.; Ilyas, M. PTFE-coated non-stick cookware and toxicity concerns: a perspective <https://doi.org/10.1007/s11356-017-0095-y>.
- [19] <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32004R1935>
- [20] <https://eur-lex.europa.eu/eli/reg/2004/882/oj>.
- [21] Karaaslan, M. A.; Kadla, J. F.; Ko, F. K. 5 - Lignin-Based Aerogels ed. by Faruk, O.; Sain, M., <https://www.sciencedirect.com/science/article/pii/B9780323355650000059>.
- [22] https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.
- [23] https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html.
- [24] <https://www.britannica.com/science/human-respiratory-system/Transport-of-oxygen>.
- [25] https://www.osmosis.org/learn/Oxygen_binding_capacity_and_oxygen_content.
- [26] Murray and Nadel's Textbook of Respiratory Medicine (Sixth Edition), Volume 1, 2016, Chapter 4: Ventilation, Blood Flow, and Gas Exchange.
- [27] [https://www.ncbi.nlm.nih.gov/books/NBK538336/#:~:text=Hemoglobin%20\(Hgb%20or%20Hb\)%20is,is%20dissolved%20directly%20in%20plasma](https://www.ncbi.nlm.nih.gov/books/NBK538336/#:~:text=Hemoglobin%20(Hgb%20or%20Hb)%20is,is%20dissolved%20directly%20in%20plasma).
- [28] <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4666443/>.