Sous Vide Cooking

Which is right for you?

	Book	Web Guide	Review Article
Title	*Sous Vide for the Home Cook*	A Practical Guide to Sous Vide Cooking	Sous Vide Cooking: A Review
Intended reader	Mostly home cooks but also restaurant chefs	Science minded cooks and chefs	Scientists and health departments
Number of recipes	200+	12	0
Length	271 pages	~40 pages	16 pages
Cost	$24.95	Free	Free
Get it	Amazon.com (under “Available from these sellers.”) or see below	Below	Final (ScienceDirect) or preprint (PDF)

Sous Vide for the Home Cook

My book, *Sous Vide for the Home Cook*, came out in 2010. You can now order the second eddition from Amazon.com (under "See All Buying Options."), Amazon.co.uk (under "Available from these sellers."), Vac-Star in Germany, and the SousVide Supreme site.

My book has over 200 delicious recipes for beef, pork, lamb, game, chicken, turkey, duck, fish, shellfish, vegetables, fruits, legumes, ice cream bases, sauces, and yogurt. I first cover the basics of sous vide cooking with "learn by doing" sections; then I have a 10-page table with times and temperatures for every cut of meat or type of vegetable you're likely to come across; this is followed by over 200 detailed recipes; and finally chapters on equipment, food safety, a select bibliography, and an index.

I hope you enjoy using my book as much as I enjoyed writing it. As always, if you have any questions or comments, please feel free to email me.

A Practical Guide to Sous Vide Cooking

Version 0.4j (Version History)

If you have any questions or comments on sous vide cooking or this guide, please feel free to email me.

News:

- I joined the ChefSteps team on 1 June 2014.
- I gave a second ACS Webinar on sous vide cooking for the holidays in November 2013. Slides (PDF 3.9MB) and transcript (PDF).
- I gave an ACS Webinar on sous vide cooking in May 2013 to 541 attendees.Slides (PDF) and transcript (PDF).
- As of 9 May 2013, I'm officially *Doctor* Douglas Baldwin!

Interview with Jeff Potter in *Cooking for Geeks*; Interview with Martin Lersch for Khymos.org.

Translation into French by Addelice [PDF] (Mirror)

Translation into German by Addelice [PDF] (Mirror)

Translation into Portuguese by Gastronomy Lab [PDF] (Mirror)

Translation into Finnish by Olli Jarva [HTML] [PDF] (PDF Mirror)

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Preface

Sous vide is French for “under vacuum” and describes a method of cooking in vacuum sealed plastic pouches at precisely controlled temperatures. With the proper equipment and some basic knowledge, you can prepare consistently delicious and safe food. With more advanced knowledge, you can safely create (or modify) recipes to realize your unique vision.

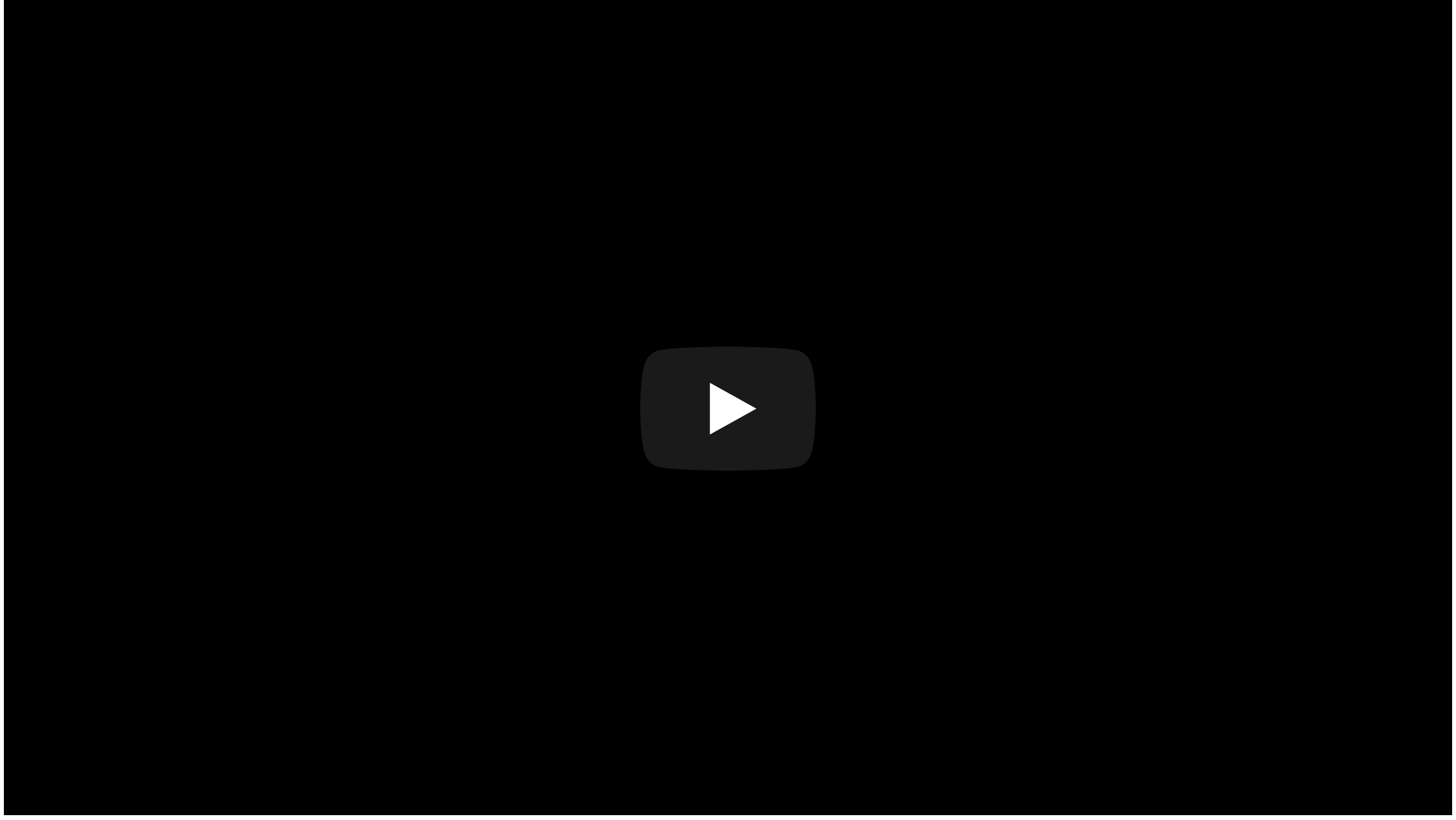
This guide attempts to distill the science of sous vide cooking to provide you with the tools you needed to safely realize your creative visions. Part I discusses the techniques and safety concerns of sous vide cooking. Some prototypical recipes are explored in Part II. The mathematics of sous vide cooking are detailed in Appendix A. Finally, Appendix B discusses the specialized equipment used in sous vide cooking.

Introduction

Sous vide is a method of cooking in vacuum sealed plastic pouches at relatively low temperatures for fairly long times. Sous vide differs from conventional cooking methods in two fundamental ways: (i) the raw food is vacuum sealed in heat-stable, food-grade plastic pouches and (ii) the food is cooked using precisely controlled heating.

Vacuum packaging prevents evaporative losses of flavor volatiles and moisture during cooking and inhibits off-flavors from oxidation (Church and Parsons, 2000). This results in especially flavorful and nutritious food (Church, 1998; Creed, 1998; García-Linares et al., 2004; Ghazala et al., 1996; Lassen et al., 2002; Schellekens, 1996; Stea et al., 2006). Vacuum sealing also reduces aerobic bacterial growth and allows for the efficient transfer of thermal energy from the water (or steam) to the food.

Precise temperature control is important when you cook fish, meat, or poultry. Suppose you want to cook a thick-cut steak medium rare. You could cook it on a grill at over 1,000°F (500°C) until the center hits 120°F (50°C) and then hope the center will come up to 130°F (55°C) after a short rest. You might sear one side of the steak in a pan, flip the steak over, put it in a 275°F (135°C) oven, and pull it out just before the center comes up to 130°F (55°C). Or you could vacuum seal the steak, drop it in a 130°F (55°C) water bath for a few hours, pull it out of your water bath just before you want to serve it, and sear the outside in either a smoking hot pan or with a blowtorch; what you'll get is a medium-rare steak with a great crust that is the same doneness at the edge as it is at the center. Moreover, you can cook the flavorful flat iron steak (very safely) in a 130°F (55°C) water bath for 12 hours and it'll be both medium-rare and as tender as filet mignon.



Part I: Technique

1. Food Safety

Non-technical Summary

You cook food to make it safe and tasty. Sous vide cooking is no different: you just have more control over both taste and safety. In sous vide cooking, you pick the temperature that equals the doneness you want and then you cook it until it's safe and has the right texture.

Raw food often has millions of microorganisms on or in it; most of these microorganisms are spoilage or beneficial bacteria and won't make you sick. But some of these microorganisms are pathogens that can make you sick if you eat too many of them. Most food pathogens are bacteria, but some are viruses, funguses, and parasites. Your yogurt, aged cheese, and cured salami can have hundreds of millions of spoilage or beneficial bacteria in every serving; but they don't make you sick because spoilage and beneficial bacteria are distinct from pathogens. Since pathogens don't spoil food, you can't see, smell, or taste them.

While there are many ways to kill food pathogens, cooking is the easiest. Every food pathogen has a temperature that it can't grow above and a temperature it can't grow below. They start to die above the temperature that they stop growing at and the higher above this temperature you go, the faster they die. Most food pathogens grow fastest a few degrees below the temperature that they start to die. Most food pathogens stop growing by 122°F (50°C), but the common food pathogen *Clostridium perfringens* can grow at up to

126.1°F (52.3°C). So in sous vide cooking, you usually cook at 130°F (54.4°C) or higher. (You could cook your food at slightly lower temperatures, but it would take you a lot longer to kill the food pathogens.)

While there are a lot of different food pathogens that can make you sick, you only need to worry about killing the toughest and most dangerous. The three food pathogens you should worry about when cooking sous vide are the *Salmonella* species, *Listeria monocytogenes*, and the pathogenic strains of *Escherichia coli*. *Listeria* is the hardest to kill but it takes fewer *Salmonella* or *E. coli* bacteria to make you sick. Since you don't know how many pathogens are in your food, most experts recommend that you cook your food to reduce: *Listeria* by at least a million to one; *Salmonella* by ten million to one; and *E. coli* by a hundred thousand to one. You can easily do this when you cook sous vide: you just keep your food in a 130°F (54.4°C) or hotter water bath until enough bacteria have been killed.

How long does it take for you to reduce, say, *Listeria* by a million to one? Your water bath temperature is very important: when cooking beef, it'll take you four times longer at 130°F (54.4°C) as it does at 140°F (60°C). What you are cooking is also important: at 140°F (60°C), it'll take you about 60% longer for chicken as it does for beef. Other things, like salt and fat content, also affect how long it takes; but these difference are small compared with temperature and species.

Since sous vide cooking in a water bath is very consistent, I've calculated the worst-case cooking times so you don't have to. My worst-case cooking times are based on the temperature, thickness, and type of the food and will give at least a million to one reduction in *Listeria*, a ten million to one reduction in *Salmonella*, and a hundred thousand to one reduction in *E. coli*:

- Table 3.1 has the pasteurization times for fish;
- Table 4.1 has the pasteurization times for poultry; and
- Table 5.1 has the pasteurization times for meat (beef, pork, and lamb).

Thick pieces of food, like a rib-roast, take much longer to cook and cool than thin pieces of food: a steak that is twice as thick takes about four times longer to cook and cool! So unless you are cooking a rib-roast for a party, you should cut your food into individual portions that can be cooled quickly and easily. It's important that your pouches of food do not crowd or overlap each other in your water bath and are completely under the water; otherwise my tables will underestimate the cooking time.

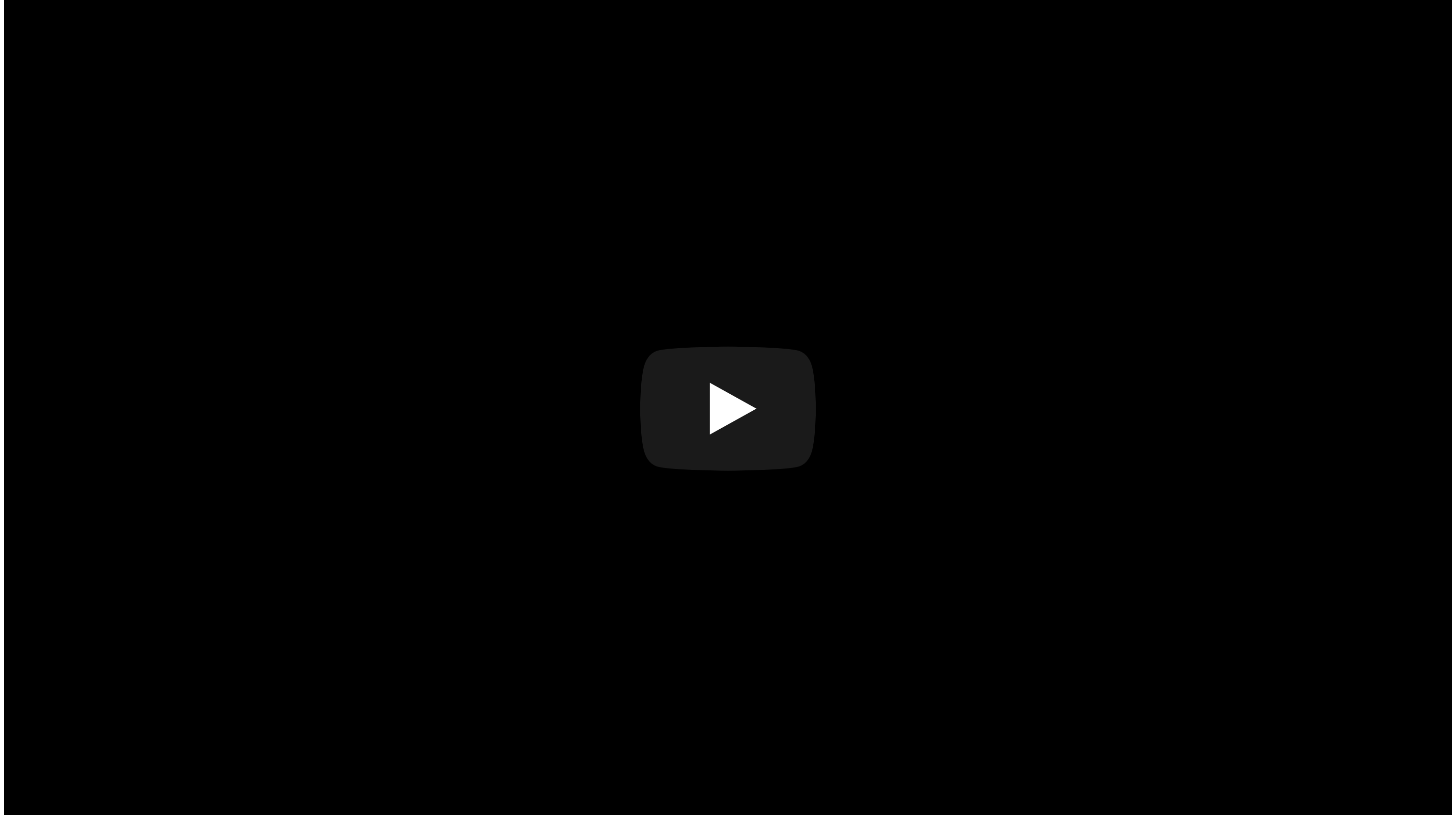
If you're not going to eat all your food immediately, then you need to know that some bacteria are able to make spores. Spores themselves will not make you sick, but they can become active bacteria that could. Cooking to kill active bacteria like *Listeria*, *Salmonella*, and *E. coli* will leave these spores unharmed. If you keep your food hot, then the spores will not become active bacteria. But when you cool your food, the spores can become active bacteria: if you cool your food too slowly or store it for too long, then these active bacteria can multiply and make you sick. To keep these spores from becoming active bacteria, you must quickly cool your food – still sealed in its pouch – in ice water that is at least half ice until it's cold all the way through. You can then store your food in your refrigerator for a few days or freeze it for up to a year. Table 1.1 has approximate cooling times in ice water based on thickness and shape.

If you want to learn more about food safety, please continue reading below; see my book *Sous Vide for the Home Cook*; the excellent free guide by Dr Snyder; the FDA's food safety website; or your local health and human services department.

Cooling Time to 41°F (5°C) in Ice Water

Thickness	*Slab-like*	*Cylinder-like*	*Sphere-like*
5 mm	5 min	3 min	3 min
10 mm	14 min	8 min	6 min
15 mm	25 min	14 min	10 min
20 mm	35 min	20 min	15 min
25 mm	50 min	30 min	20 min
30 mm	1¼ hr	40 min	30 min
35 mm	1½ hr	50 min	35 min
40 mm	1¾ hr	1 hr	45 min
45 mm	2¼ hr	1¼ hr	55 min
50 mm	2¾ hr	1½ hr	1 hr
55 mm	3¼ hr	1¾ hr	1¼ hr
60 mm	3¾ hr	2 hr	1½ hr
65 mm	4¼ hr	2¼ hr	1¾ hr
70 mm	4¾ hr	2¾ hr	2 hr
75 mm	5½ hr	3 hr	2¼ hr
80 mm	—	3½ hr	2½ hr
85 mm	—	3¾ hr	2¾ hr
90 mm	—	4¼ hr	3 hr
95 mm	—	4¾ hr	3½ hr
100 mm	—	5 hr	3¾ hr
105 mm	—	5½ hr	4 hr
110 mm	—	6 hr	4½ hr
115 mm	—	—	4¾ hr

Table 1.1: Approximate cooling time from 130–175°F (55–80°C) to 41°F (5°C) in an ice water bath that's at least half ice. (My calculations assume that the food's thermal diffusivity is $1.1\times10^{-7}\text{m}^2/\text{s}$ and the ice water bath has a surface heat transfer coefficient of 100 W/m^2-K. For more details, see Appendix A.)



Technical Background

My goal is to maximizing taste and minimizing the risk from food pathogens. While pathogenic microorganisms can be controlled with acids, salts, and some spices, sous vide cooking relies heavily on temperature control (Rybka-Rodgers, 2001).

You were probably taught that there's a "danger zone" between 40°F and 140°F (4.4°C and 60°C). These temperatures aren't quite right: it's well known that food pathogens can only multiply between 29.7°F (-1.3°C) and 126.1°F (52.3°C), while spoilage bacteria begin multiplying at 23°F (-5°C) (Snyder, 2006; Juneja et al., 1999; FDA, 2011). Moreover, contrary to popular belief, food pathogens and toxins cannot be seen, smelt, or tasted.

So why were you taught that food pathogens stop multiplying at 40°F (4.4°C) and grow all the way up to 140°F (60°C)? Because it takes days for food pathogens to grow to a dangerous level at 40°F (4.4°C) (FDA, 2011) and it takes many hours for food to be made safe at just above 126.1°F (52.3°C) – compared with only about 12 minutes (for meat) and 35 minutes (for poultry) to be made safe when the coldest part is 140°F (60°C) (FSIS, 2005; FDA, 2009, 3-401.11.B.2). Indeed, the food pathogens that can multiply down to 29.7°F (-1.3°C) – *Yersinia enterocolitica* and *Listeria monocytogenes* – can only multiply about once per day at 40°F (4.4°C) and so you can hold food below 40°F (4.4°C) for five to seven days (FDA, 2011). At 126.1°F (52.3°C), when the common food pathogen *Clostridium perfringens* stops multiplying, it takes a very long time to reduce the food pathogens we're worried about – namely the *Salmonella* species, *Listeria monocytogenes*, and the pathogenic strains of *Escherichia coli* – to a safe level; in a 130°F (54.4°C) water bath (the lowest temperature I recommend for cooking sous vide) it'll take you about 2½ hours to reduce *E. coli* to a safe level in a 1 inch (25 mm) thick hamburger patty and holding a hamburger patty at 130°F (54.4°C) for 2½ hours is inconceivable with traditional cooking methods – which is why the "danger zone" conceived for traditional cooking methods doesn't start at 130°F (54.4°C). [Note that Johnson et al. (1983) reported that *Bacillus cereus* could multiply at 131°F/55°C, but no one else has demonstrated growth at this temperature and so *Clostridium perfringens* is used instead.]

We can divide sous vide prepared foods into three categories: (i) raw or unpasteurized, (ii) pasteurized, and (iii) sterilized. Most people cook food to make it more palatable and to kill most the pathogenic microorganisms on or in it. Killing enough active, multiplying food pathogens to make your food safe is called pasteurization. Some bacteria are also able to form spores that are very resistant to heat and chemicals; heat the food to kill both the active microorganisms and the spores is called sterilization. [Sterilization is typically achieved by using a pressure cooker to heat the center of the food to 250°F (121°C) for 2.4 minutes (Snyder, 2006). To sterilize food sous vide, you'll need special retort plastic bags that can be used in a pressure cooker or an autoclave.]

Foods you've pasteurized must either be eaten immediately or rapidly chilled and refrigerated to prevent the outgrowth and multiplication of spores. Moreover, the center of the food should reach 130°F (54.4°C) within 6 hours to prevent the toxin producing pathogen *Clostridium perfringens* from multiplying to dangerous levels (Willardsen et al., 1977).

Raw or unpasteurized food must never be served to highly susceptible or immune compromised people. Even for immune competent individuals, it's important that raw and unpasteurized foods are consumed before food pathogens have had time to multiply to harmful levels. With this in mind, the US Food Code requires that such food can only be between 41°F (5°C) and 130°F (54.4°C) for less than 4 hours (FDA, 2009, 3-501.19.B).

Pasteurization is a combination of both temperature and time. Consider the common food pathogen *Salmonella* species. At 140°F (60°C), all the *Salmonella* in a piece of ground beef doesn't instantly die – it is reduced by a factor ten every 5.48 minutes (Juneja et al., 2001). This is often referred as a one decimal reduction and is written $D_{60}^{6.0}$ = 5.48 minutes, where the subscript specifies the temperature (in °C) that the D-value refers to and the superscript is the z-value (in °C). The z-value specifies how the D-value changes with temperature; increasing the temperature by the z-value decreases the time needed for a one decimal reduction by a factor ten. So, $D_{66}^{6.0}$ = 0.55 minutes and $D_{54}^{6.0}$ = 54.8 minutes. How many decimal reductions are necessary depends on how contaminated the beef is and how susceptible you are to *Salmonella* species – neither of which you're likely to know. FSIS (2005) recommends a 6.5 decimal reduction of *Salmonella* in beef, so the coldest part should be at least 140°F (60°C) for at least $6.5D_{60}^{6.0}$ = 35.6 minutes.

The rate at which the bacteria die depends on many factors, including temperature, meat species, muscle type, fat content, acidity, salt content, certain spices, and water content. The addition of acids, salts, or spices can all decrease the number of active pathogens – this is why mayonnaise (with a pH less than 4.1) does not need to be cooked. Chemical additives like sodium lactate and calcium lactate are often used in the food industry to reduce the risk of spore forming pathogens like *Clostridium* species and *Bacillus cereus* (Aran, 2001; Rybka-Rodgers, 2001).

Pathogens of Interest

Sous vide processing is used in the food industry to extend the shelf-life of food products; when pasteurized sous vide pouches are held at below 38°F (3.3°C), they remain safe and palatable for three to four weeks (Armstrong and McIlveen, 2000; Betts and Gaze, 1995; Church, 1998; Creed, 1995; González- Fandos et al., 2004, 2005; Hansen et al., 1995; Mossel and Struijk, 1991; Nyati, 2000a; Peck, 1997; Peck and Stringer, 2005; Rybka-Rodgers, 2001; Simpson et al., 1994; Vaudagna et al., 2002).

The simplest and safest method of sous vide cooking is cook-hold: the raw (or partially cooked) ingredients are vacuum sealed, pasteurized, and then held at 130°F (54.4°C) or above until served. While hot holding the food will prevent any food pathogens from growing, meat and vegetables will continue to soften and may become mushy if held for too long. How long is too long depends on both the holding temperature and what is being cooked. Most foods have an optimal holding time at a given temperature; adding or subtracting 10% to this time won't change the taste or texture noticeably; holding for up to twice this time is usually acceptable.

For cook-hold sous vide, the main pathogens of interest are the *Salmonella* species and the pathogenic strains of *Escherichia coli*. There are, of course, many other food pathogens but these two species are relatively heat resistant and require very few active bacteria (measured in colony forming units, CFU, per gram) to make you sick. Since you're unlikely to know how contaminated your food is or how many of these bacteria your (or your guests) immune system can handle, most experts recommend a 6.5 to 7 decimal reductions of all *Salmonella* species and a 5 decimal reduction of pathogenic *E. coli*.

The most popular methods of sous vide cooking are cook-chill and cook-freeze – raw (or partially cooked) ingredients are vacuum sealed, pasteurized, rapidly chilled (to avoid sporulation of *C. perfringens* (Andersson et al., 1995)), and either refrigerated or frozen until reheating for service. Typically, the pasteurized food pouches are rapidly chilled by placing them in an ice water bath for at least the time listed in Table 1.1.

For cook-chill sous vide, *Listeria monocytogenes* and the spore forming pathogenic bacteria are our pathogens of interest. That's because *Listeria* is the most heat resistant non-spore forming pathogen and can grow at refrigerator temperatures (Nyati, 2000b; Rybka-Rodgers, 2001), but appears to require more bacteria to make you sick than *Salmonella* or *E. coli*. Most experts recommend a 6 decimal reduction in *Listeria* if you don't know the contamination level of your food.

While keeping your food sealed in plastic pouches prevents recontamination after cooking, spores of *Clostridium botulinum*, *C. perfringens*, and *B. cereus* can all survive the mild heat treatment of pasteurization. Therefore, after rapid chilling, the food must either be frozen or held at

1. below 36.5°F (2.5°C) for up to 90 days,
2. below 38°F (3.3°C) for less than 31 days,
3. below 41°F (5°C) for less than 10 days, or
4. below 44.5°F (7°C) for less than 5 days

to prevent spores of non-proteolytic *C. botulinum* from outgrowing and producing deadly neurotoxin (Gould, 1999; Peck, 1997).

A few sous vide recipes use temperature and time combinations which can reduce non-proteolytic *C. botulinum* to a safe level; specifically, a 6 decimal reduction in non-proteolytic *C. botulinum* requires 520 minutes (8 hours 40 minutes) at 167°F (75°C), 75 minutes at 176°F (80°C), or 25 minutes at 185°F (85°C) (Fernández and Peck, 1999). The food may then be stored at below 39°F (4°C) indefinitely, the minimum temperature at which *B. cereus* can grow (Andersson et al., 1995). While O'Mahony et al. (2004) found that the majority of pouches after vacuum packaging had high levels of residual oxygen, this doesn't imply that the *Clostridium* species – which require the absence of oxygen to grow – aren't a problem since the interior of the food often has an absence of oxygen. Most other food pathogens are able to grow with or without oxygen.

2. Basic Technique

Sous vide typically consists of three stages: preparing for packaging, cooking and finishing.

In almost all cases, the cooking medium is either a water bath or a convection steam oven. Convection steam ovens allow large quantities of food to be prepared, but do not heat uniformly enough to use the tables in this guide. Sheard and Rodger (1995) found that none of the convection steam ovens they tested heated sous vide pouches uniformly when fully loaded. Indeed, it took the slowest heating (standardized) pouch 70%–200% longer than the fastest heating pouch to go from 68°F to 167°F (20°C to 75°C) when set to an operating temperature of 176°F (80°C). They believe this variation is a result of the relatively poor distribution of steam at temperatures below 212°F (100°C) and the ovens dependence on condensing steam as the heat transfer medium.

In contrast, circulating water baths heat very uniformly and typically have temperature swings of less than 0.1°F (0.05°C). To prevent undercooking, it is very important that the pouches are completely submerged and are not tightly arranged or overlapping (Rybka-Rodgers, 1999). At higher cooking temperatures, the pouches often balloon (with water vapor) and must be held under water with a wire rack or some other constraint.

Preparing for Packaging

Seasoning

Seasoning can be a little tricky when cooking sous vide: while many herbs and spices act as expected, others are amplified and can easily overpower a dish. Additionally, aromatics (such as carrots, onions, celery, bell peppers, etc.) will not soften or flavor the dish as they do in conventional cooking methods because the temperature is too low to soften the starches and cell walls. Indeed, most vegetables require much higher temperatures than meats and so must be cooked separately. Finally, raw garlic produces very pronounced and unpleasant results and powdered garlic (in very small quantities) should be substituted.

For long cooking times (of more than a couple hours), some people find that using extra virgin olive oil results in an off, metallic, blood taste. (Since the extra virgin oil is unheated and unrefined during production, it is reasonable that some of the oil will breakdown even at a low temperature if give enough time.) A simple solution is to use grape seed or any other processed oil for longer cooking times; extra virgin olive oil can then be used for seasoning after cooking.

Marinating, Tenderizing and Brining

Since todays meat is younger and leaner than the meat of the past, many cooks marinate, tenderize or brine the meat before vacuum packaging.

Most marinades are acidic and contain either vinegar, wine, fruit juice, buttermilk or yogurt. Of these ingredients, only wine presents any significant problems when cooking sous vide. If the alcohol is not cooked off before marinating, some of it will change phase from liquid to vapor while in the bag and cause the meat to cook unevenly. Simply cooking off the alcohol before marinating easily solves this problem.

Mechanical tenderizing with a Jaccard has become quite common. A Jaccard is a set of thin blades that poke through the meat and cut some of the internal fibers. The Jaccard does not typically leave any obvious marks on the meat and is often used in steak houses. By cutting many of the internal fibers that would typically contract with heat and squeeze out the juices, it can slightly reduce the amount of moisture lost during cooking. For instance, when cooking a chuck steak for 24 hours at 131°F (55°C) the Jaccarded steak lost 18.8% of its weight compared to 19.9% for the non-Jaccarded steak. In general, more liquid weight is lost the longer a piece of meat is cooked at a given temperature– however, this additional weight loss is balanced by the increased tenderness from collagen dissolving into gelatin.

Brining has become increasingly popular in modern cooking, especially when cooking pork and poultry. Typically the meat is placed in a 3 to 10% (30 to 100 grams per liter) salt solution for a couple of hours, then rinsed and cooked as usual. Brining has two effects: it dissolves some of the support structure of the muscle fibers so they cannot coagulate into dense aggregates and it allows the meat to absorb between 10–25% of its weight in water (which may include aromatics from herbs and spices) (Graiver et al., 2006; McGee, 2004). While the meat will still lose around 20% of its weight when cooked, the net effect will be a loss of only about 0–12% of its original weight.

Cooking

There are two schools of thought when cooking sous vide: either the temperature of the water bath is (i) just above or (ii) significantly higher than the desired final core temperature of the food. While (ii) is closer to traditional cooking methods and is used extensively in (Roca and Brugués, 2005), (i) has several significant advantages over (ii). Through out this guide, I define just above as 1°F (0.5°C) higher than the desired final core temperature of the food.

When cooking in a water bath with a temperature significantly higher than the desired final core temperature of the food, the food must be removed from the bath once it has come up to temperature to keep it from overcooking. This precludes pasteurizing in the same water bath that the food is cooked in. Since there is significant variation in the rate at which foods heat (see Appendix A), a needle temperature probe must be used to determine when the food has come up to temperature. To prevent air or water from entering the punctured bag, the temperature probe must be inserted through closed cell foam tape. Even when using closed cell foam tape (which is similar to high density foam weather stripping), air will be able to enter the plastic pouch once the temperature probe is removed.

In contrast, cooking in a water bath with a temperature just above the desired final core temperature of the food means the food can remain in the water bath (almost) indefinitely without being overcooked. Thus, food can be pasteurized in the same water bath it is cooked in. While cooking times are longer than traditional cooking methods, the meat comes up to temperature surprisingly quickly because the thermal conductivity of water is 23 times greater than that of air. Moreover, temperature probes are not necessary because maximum cooking times can be tabulated (see Appendix A and Tables 2.2 and 2.3).

Effects of Heat on Meat

Muscle meat is roughly 75% water, 20% protein and 5% fat and other substances. The protein in meat can be divided into three groups: myofibrillar (50–55%), sarcoplasmic (30–34%) and connective tissue (10–15%). The myofibrillar proteins (mostly myosin and actin) and the connective tissue proteins (mostly collagen) contract when heated, while the sarcoplasmic proteins expand when heated. These changes are usually called denaturation.

During heating, the muscle fibers shrink transversely and longitudinally, the sarcoplasmic proteins aggregate and gel, and connective tissues shrink and solubilize. The muscle fibers begin to shrink at 95–105°F (35–40°C) and shrinkage increases almost linearly with temperature up to 175°F (80°C). The aggregation and gelation of sarcoplasmic proteins begins around 105°F (40°C) and finishs around 140°F (60°C). Connective tissues start shrinking around 140°F (60°C) but contract more intensely over 150°F (65°C).

The water-holding capacity of whole muscle meat is governed by the shrinking and swelling of myofibrils. Around 80% of the water in muscle meat is held within the myofibrils between the thick (myosin) and thin (actin) filaments. Between 105°F and 140°F (40°C and 60°C), the muscle fibers shrink transversely and widen the gap between fibers. Then, above 140°F–150°F (60°C–65°C) the muscle fibers shrink longitudinally and cause substantial water loss; the extent of this contraction increases with temperature.

For more information, see either the nontechnical description in (McGee, 2004, Chap 3) or the excellent review article by Tornberg (2005).

Tender Meat

When cooking tender meats, we just need to get the center up to temperature and, if pasteurizing, hold it there from some length of time. Cooking times depend critically on the thickness of the meat: doubling the thickness of the meat increases the cooking time four fold!

	Rare	*Medium-Rare*	*Medium*
Meat	125°F (50°C)	130°F (55°C)	140°F (60°C)
Fish	108°F (42°C)	122°F (50°C)	140°F (60°C)

Table 2.1: Temperatures corresponding to rare, medium-rare and medium in meat and fish.

While there is no consensus as to what temperatures rare, medium-rare and medium correspond to, I use the temperatures in Table 2.1. In general, the tenderness of meat increases from 122°F to 150°F (50°C to 65°C) but then decreases up to 175°F (80°C) (Powell et al., 2000; Tornberg, 2005). The approximate heating times for thawed and frozen meats are given in Tables 2.2 and 2.3. For a complete discussion on how these times were computed, please see Appendix A.

Heating Time from 41°F (5°C) to 1°F (0.5°C) Less Than the Water Bath's Temperature

Thickness	*Slab-like*	*Cylinder-like*	*Sphere-like*
5 mm	5 min	5 min	4 min
10 mm	19 min	11 min	8 min
15 mm	35 min	18 min	13 min
20 mm	50 min	30 min	20 min
25 mm	1¼ hr	40 min	25 min
30 mm	1½ hr	50 min	35 min
35 mm	2 hr	1 hr	45 min
40 mm	2½ hr	1¼ hr	55 min
45 mm	3 hr	1½ hr	1¼ hr
50 mm	3½ hr	2 hr	1½ hr
55 mm	4 hr	2¼ hr	1½ hr
60 mm	4¾ hr	2½ hr	2 hr
65 mm	5½ hr	3 hr	2¼ hr
70 mm	—	3½ hr	2½ hr
75 mm	—	3¾ hr	2¾ hr
80 mm	—	4¼ hr	3 hr
85 mm	—	4¾ hr	3½ hr
90 mm	—	5¼ hr	3¾ hr
95 mm	—	6 hr	4¼ hr
100 mm	—	—	4¾ hr
105 mm	—	—	5 hr
110 mm	—	—	5½ hr
115 mm	—	—	6 hr

Table 2.2: Approximate heating times for thawed meat to 1°F (0.5°C) less than the water bath's temperature. You can decrease the time by

about 13% if you only want to heat the meat to within 2°F (1°C) of the water bath's temperature. **Do not use these times to compute pasteurization times: use the pasteurization tables below.** (My calculations assume that the water bath's temperature is between 110°F (45°C) and 175°F (80°C). I use a typical thermal diffusivity of 1.4×10^{-7} m^2/s and surface heat transfer coefficient of 95 W/m^2-K.) For thicker cuts and warmer water baths, heating time may (counter-intuitively) be *longer* than pasteurization time.

Heating Time from Frozen to 1°F (0.5°C) Less Than the Water Bath's Temperature

Thickness	*Slab-like*	*Cylinder-like*	*Sphere-like*
5 mm	7 min	7 min	6 min
10 mm	30 min	17 min	12 min
15 mm	50 min	30 min	20 min
20 mm	1¼ hr	40 min	30 min
25 mm	1¾ hr	55 min	40 min
30 mm	2¼ hr	1¼ hr	55 min
35 mm	3 hr	1½ hr	1¼ hr
40 mm	3½ hr	2 hr	1½ hr
45 mm	4½ hr	2½ hr	1¾ hr
50 mm	5¼ hr	2¾ hr	2 hr
55 mm	6¼ hr	3¼ hr	2½ hr
60 mm	7¼ hr	4 hr	2¾ hr
65 mm	8¼ hr	4½ hr	3¼ hr
70 mm	—	5 hr	3¾ hr
75 mm	—	5¾ hr	4¼ hr
80 mm	—	6½ hr	4¾ hr
85 mm	—	7¼ hr	5¼ hr
90 mm	—	8 hr	5¾ hr
95 mm	—	8¾ hr	6¼ hr
100 mm	—	—	7 hr
105 mm	—	—	7½ hr
110 mm	—	—	8¼ hr
115 mm	—	—	9 hr

Table 2.3: Approximate heating times for frozen meat to 1°F (0.5°C) less than the water bath's temperature. You can decrease the time by about 13% if you only want to heat the meat to within 2°F (1°C) of the water bath's temperature. **Do not use these times to compute pasteurization times: use the pasteurization tables below.** (My calculations assume that the water bath's temperature is between 110°F (45°C) and 175°F (80°C). I use a typical thermal diffusivity of 1.4×10^{-7} m^2/s and surface heat transfer coefficient of 95 W/m^2-K.)

If the food is not being pasteurized (as is the case with fish and rare meat), it is important that the food come up to temperature and be served within four hours. Unlike conventional cooking methods, this is easily accomplished by cutting the food into individual portion sizes before cooking–which is why cooking times over four hours are not shown for temperatures below 131°F (55°C). It is important that only immune-competent individuals consume unpasteurized food and that they understand the risks associated with eating unpasteurized food.

Tough Meat

Prolonged cooking (e.g., braising) has been used to make tough cuts of meat more palatable since ancient times. Indeed, prolonged cooking can more than double the tenderness of the meat by dissolving all the collagen into gelatin and reducing inter-fiber adhesion to essentially nothing (Davey et al., 1976). At 176°F (80°C), Davey et al. (1976) found that these effects occur within about 12–24 hours with tenderness increasing only slightly when cooked for 50 to 100 hours.

At lower temperatures (120°F/50°C to 150°F/ 65°C), Bouton and Harris (1981) found that tough cuts of beef (from animals 0–4 years old) were the most tender when cooked to between 131°F and 140°F (55°C and 60°C). Cooking the beef for 24 hours at these temperatures significantly increased its tenderness (with shear forces decreasing 26%–72% compared to 1 hour of cooking). This tenderizing is caused by weakening of connective tissue and proteolytic enzymes decreasing myofibrillar tensile strength. Indeed, collagen begins to dissolve into gelatin above 122°F to 131°F (50°C to 55°C) (Neklyudov, 2003; This, 2006). Moreover, the sarcoplasmic protein enzyme collagenase remains active below 140°F (60°C) and can significantly tenderize the meat if held for more than 6 hours (Tornberg, 2005). This is why beef chuck roast cooked in a 131°F–140°F (55°C–60°C) water bath for 24–48 hours has the texture of filet mignon.

Chilling for Later Use

In the food industry, sous vide is used to extend the shelf life of cooked foods. After pasteurizing, the food is rapidly chilled in its vacuum sealed pouch and refrigerated (or frozen) until needed. Before finishing for service, the food is then reheated in a water bath at or below the temperature it was cooked in. Typically, meat is reheated in a 131°F (55°C) water bath for the times listed in Tables 2.2 or 2.3 since the optimal serving temperature for meat is between 120°F–130°F (50°C–55°C).

The danger with cook-chill is that pasteurizing does not reduce pathogenic spores to a safe level. If the food is not chilled rapidly enough or is refrigerated for too long, then pathogenic spores can outgrow and multiply to dangerous levels. For cooling and refrigeration guidelines, see Chapter 1.

Finishing for Service

Since sous vide is essentially a very controlled and precise poach, most food cooked sous vide has the appearance of being poached. So foods like fish, shellfish, eggs, and skinless poultry can be served as is. However, steaks and pork chops are not traditionally poached and usually require searing or saucing. Searing the meat is particularly popular because the Maillard reaction (the browning) adds considerable flavor.

Maillard Reaction

The Maillard or browning reaction is a very complex reaction between amino acids and reducing sugars. After the initial reaction, an unstable intermediate structure is formed which undergoes further changes and produces hundreds of reaction by-products. See McGee (2004) for a nontechnical description or Belitz et al. (2004) for a technical description.

The flavor of cooked meat comes from the Maillard reaction and the thermal (and oxidative) degradation of lipids (fats); the species characteristics are mainly due to the fatty tissues, while the Maillard reaction in the lean tissues provides the savoury, roast and boiled flavors (Mottram, 1998). The Maillard reaction can be increased by adding a reducing sugar (glucose, fructose or lactose), increasing the pH (e.g., adding a pinch of baking soda), or increasing the temperature. Even small increases in pH, greatly increases the Maillard reaction and results in sweeter, nuttier and more roasted-meat-like aromas (Meynier and Mottram, 1995). The addition of a little glucose (e.g., corn syrup) has been shown to increase the Maillard reaction and improve the flavor profile (Meinert et al., 2009). The Maillard reaction occurs noticeably around 265°F (130°C), but produces a boiled rather than a roasted aroma; good browning and a roasted flavor can be achieved at temperatures around 300°F (150°C) with the addition of glucose (Skog, 1993). Although higher temperatures significantly increase the rate of the Maillard reaction, prolonged heating at over 350°F (175°C) can significantly increase the production of mutagens.

Mutagens formed in the Maillard reaction (heterocyclic amines) have been shown to be carcinogenic in mice, rats and non-human primates; however, while some epidemiological studies have shown a relation with cancer development, others have shown no significant relation in humans (Arvidsson et al., 1997). These mutagens depend strongly on both temperature and time: they increase almost linearly in time before leveling off (after 5–10 minutes); an increase in temperature of 45°F (25°C) (from 300°F/150°C to 350°F/175°C or 350°F/175°C to 390°F/200°C) roughly doubles the quantity of mutagens (Jägerstad et al., 1998). While adding glucose increases browning, it can decreases the production of mutagens (Skog, 1993; Skog et al., 1992). The type of fat used to sear the meat in a pan has only minor effects on the formation of mutagens, but the pan residue using butter was significantly higher in mutagens than when using vegetable oil (Johansson et al., 1995).

In order to limit overcooking of the meat's interior, very high temperatures are often used to brown meat cooked sous vide. Typically, this means either using a blowtorch or a heavy skillet with just smoking vegetable oil. Butane and propane blowtorches can burn at over 3 500°F (1 900°C) in air, and produce a particularly nice crust on beef; while many use a hardware propane blowtorch, I highly recommend using an Iwatani butane blowtorch since propane can leave an off-flavor. I prefer the lower temperature of a skillet with just smoking vegetable or nut oil (400°F/200°C to 500°F/250°C) when searing fish, poultry and pork. Since the searing time at these high temperatures is very short (5–30 seconds), mutagens formation is unlikely to be significant (Skog, 2009).

Part II: Recipes

3. Fish and Shellfish

Fish lends itself particularly well to being cooked sous vide. Since sous vide brings out the natural flavors of the fish, it is important that only very fresh fish which still smells of the sea be used. When purchasing fish, the flesh should be shiny, moist and firm to the touch; have your fishmonger package the fish with ice and store the fish on ice in your refrigerator. Just before cooking, always check for and remove any scales or pin bones (with needle-nose pliers or tweezers).

Most fin and shellfish are best cooked medium (140°F/60°C) to medium-rare (120°F/49°C). The exceptions being arctic char and salmon which are best cooked medium-rare (120°F/49°C) to rare (110°F/43°C) and tuna which is best cooked rare (110°F/43.5°C) to very rare (100°F/38°C).

Fish intended for immune compromised individuals or for cold holding (i.e., cook-chill) should be pasteurized for at least the times in Table 3.1 (to achieve 6D reduction of Listeria monocytogenes). While such a pasteurization will reduce all non-spore forming pathogens and parasites to a safe level, it will not reduce the risk of HAV or norovirus infection from shellfish. Since a 4D reduction of HAV in molluscan shellfish requires holding at an internal temperature of 194°F (90°C) for 1.5 minutes, the risk of viral contamination is best controlled through proper sanitation and hygiene (National Advisory Committee on Microbiological Criteria for Food, 2008). Since the spores of non-proteolytic C. botulinum are not inactivated by pasteurization, the fish should be stored at below 38°F (3.3°C) for no more than three to four weeks.

Pasteurization Time for Lean Fish
(starting at 41°F / 5°C and put in a 131–140°F / 55–60°C water bath)

	55°C	*56°C*	*57°C*	*58°C*	*59°C*	*60°C*
Thickness	*131°F*	*133°F*	*134.5°F*	*136.5°F*	*138°F*	*140°F*
5 mm	2½ hr	1¾ hr	1¼ hr	50 min	35 min	30 min
10 mm	2¾ hr	2 hr	1½ hr	60 min	45 min	35 min
15 mm	2¾ hr	2 hr	1½ hr	1¼ hr	55 min	50 min
20 mm	3 hr	2¼ hr	1¾ hr	1½ hr	1¼ hr	60 min
25 mm	3¼ hr	2½ hr	2 hr	1¾ hr	1½ hr	1¼ hr
30 mm	3¾ hr	3 hr	2½ hr	2 hr	1¾ hr	1¾ hr
35 mm	4 hr	3¼ hr	2¾ hr	2½ hr	2¼ hr	2 hr
40 mm	4½ hr	3¾ hr	3 hr	2¾ hr	2½ hr	2¼ hr
45 mm	4¾ hr	4 hr	3½ hr	3¼ hr	2¾ hr	2½ hr

50 mm	5¼ hr	4½ hr	4 hr	3½ hr	3¼ hr	3 hr
55 mm	5¾ hr	5 hr	4½ hr	4 hr	3¾ hr	3½ hr
60 mm	6¼ hr	5½ hr	5 hr	4½ hr	4 hr	3¾ hr
65 mm	7 hr	6 hr	5½ hr	5 hr	4½ hr	4¼ hr
70 mm	7½ hr	6¾ hr	6 hr	5½ hr	5 hr	4¾ hr

Pasteurization Time for Fatty Fish
(starting at 41°F / 5°C and put in a 131–140°F / 55–60°C water bath)

	55°C	*56°C*	*57°C*	*58°C*	*59°C*	*60°C*
Thickness	*131°F*	*133°F*	*134.5°F*	*136.5°F*	*138°F*	*140°F*
5 mm	4¼ hr	3 hr	2 hr	1½ hr	60 min	40 min
10 mm	4¼ hr	3 hr	2 hr	1½ hr	1¼ hr	50 min
15 mm	4½ hr	3¼ hr	2¼ hr	1¾ hr	1¼ hr	60 min
20 mm	4¾ hr	3½ hr	2½ hr	2 hr	1½ hr	1¼ hr
25 mm	5 hr	3¾ hr	2¾ hr	2¼ hr	1¾ hr	1½ hr
30 mm	5¼ hr	4 hr	3¼ hr	2½ hr	2¼ hr	2 hr
35 mm	5½ hr	4¼ hr	3½ hr	3 hr	2½ hr	2¼ hr
40 mm	6 hr	4¾ hr	4 hr	3¼ hr	3 hr	2½ hr
45 mm	6½ hr	5¼ hr	4¼ hr	3¾ hr	3¼ hr	3 hr
50 mm	7 hr	5¾ hr	4¾ hr	4¼ hr	3¾ hr	3¼ hr
55 mm	7½ hr	6¼ hr	5¼ hr	4¾ hr	4¼ hr	3¾ hr
60 mm	8 hr	6¾ hr	5¾ hr	5¼ hr	4¾ hr	4¼ hr
65 mm	8½ hr	7¼ hr	6¼ hr	5¾ hr	5¼ hr	4¾ hr
70 mm	9¼ hr	8 hr	7 hr	6¼ hr	5¾ hr	5¼ hr

Table 3.1: Pasteurization times for a one million to one reduction of *Listeria* in fin-fish. I used $D_{60}^{5.59} = 2.88$ minutes for lean fish (such as cod) and $D_{60}^{5.68} = 5.13$ minutes for fatty fish (such as salmon) from Embarek and Huss (1993). For my calculations I used a thermal diffusivity of 0.995×10^{-7} m^2/s, a surface heat transfer coefficient of 95 W/m^2-K, and took $\beta = 0.28$ (to simulate the heating speed of a 2:3:5 box).

Poached Fish

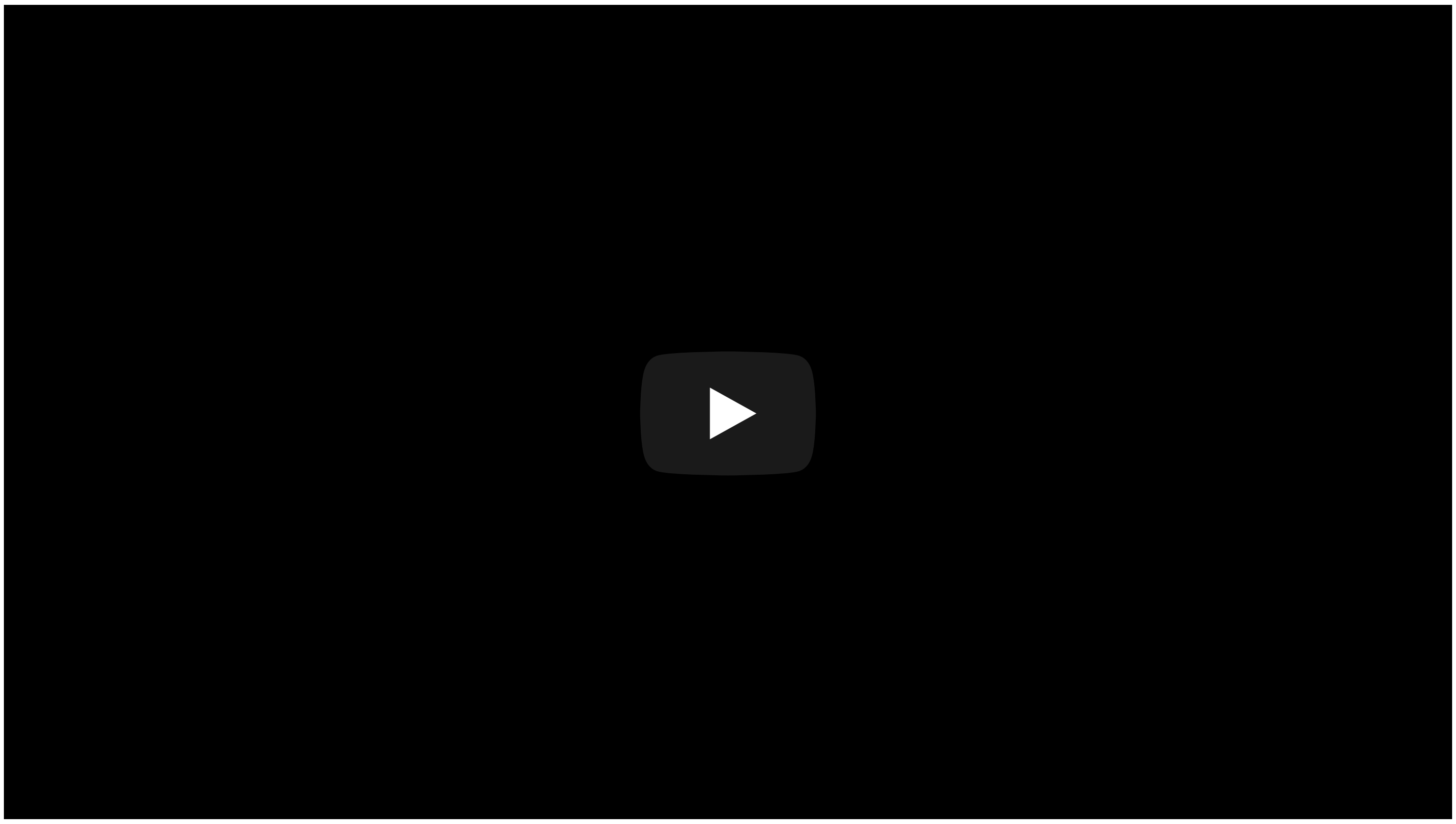
- Fish Fillets (Cod, Snapper, Monkfish, Sea Bass, Mahi-Mahi, etc.)
- Salt and Pepper
- Garlic Powder (Optional)
- Olive Oil

Remove the skin from the fillets. Season the fillets with Kosher/sea salt, black pepper, and a little garlic powder. Then individually vacuum seal the fillets with 1–2 tablespoons of olive oil or butter.

After determining the thickness of the thickest fish fillet, cook the fillets in a 131°F (55°C) to 141°F (60.5°C) water bath for at least the times listed in Table 3.1.

After removing the fillets from the water bath, the fish may either be served immediately (perhaps after quickly searing in a hot skillet with just smoking oil) or rapidly chilled in an ice water bath (see Table 1.1) and either frozen or stored at below 38°F (3.3°C) for three to four weeks. Note that Fagan and Gormley (2005) found that freezing did not reduce the quality of fish which was cooked sous vide.

Salmon 'Mi-Cuit'



While salmon mi-cuit is a popular among sous vide enthusiast, it should never be served to immune compromised individuals. The low cooking temperatures in this recipe are not sufficient to reduce the number of foodborne pathogens or parasites. Since the prevalence of the parasite Anisakids simplex may exceed 75% in various types of fresh U.S. commercial wild salmon (National Advisory Committee on Microbiological Criteria for Food, 2008), I recommend either freezing the fish (below −4°F/−20°C for at least 24 hours) to kill the parasites or pasteurizing the fish using the times and temperatures in Table 3.1.

The texture of sous vide prepared salmon is very moist and tender. To contrast this texture, the skin should be removed before vacuum packaging, crisped, and served as garnish.

A common problem when cooking salmon, is that the protein albumin leaches out of the fish and coagulates unattractively on the surface. This can be lessened by brining the fish in a 10% salt water solution for 10 minutes.

- Salmon (Coho, Sockeye, Chinook, or Steelhead)
- Olive Oil

- Salt and Pepper
- Garlic Powder (Optional)

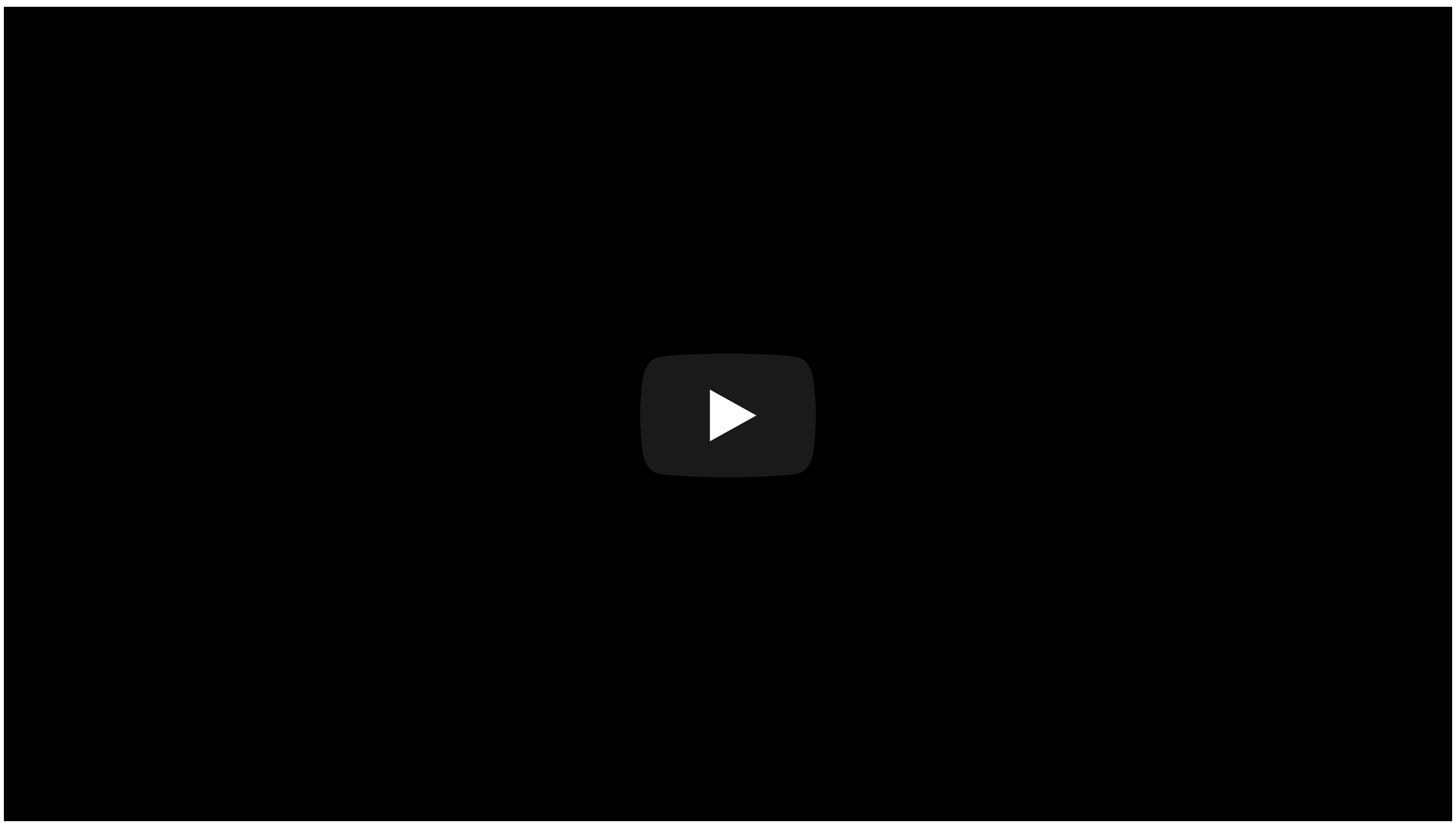
Set the temperature of the water bath to 108°F (42°C) for rare salmon, 122°F (50°C) for medium--rare salmon, or 140°F (60°C) for medium salmon. Then prepare a 10% salt water solution (100 grams salt per 1 liter cold water).

For crisp salmon skin to contrast the very moist and tender texture of the salmon, remove the skin from the salmon and then brine the salmon in the refrigerator for 10 minutes.

If cooking the salmon medium, the easiest way to crisp the skin and remove it from the salmon is to quickly sear the salmon (skin side only) in a pan over high heat with just smoking oil. The skin will then easily peel off the flesh. The skin can then be finished with a blowtorch or simply placed in a warm oven until needed. If cooking the salmon rare or medium-rare, cut the skin off the fish and then crisp it between cooking sheets in the oven.

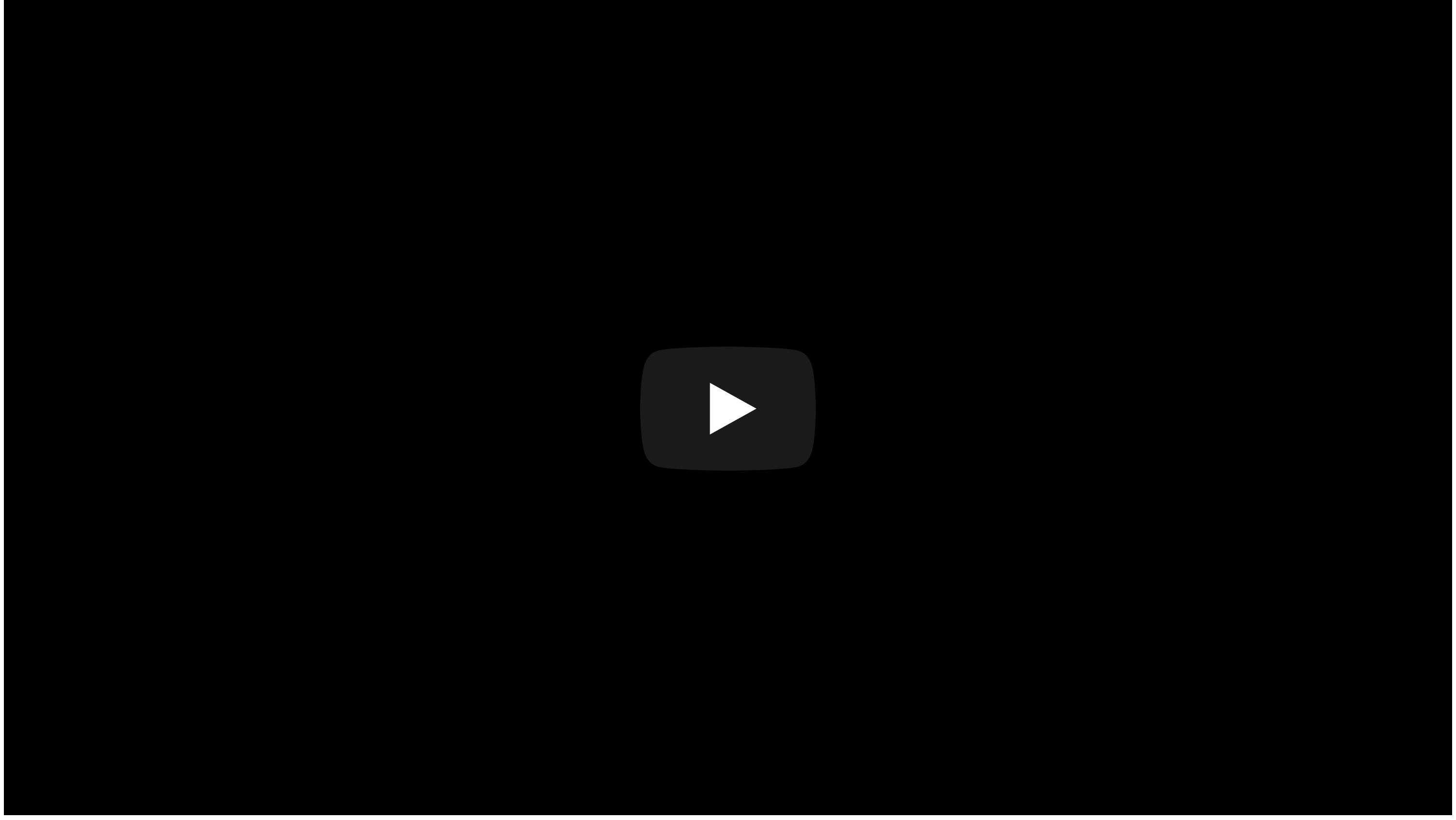
After the salmon has finished brining, rinse and pat dry with paper towels. Then season with salt, pepper and a hint of garlic powder. Vacuum seal the seasoned salmon in a plastic pouch with 1–2 tablespoons extra virgin olive oil (frozen overnight if using a clamp style vacuum sealer).

Cut the salmon into individual servings and vacuum seal. For rare and medium-rare salmon, cook the salmon for 15–20 minutes. For medium salmon, pasteurize it for the time listed in Table 3.1. Then remove the salmon from its pouch, garnish with crisped salmon skin, and serve immediately.



4. Poultry and Eggs

Chicken or Turkey Breast



Traditionally, light poultry meat is cooked well-done (160°F/70°C to 175°F/80°C) for "food safety" reasons. When cooking chicken and turkey breasts sous vide, they can be cooked to a medium doneness (140°F/60°C to 150°F/65°C) while still being pasteurized for safety.

- Boneless Chicken or Turkey Breast
- Salt and Pepper

Remove any skin from the breast and reserve for garnish or discard. Reserved skin can easily be crisped using either a salamander/broiler or with a blowtorch.

If brining, place the poultry meat in a 5% salt water solution (50 grams per 1 liter) in the refrigerator for 30 minutes to 1 hour. (If tenderizing with a Jaccard, do so before brining.)

Rinse and dry with paper towels. Then season with Kosher/sea salt and coarse ground pepper. Vacuum seal breasts (one per bag). The breasts may be frozen at this point until needed.

To cook and pasteurize, place (thawed) breast in a 146°F (63.5°C) water bath for the times listed in Table 4.1. [After cooking, the breasts may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

Remove breast from plastic pouch and dry with a paper towel. The meat can then be served as is or browned slightly by using either a very hot pan (with just smoking oil) or a blowtorch. Serve immediately (garnished with crisped skin).

Pasteurization Time for Poultry
(starting at 41°F / 5°C and put in a 134.5–149°F / 57–65°C water bath)

	134.5°F	*136.5°F*	*138°F*	*140°F*	*142°F*	*143.5°F*	*145.5°F*	*147°F*	*149°F*
Thickness	*57°C*	*58°C*	*59°C*	*60°C*	*61°C*	*62°C*	*63°C*	*64°C*	*65°C*

5 mm	2¼ hr	1¾ hr	1¼ hr	45 min	35 min	25 min	18 min	15 min	13 min
10 mm	2¼ hr	1¾ hr	1¼ hr	55 min	40 min	35 min	30 min	25 min	20 min
15 mm	2½ hr	1¾ hr	1½ hr	1¼ hr	50 min	45 min	40 min	35 min	30 min
20 mm	2¾ hr	2 hr	1¾ hr	1¼ hr	1¼ hr	55 min	50 min	45 min	40 min
25 mm	3 hr	2¼ hr	2 hr	1½ hr	1½ hr	1¼ hr	1¼ hr	60 min	55 min
30 mm	3¼ hr	2¾ hr	2¼ hr	2 hr	1¾ hr	1½ hr	1½ hr	1¼ hr	1¼ hr
35 mm	3¾ hr	3 hr	2½ hr	2¼ hr	2 hr	1¾ hr	1¾ hr	1½ hr	1½ hr
40 mm	4 hr	3¼ hr	2¾ hr	2½ hr	2¼ hr	2 hr	2 hr	1¾ hr	1¾ hr
45 mm	4½ hr	3¾ hr	3¼ hr	3 hr	2¾ hr	2½ hr	2¼ hr	2 hr	2 hr
50 mm	4¾ hr	4¼ hr	3¾ hr	3¼ hr	3 hr	2¾ hr	2½ hr	2½ hr	2¼ hr
55 mm	5¼ hr	4½ hr	4 hr	3¾ hr	3½ hr	3¼ hr	3 hr	2¾ hr	2¾ hr
60 mm	5¾ hr	5 hr	4½ hr	4¼ hr	3¾ hr	3½ hr	3¼ hr	3¼ hr	3 hr
65 mm	6¼ hr	5½ hr	5 hr	4½ hr	4¼ hr	4 hr	3¾ hr	3½ hr	3¼ hr
70 mm	7 hr	6 hr	5½ hr	5 hr	4¾ hr	4½ hr	4¼ hr	4 hr	3¾ hr

Table 4.1: Time required for at least a one million to one reduction in *Listeria* and a ten million to one reduction in *Salmonella* in poultry starting at 41°F (5°C). I calculated the D- and z-values using linear regression from (O'Bryan et al., 2006): for *Salmonella* I used $D_{60}^{6.45}$ = 4.68 minutes and for *Listeria* I used $D_{60}^{5.66}$ = 5.94 minutes. For my calculations I used a thermal diffusivity of $1.08{\times}10^{-7}$ m^2/s, a surface heat transfer coefficient of 95 W/m^2-K, and took β=0.28 (to simulate the heating speed of a 2:3:5 box). For more information on calculating log reductions, see Appendix A.

Turkey, Duck or Goose Leg Confit

- Duck, Goose or Turkey Legs
- Rendered Duck or Goose Fat (or Lard)
- Salt and Pepper

Place legs in a 5–10% brine (50–100 grams salt per 1 liter) for three to six hours. The brine may be flavored with sprigs of thyme, bay leaves, garlic, and orange/ lemon slices.

After brining, rinse legs and pat dry with paper towels. Season with Kosher/sea salt and coarse ground pepper. Individually vacuum seal the legs with 2–4 tablespoons of rendered fat.

Place the vacuum sealed legs in a 176°F (80°C) water bath for 8 to 12 hours. Since some of the liquid in the bag will change phase (to gas), the bag will puff and may float to the surface. To prevent uneven cooking, the bags should be held under water using a wire rack or some other restraint. [After cooking, the legs may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 39°F (4°C) indefinitely.]

To serve, (reheat and) sear until skin is crispy. May also be served without skin and torn into pieces.

Perfect Egg

The custardy texture of the white and yolk of the so called "perfect egg" is caused by the denaturing of the egg protein conalbumin at 148°F (64.5°C). In Figure 4.1, we observe that the denaturing of the protein ovotransferrin at 144°F (62°C) causes the egg white to coagulate (This, 2006, Chap 3).

Place egg in a 148°F (64.5°C) water bath for 45 minutes to 1 hour. Crack egg and serve immediately.

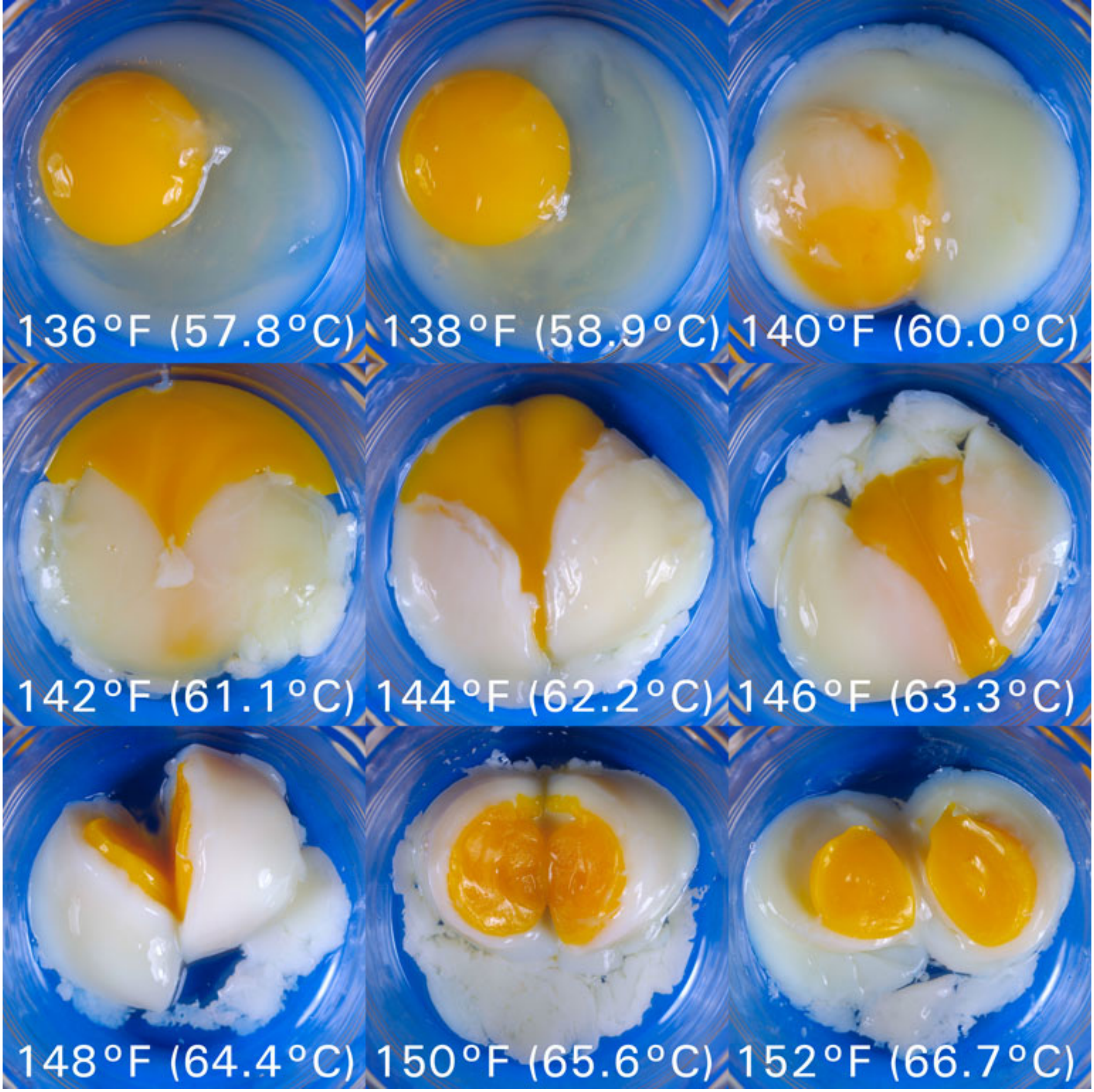


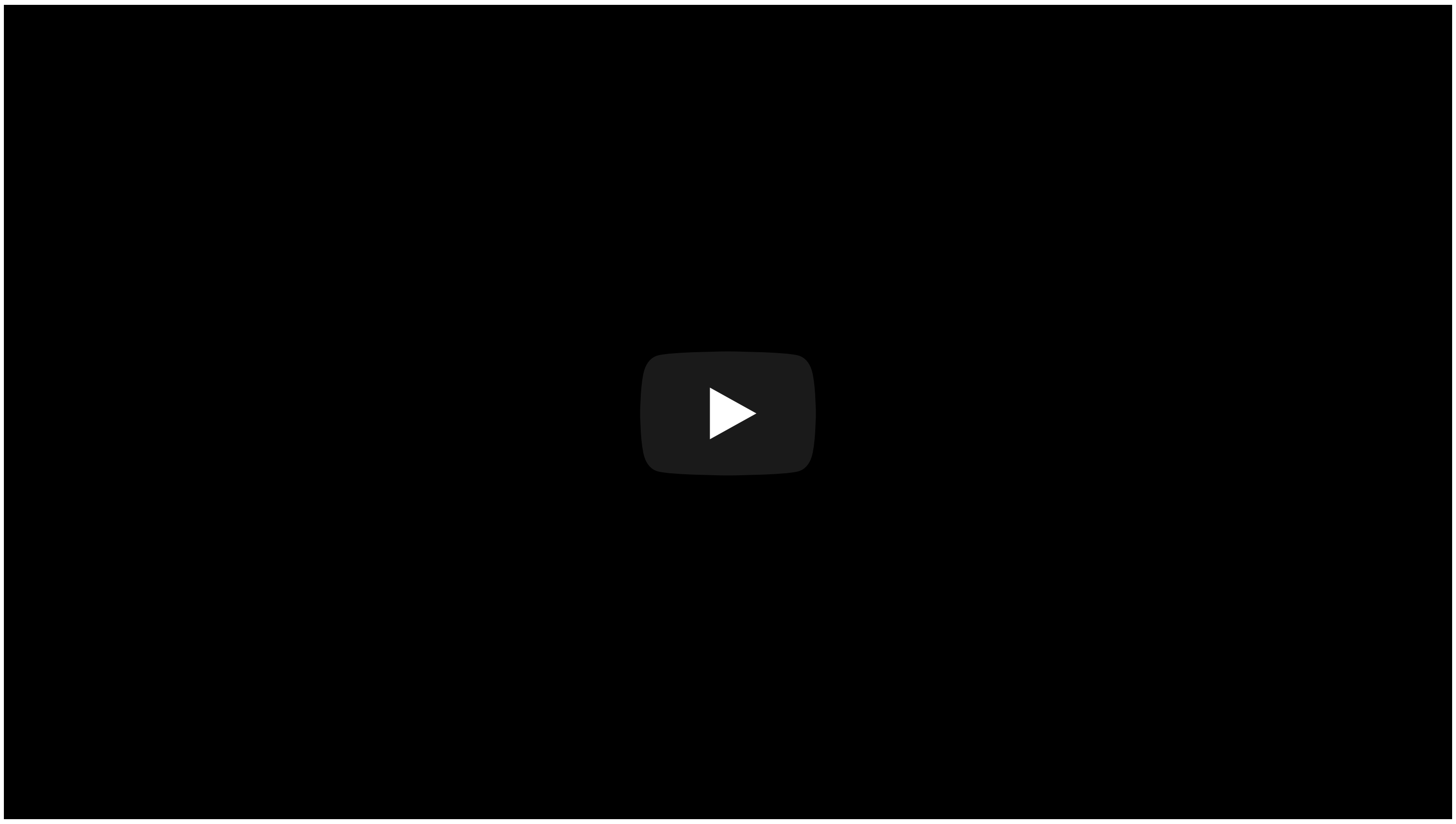
Figure 4.1: Pictures of intact eggs cooked in a water bath for 75 minutes at temperatures ranging from 136°F (57.8°C) to 152°F (66.7°C). From left-to-right and top-to-bottom, the water bath temperature was 136.0°F (57.8°C), 138.0°F (58.9°C), 140.0°F (60.0°C), …, 152°F (66.7°C).

Pasteurized in Shell Egg

While only 1 in 10,000–20,000 intact shell eggs contain hazardous levels of Salmonella enteritidis (McGee, 2004; Snyder, 2006), Grade A eggs were implicated in 82% of outbreaks between 1985 and 1991 (Mishu et al., 1994). Therefore, when working with highly susceptible or immune compromised populations, pasteurized eggs should always be used in dishes which call for raw eggs (e.g., chocolate mousses).

Place egg in a 135°F (57°C) water bath for at least 1 hour and 15 minutes (Schuman et al., 1997).

Pasteurized intact eggs can be stored and used just like raw eggs. While the properties of the egg yolk are unaffected, the egg white is milky compared to a raw egg. Whipping time is significantly longer for pasteurized eggs, but the final whip volume is nearly the same (Schuman et al., 1997).



5. Beef

For tender cuts of beef–such as tenderloin, sirloin and rib-eye–season, vacuum seal in heat stable plastic pouches, and cook either very-rare (120°F/ 49°C), rare (125°F/51.5°C), medium-rare (130°F/ 54.5°C), or medium (140°F/60°C) for the time listed in Table 2.2. For extended shelf-life (i.e., cook-chill or cook-freeze) or when serving immune compromised individuals, the beef must be pasteurized for at least the times in Table 5.1. After heating, sear the beef using either a blowtorch, a very hot grill, or a pan with just smoking oil.

As the cooking temperature increases from 120°F to 150°F (50°C to 65°C), Vaudagna et al. (2002) found that cooking weight loss increased and shear force decreased. They also found that holding the beef in the water bath for 90–360 minutes did not have a significant effect on the cooking weight or the shear force. Above 160°F (70°C), tenderness decreases and cooking weight loss continues to increase because of myofibrillar hardening (Powell et al., 2000). When compared to other cooking methods, beef cooked sous vide to the same temperature has a more intense reddish color (García- Segovia et al., 2007).

Pasteurization Time for Meat (Beef, Pork, and Lamb)
(starting at 41°F / 5°C and put in a 131–151°F / 55–66°C water bath)

55°C	*56°C*	*57°C*	*58°C*	*59°C*	*60°C*

Thickness	*131°F*	*133°F*	*134.5°F*	*136.5°F*	*138°F*	*140°F*
5 mm	2 hr	1¼ hr	60 min	45 min	40 min	30 min
10 mm	2 hr	1½ hr	1¼ hr	55 min	45 min	40 min
15 mm	2¼ hr	1¾ hr	1½ hr	1¼ hr	60 min	55 min
20 mm	2½ hr	2 hr	1¾ hr	1½ hr	1¼ hr	1¼ hr
25 mm	2¾ hr	2¼ hr	2 hr	1¾ hr	1½ hr	1½ hr
30 mm	3 hr	2½ hr	2 hr	2 hr	1¾ hr	1½ hr
35 mm	3¼ hr	2¾ hr	2¼ hr	2 hr	2 hr	1¾ hr
40 mm	3½ hr	3 hr	2½ hr	2¼ hr	2¼ hr	2 hr
45 mm	4 hr	3¼ hr	3 hr	2¾ hr	2½ hr	2¼ hr
50 mm	4½ hr	3¾ hr	3¼ hr	3 hr	2¾ hr	2½ hr
55 mm	5 hr	4¼ hr	3¾ hr	3½ hr	3 hr	3 hr
60 mm	5¼ hr	4¾ hr	4¼ hr	3¾ hr	3½ hr	3¼ hr
65 mm	6 hr	5¼ hr	4¾ hr	4¼ hr	4 hr	3¾ hr
70 mm	6½ hr	5¾ hr	5¼ hr	4¾ hr	4¼ hr	4 hr

	61°C	*62°C*	*63°C*	*64°C*	*65°C*	*66°C*
Thickness	*142°F*	*143.5°F*	*145.5°F*	*147°F*	*149°F*	*151°F*
5 mm	25 min	25 min	18 min	16 min	14 min	13 min
10 mm	35 min	30 min	30 min	25 min	25 min	25 min
15 mm	50 min	45 min	40 min	40 min	35 min	35 min
20 mm	60 min	55 min	55 min	50 min	45 min	45 min
25 mm	1¼ hr	1¼ hr	1¼ hr	60 min	55 min	55 min
30 mm	1½ hr	1½ hr	1¼ hr	1¼ hr	1¼ hr	1¼ hr
35 mm	1¾ hr	1½ hr	1½ hr	1½ hr	1¼ hr	1¼ hr
40 mm	1¾ hr	1¾ hr	1¾ hr	1½ hr	1½ hr	1½ hr
45 mm	2¼ hr	2 hr	2 hr	1¾ hr	1¾ hr	1¾ hr
50 mm	2½ hr	2¼ hr	2¼ hr	2 hr	2 hr	2 hr
55 mm	2¾ hr	2¾ hr	2½ hr	2½ hr	2¼ hr	2¼ hr
60 mm	3 hr	3 hr	2¾ hr	2¾ hr	2½ hr	2½ hr
65 mm	3½ hr	3¼ hr	3¼ hr	3 hr	3 hr	2¾ hr
70 mm	3¾ hr	3¾ hr	3½ hr	3¼ hr	3¼ hr	3¼ hr

Table 5.1: Time required to reduce *Listeria* by at least a million to one, *Salmonella* by at least three million to one, and *E. coli* by at least a hundred thousand to one in thawed meat starting at 41°F (5°C). I calculated the D- and z-values using linear regression from O'Bryan et al. (2006), Bolton et al. (2000), and Hansen and Knøchel (1996): for *E. coli* I use $D_{55}^{4.87}$ = 19.35 min; for *Salmonella* I use $D_{55}^{7.58}$ = 13.18 min; and for *Listeria* I use $D_{55}^{9.22}$ = 12.66 min. For my calculations I used a thermal diffusivity of $1.11{\times}10^{-7}$ m^2/s, a surface heat transfer coefficient

of 95 W/m^2-K, and took β=0 up to 30 mm and β=0.28 above 30 mm (to simulate the heating speed of a 2:3:5 box). For more information on calculating log reductions, see Appendix A. [Note that if the beef is seasoned using a sauce or marinate which will acidify the beef, then the pasteurizing times may need to be doubled to accommodate the increased thermal tolerance of *Listeria* (Hansen and Knøchel, 1996).]

For tough but flavorful cuts of beef–such as top blade, chuck, and top round–season the meat and cook in a 131°F (55°C) water bath for 24–48 hours. This is the lowest temperature at which (insoluble) collagen denatures (dissolves) into gelatin, at higher temperatures the denaturing occurs more quickly (Powell et al., 2000; This, 2006).

Flat Iron Steak

Beef cooked in a vacuum will look paler than medium-rare when first cut, but will get redder once exposed to oxygen.

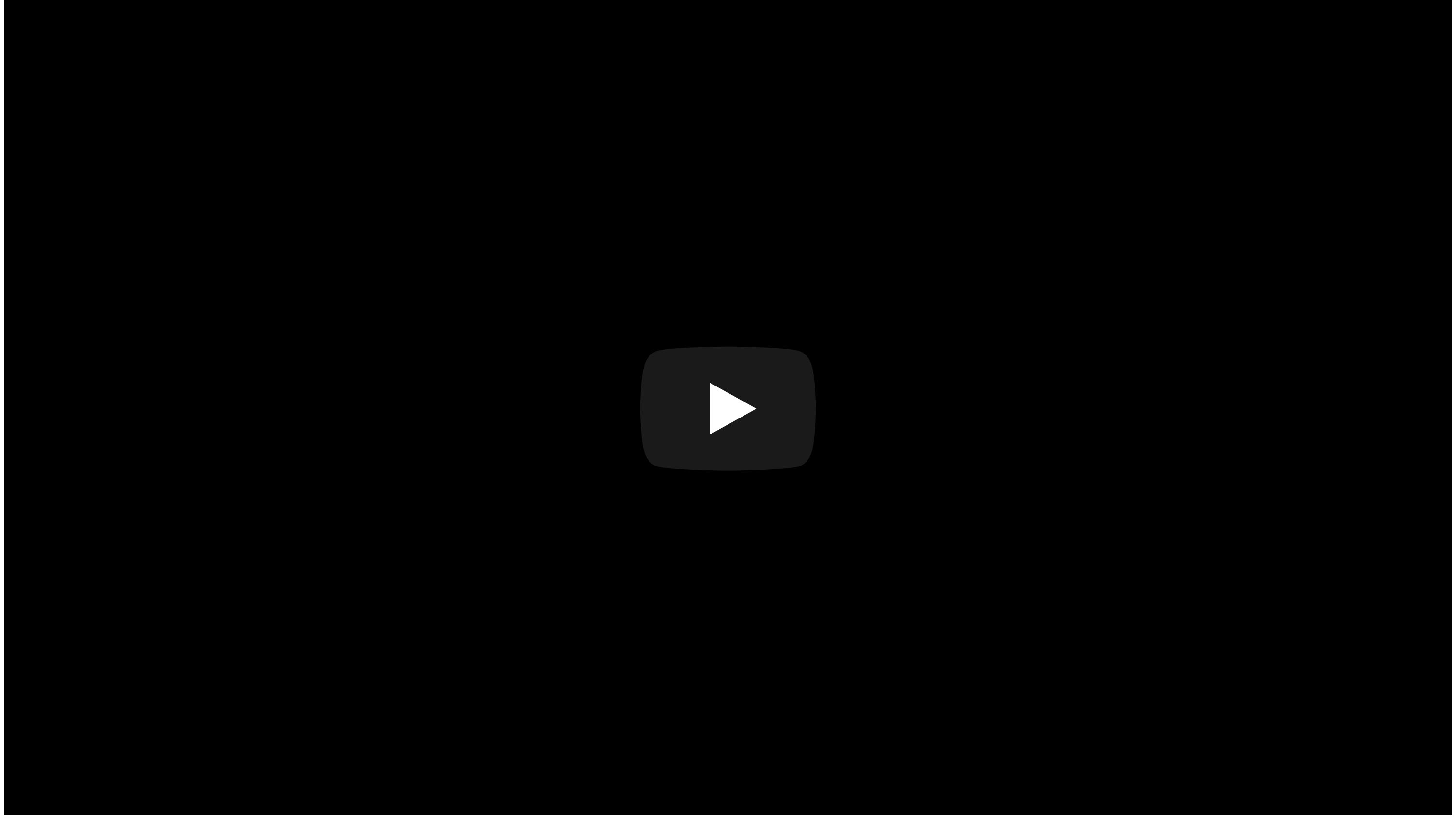
- Flat Iron (Paleron or Top Blade) Steak
- Salt and Pepper

Rinse and dry steak with a paper towel. Jaccard steak, then season with salt and pepper. Vacuum seal (and freeze until needed).

Place vacuum sealed steak in a 131°F (55°C) water bath for about 12 hours. The meat will have a greenish-brown color after cooking which will disappear after searing. [The steak may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

Remove steak from vacuum bag, pat dry with a paper towel, and sear quickly with a blowtorch or in a pan with smoking vegetable or nut oil.

Roast Beef



- Top Blade, Chuck, or Top Round Roast
- Salt and Pepper

Dry roast with a paper towel. Then cut the roast so that it is no more than 70 mm (2.75 in) thick; or, slice the roast into individual servings and follow the recipe above for flat iron steaks.

Season the roast with Kosher/sea salt and coarse ground pepper. Then vacuum seal and place the roast in a 131°F (55°C) water bath for about 24 hours. [After cooking, the roast may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

After removing the roast from its vacuum pouch, pat the roast dry with paper towels. Then sear the roast to a deep mahogany color using a blowtorch. Then slice and serve immediately.

Brisket

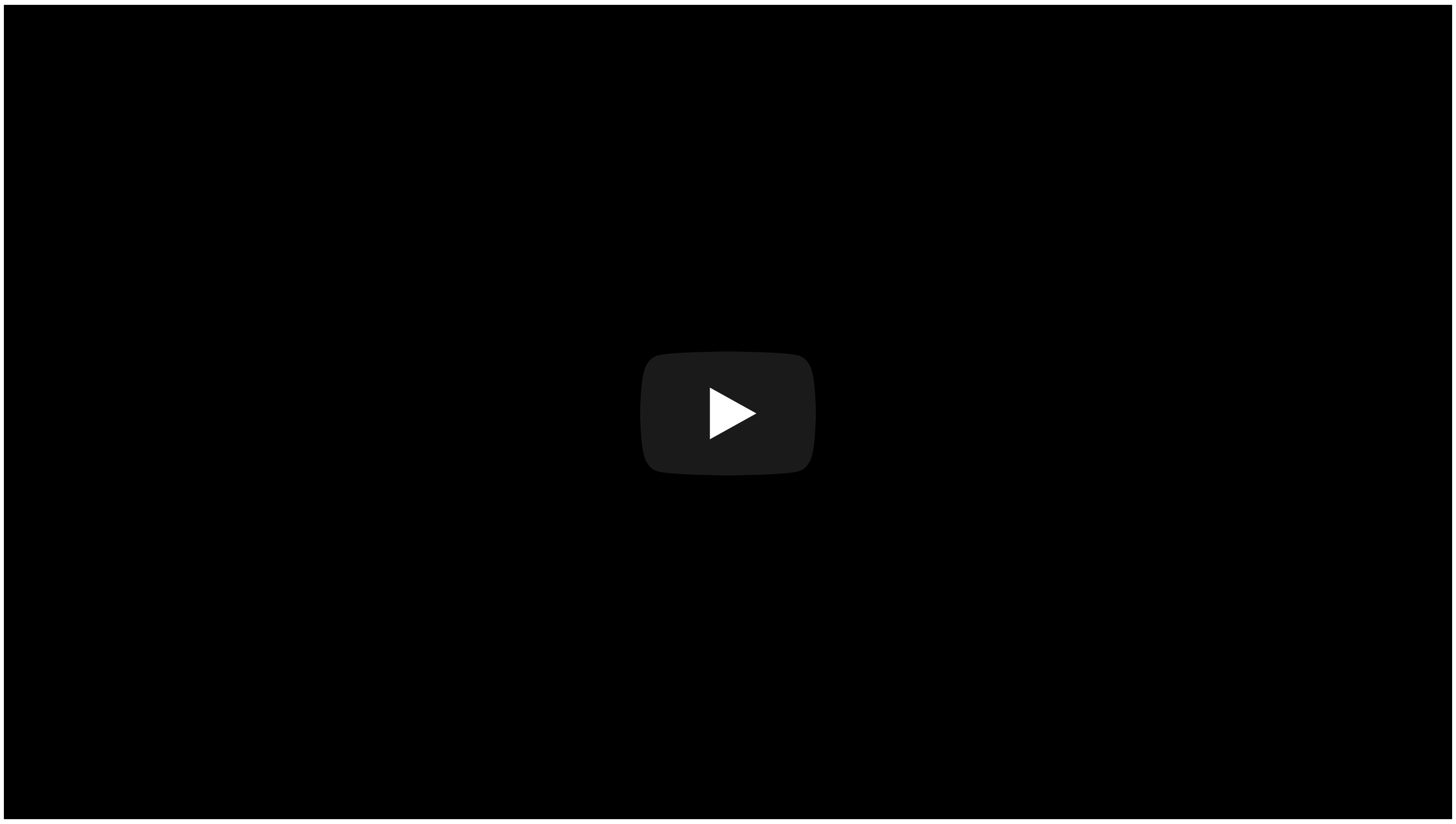
- Beef Brisket
- Sugar, Salt and Pepper

Cut slits in the fat cap in a crosshatch patter. Brine the brisket in a 4% salt, 3% sugar solution (40 grams salt and 30 grams sugar per liter of water) in the refrigerator for 2–3 hours. Rinse and dry brisket with paper towels.

Flavor the brisket either by smoking it for 30–60 minutes or by searing the fat cap with a blowtorch. Then vacuum seal the brisket either whole or cut into two to four pieces.

While the famed French Laundry is said to cook their brisket in a 147°F (64°C) water bath for 48 hours, I prefer to cook brisket at 176°F (80°C) for 24–36 hours. Alternatively, some like to cook brisket at 135°F (57°C) for 36–48 hours. Since some of the liquid in the bag will change phase (to gas), the bag will puff and may float to the surface. To prevent uneven cooking, the bags should be held under water using a wire rack or some other restraint. [After cooking, the brisket may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

Remove the brisket from the vacuum sealed pouch and use the liquid from the bag to create a quick sauce (by reducing in a pan over medium-high heat and adding a corn starch slurry to thicken). Slice the meat across grain into long, thin slices and serve with beef glace.



6. Pork

Traditional Style Pork Chops

While pork can be safely cooked at 130°F (54.4°C), many people find the slightly pink color of pork cooked at this temperature to be unsettling. To compensate for cooking to medium (instead of mediumrare), I highly recommend brining the pork chops to break down some of the support structure of the muscle fibers and to increase the water holding capacity of the meat; the maximum water uptake occurs when brining in a 7–10% salt solution, with the chop absorbing 20–25% of its weight (Graiver et al., 2006).

Brine in a 7% salt, 3% sugar water solution (70 grams salt and 30 grams sugar per 1 liter) in the refrigerator for one to two hour. (If tenderizing with a Jaccard, do so before brining.)

Rinse, dry with paper towels and season with Kosher/ sea salt and coarse ground pepper. Vacuum seal pork chops (one per bag).

To cook, place in a 141°F (61°C) water bath for the cooking times in the Table 5.1. [The chop may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

Remove chop from vacuum bag, pat dry with a paper towel, then sear quickly with a blowtorch or in a pan with smoking vegetable or nut oil.

Slow Cooked Pork Chops

Season thick-cut pork chops with Kosher/sea salt and coarse ground pepper. Then vacuum seal pork chops (one per bag) and place in a 131°F (55°C) water bath for 12 hours. [The chop may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for up to three to four weeks until needed.]

Remove chop from vacuum bag, pat dry with a paper towel, then sear quickly with a blowtorch or in a pan with smoking vegetable or nut oil.

Pulled Pork

- Pork Roast (Boston Butt Roast or Picnic Roast)
- Lard
- Salt and Pepper

If bone-in, remove the bone from the pork roast with a boning knife. Either cut roast into steaks which are roughly 7 ounces each, or cut the roast so that it is no more than 70 mm (2.75 in) thick. Then brine roast in a 7–10% salt, 0–3% sugar water solution (70–100 grams salt and 0–30 grams sugar per 1 liter) in the refrigerator for six to twelve hours.

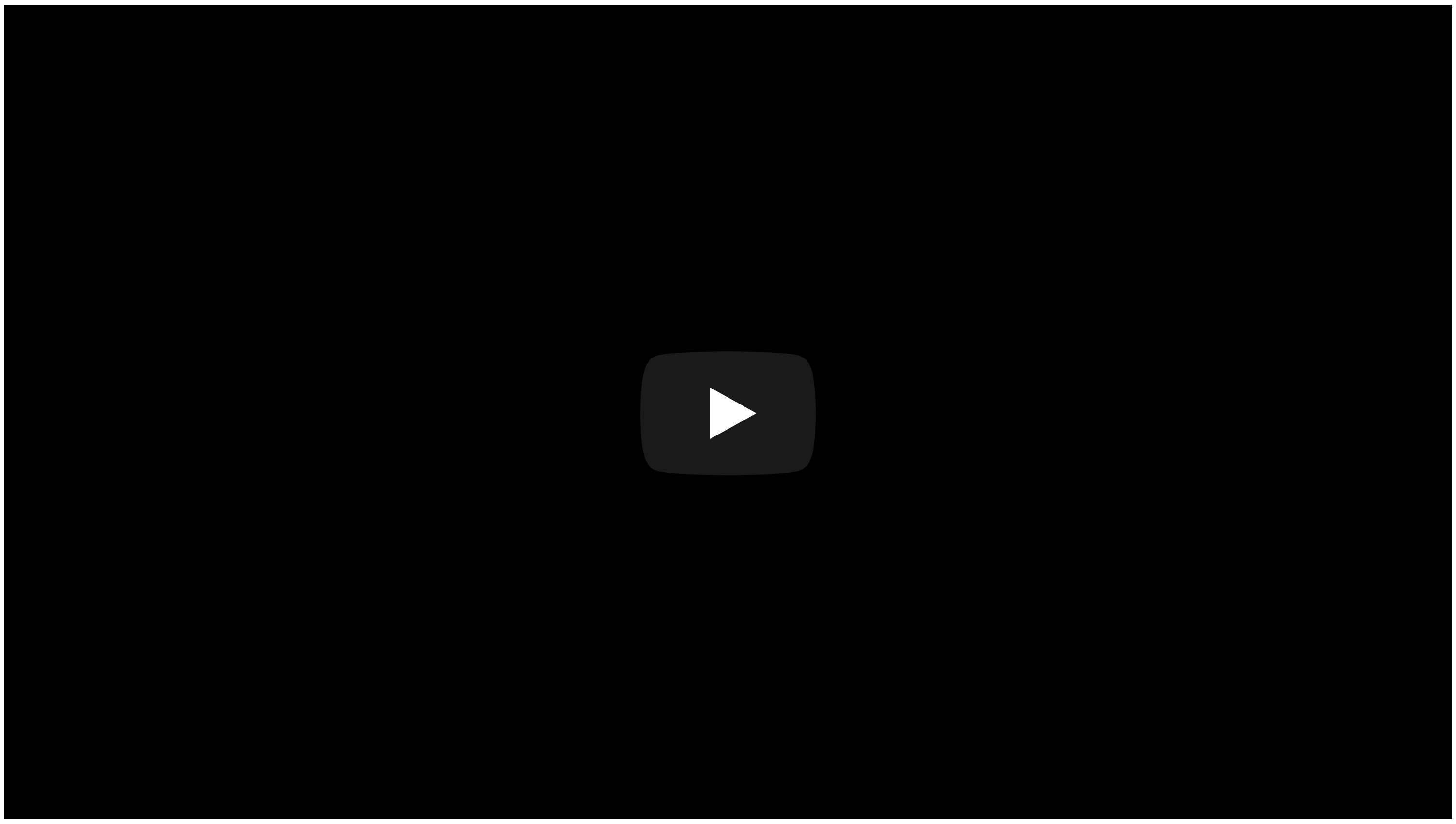
Drain, rinse and pat dry with paper towels. Season the pork with Kosher/sea salt and coarse ground pepper. Place each piece of pork in a vacuum bag with 1–2 tablespoons of lard (preferably non-hydrogenated) and seal.

Place the pork either in a 176°F (80°C) water bath for 8–12 hours or in 155°F (68°C) water bath for 24 hours. When cooking at 176°F (80°C), the bag will puff (from water vapor) and may float to the surface. To prevent uneven cooking, the bags should be held under water using a wire rack or some other restraint. [After cooking, the pork may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for three to four weeks.]

Remove the pork from the bag and reserve the liquid from the bag. (Place the liquid in a container in the fridge overnight, skim the fat off and reserve the jellied stock for future use.) Dry the surface of the meat with a paper towel.

For American style pulled pork, shred and serve with your favorite barbecue sauce. For Mexican style pulled pork, sear the surface with a blowtorch (or in a pan with just smoking vegetable or nut oil) before shredding.

Barbecue Ribs



- Pork Spare Ribs
- Barbecue Dry Rub
- Salt and Pepper

Cut the ribs into portions which will fit in the vacuum pouches (say 3–4 ribs per piece). Then brine roast in a 7–10% salt, 0–3% sugar water solution (70–100 grams salt and 0–30 grams sugar per 1 liter) in the refrigerator for 12–24 hours.

Drain, rinse and pat dry with paper towels. Generously season the top of each rib with a barbecue spice rub (say 2T paprika, 1.5T celery salt, 1.5T garlic powder, 1T black pepper, 1T chili powder, 1T ground cumin, 1T brown sugar, 1T table salt, 1t white sugar, 1t dried oregano, and 1t cayenne pepper). Place each piece of pork in a vacuum pouch and seal.

Place the pork either in a 176°F (80°C) water bath for 8–12 hours or in 155°F (68°C) water bath for 24 hours. When cooking at 176°F (80°C), the bag will puff (from water vapor) and may float to the surface. To prevent uneven cooking, the bags should be held under water using a wire rack or some other restraint. [After cooking, the pork may be rapidly cooled in ice water (see Table 1.1) and frozen or refrigerated at below 38°F (3.3°C) for three to four weeks.]

After removing the ribs from the bag, sear the top with a blowtorch. Then, serve immediately with barbecue sauce.

Part III: Appendix

A. The Mathematics of Sous Vide

This guide is primarily interested in modelling how long it takes the food to come up to temperature and how long it takes to pasteurize the food. These are non-trivial tasks. Many simplifications and assumptions are necessary.

Heating and Cooling Food

The transfer of heat (by conduction) is described by the partial differential equation,

$$T_t = \nabla \cdot (\alpha \nabla T),$$

where $\alpha \equiv k/(\rho C_p)$ is thermal diffusivity (m^2/sec), k is thermal conductivity (W/m-K), ρ is density (kg/m^3), and C_p is specific heat (kJ/kg-K). If we know the temperature at some initial time and can describe how the temperature at the surface changes, then we can uniquely determine T. Although k, ρ and C_p depend on position, time and temperature, we will assume the dependence on position and time is negligible.

Since we are only interested in the temperature at the slowest heating point of the food (typically the geometric center of the food), we can approximate the three dimensional heat equation by the one dimensional heat equation

$$\begin{cases} \rho C_p(T) T_t = k(T)\left[\frac{\partial^2 T}{\partial r^2} + \frac{\beta}{r}\frac{\partial T}{\partial r}\right], \\ T(r,0) = T_0, \quad \frac{\partial T}{\partial r}(0,t) = 0, \\ k(T)\frac{\partial T}{\partial r}(R,t) = h[T_{Water} - T(R,t)], \end{cases} \qquad (*)$$

where $0 \le r \le R$ and $t \ge 0$, $0 \le \beta \le 2$ is a geometric factor, T_0 is the initial temperature of the food, T_{Water} is the temperature of the fluid (air, water, steam) that the food is placed in, and *h* is the surface heat transfer coefficient (W/m^2-K). For example, a plot showing the measured and calculated core temperature of a 27 mm thick piece of Mahi- Mahi is shown in Figure A.1.

The geometric factor in (*) allows us to approximate any shape from a large slab (β = 0) to a long cylinder (b = 1) to a sphere (β = 2). Indeed, a cube is well approximated by taking β = 1.25, a square cylinder by β = 0.70, and a 2:3:5 brick by β = 0.28.

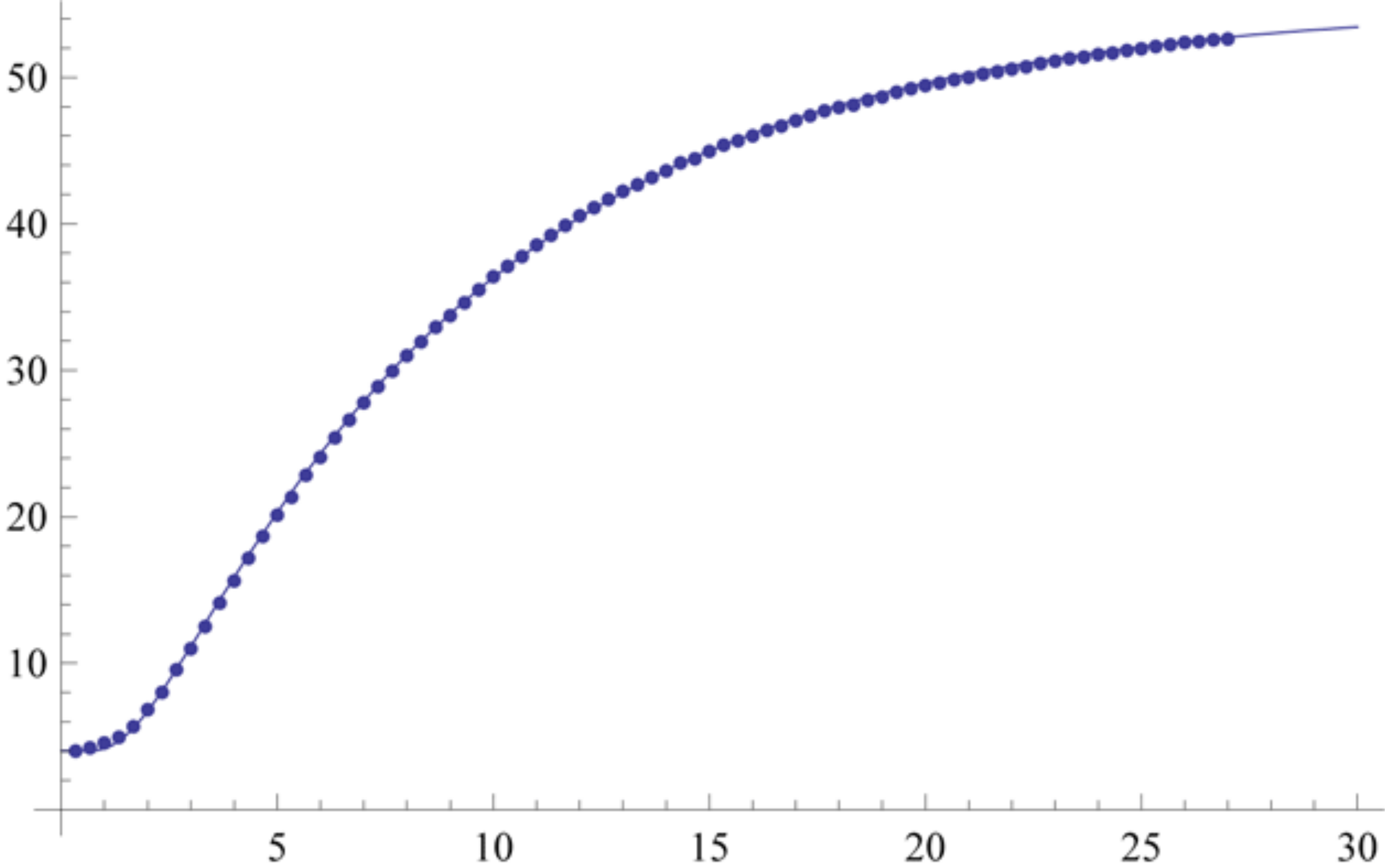


Figure A.1: Plot of temperature (°C) verse time (minutes) of a 27 mm thick piece of Mahi-Mahi cooked in a 131°F (55°C) water bath. The blue dots are the core temperature measured using a ThermoWorks MicroTherma2T with a needle probe. The blue line is the calculated core temperature of the Mahi-Mahi (where I used a thermal diffusivity of 1.71×10^{-7} m^2/sec and a heat transfer coefficient of 155 W/m^2-K).

Heating Thawed Food

For thawed foods, k, ρ and C_p are essentially constant. Sanz et al. (1987) reported that beef with above average fatness had: a thermal conductivity of 0.48 W/m-K at 32°F (0°C) and 0.49 W/m-K at 86°F (30°C); a specific heat of 3.81 kJ/kg-K at both 32°F (0°C) and 86°F (30°C); and, a density of 1077 kg/m^3 at 41°F (5°C) and 1067 kg/m^3 at 86°F (30°C). This is much less than the difference between beef sirloin ($\alpha = 1.24\times10^{-7}$ m^2/sec) and beef round ($\alpha = 1.11\times10^{-7}$ m^2/sec) (Sanz et al., 1987). Therefore, we can model the temperature of thawed foods by

$$\begin{cases} T_t = \alpha\left[\frac{\partial^2 T}{\partial r^2} + \frac{\beta}{r}\frac{\partial T}{\partial r}\right], \\ T(r,0) = T_0, \qquad \frac{\partial T}{\partial r}(0,t) = 0, \\ \frac{\partial T}{\partial r} = \frac{h}{k}[T_{Water} - T(R,t)], \end{cases}$$

for $0 \le r \le R$ and $t \ge 0$. Since h is large (95–155 W/m^2-K for most water baths), even large deviations in h/k caused only minor deviations in the core temperature of the food

(Nicolaï and Baerdemaeker, 1996); in comparison, home and (low convection) commercial ovens have surface heat transfer coefficients of only 14–30 W/m²-K and even small deviations in h can result in large deviations of the core temperature of the food.

Most foods have a thermal diffusivity between 1.2 and 1.6×10^{-7} m²/s (Baerdemaeker and Nicolaï, 1995). Thermal diffusivity depends on many things, including meat species, muscle type, temperature, and water content. Despite these variations in thermal diffusivity, we can always choose a (minimum) thermal diffusivity which will underestimate the temperature of the meat as it cooks (and overestimate the temperature as it cools). Thus, I use the lowest thermal diffusivities reported in the literature (see Table A.1) in my pasteurization tables. Moreover, the food cannot overcook if it is placed in a water bath just above its desired final core temperature. Therefore, so long as the pouches do not float to the surface or are packed too tightly in the water bath, we can generate cooking tables which will assure perfectly cooked and sufficiently pasteurized meat.

Food	Thermal Diffusivity (10^{-7} m²/s)	
Beef	1.35–1.52	Markowski et al. (2004)
	1.22–1.82	Sheridan and Shilton (2002)
	1.11–1.30	Sanz et al. (1987)
	1.18–1.33	Singh (1982)
	1.19–1.21	Donald et al. (2002)
	1.25–1.32	Tsai et al. (1998)
Pork	1.12–1.83	Sosa-Morales et al. (2006)
	1.17–1.25	Sanz et al. (1987)
	1.28–1.66	Kent et al. (1984)
	1.18–1.38	Singh (1982)
Chicken	1.36–1.42 (White) and 1.28–1.33 (Dark)	Siripon et al. (2007)
	1.46–1.48 (White)	Vélez-Ruiz et al. (2002)
	1.08–1.39	Sanz et al. (1987)
Fish	1.09–1.60	Sanz et al. (1987)
	0.996–1.73	Kent et al. (1984)
	1.22–1.47	Singh (1982)
Fruits	1.12–1.40 (Apple), 1.42 (Banana), 1.07 (Lemon), 1.39 (Peach), 1.27 (Strawberry)	Singh (1982)
Vegetables	1.68 (Beans), 1.82 (Peas), 1.23–1.70 (Potato), 1.71 (Squash), 1.06–1.91 (Sweet Potato), 1.48 (Tomato)	Singh (1982)

Table A.1: The thermal diffusivity (at 0°C to 65°C) of various types of food reported in the literature.

Computing the Destruction of Pathogens

Using the above models for the temperature at the slowest heating point of the meat, the classical model for the log reduction in pathogens is

$$LR = \frac{1}{D_{Ref}} \int_0^t 10^{[T(t')-T_{Ref}]/z} dt',$$

where D_{Ref} is the time required for a one decimal reduction in the pathogen at the reference temperature T_{Ref} and the z-value is the temperature increment needed for a ten-fold decrease in D. Despite concerns in (Geeraerd et al., 2000) that the classical model is inappropriate for the mild heat treatment of sous vide cooking, Huang (2007) found that the classical model was (1–2D) more conservative than experimental observations for Listeria.

B. Equipment

Water Baths and Steam Ovens

For short cooking times (such as when cooking fish), a pan of water on the stove can be used if you're willing to watch it closely and adjust the temperature by hand. However, this becomes increasingly tedious for longer cooking times and most cooks use a digital controller to regulate the temperature.

The three most-used options among home cooks are

- the SousVide Supreme,
- a PID-controller that controls another device, like a rice cooker, and
- the consumer immersion circulators from Anova, Nomiku, Sansaire, and PolyScience.

For professional chefs, the two most popular options are

- professional immersion circulators from PolyScience and Julabo and
- steam ovens, such as the Winston CVap and Rational's combi-ovens.

We'll discuss all these options so you'll be able to decide what's the best device for you.

Most of these options use a PID or proportional-integral-derivative controller. A PID controller how much power goes to the heater based on the temperature you set and the current temperature. When correctly tuned, a PID controller can keep the water to within a fraction of the temperature you set it at. In almost all applications, it doesn't matter if the temperature varies 1 °F (0.5°C) over the cooking time; even a variation of a few degrees doesn't matter for most foods if the average temperature is within 1 °F (0.5°C).

PID-controllered Rice Cookers, Steam Tables, Slow Cookers, and Electric Roasters

The PID-controllers by Fresh Meals Solutions and Auber Instruments have been used by home sous vide enthusiasts since the 2000s. In the last few years they've become more sophisticated and can easily control most water baths to within ½°F (¼°C). But now many home enthusiasts with a maker temperment are making their own PID controllers with a RaspberryPi or Arduino; I don't recommend making your own PID controller, especially if you're not experience working with high voltage electricity.

Most home cooks use a PID-controller use it with commercial rice cooker, a steam table or counter-top food warmer, a slow cooker or crock-pot, or a counter-top roaster. The most important consideration when purchasing such a device is that it must use a manual switch (which will not be reset when the power is turned on and off by the temperature controller). Many people prefer a rice cooker or steam table because they react faster than slow cookers and roasters (and so have less temperature over shoot). Moreover, because they are heated from below, rice cookers and steam tables often have sufficient convection currents to keep the water temperature spatially uniform; uncirculated slow cookers and roasters can have cold spots of as much as 10–20°F (5–10°C)! Regardless of the heating device, I highly recommended circulating the water with an aquarium air bubbler, which – unlike an aquarium pump that must be submerged in the water – will hold up to the heat of sous vide cooking.

With all digital controllers, I recommend setting the temperature offset (measured near the temperature at which you wish to cook) using a high quality digital thermometer. While most people find that their PID-controller is within 1°F (½°C), it's not uncommon for them to be initially off by 2–3°F (1–1½°C).

SousVide Supreme

In late 2009, Eades Appliance Technology introduced the SousVide Supreme, which combines a PID-controller and a water bath into a single appliance. I've use a SousVide Supreme since it came out and quite like it. Unlike an immersion circulator, it comes with a tight-fitting lid that greatly reduces water evaporation; this greatly reduces its electricity usage at higher temperatures and long cooking times. The bottom and sides are also insulated, which further decreases its energy footprint.

Some immersion circulator manufactures have claimed that it takes much longer to heat food in a SousVide Supreme compared with their immersion circulators. While it's true that I measured the surface heat transfer coefficient of the SousVide Supreme to be about 95 W/m^2-K compared with 155 W/m^2-K for my PolyScience 7306C immersion circulator, this didn't result in a measurable difference in the food's core temperature. In other words, once the surface heat transfer coefficient is high enough, the limiting factor is the thermal diffusivity of the food. Conventional ovens, in comparison, have a much lower surface heat transfer coefficient and here the surface heat transfer coefficient is the limiting factor – this is why the air in 400°F (200°C) oven doesn't instantly burn your hand and why boiling water does.

Immersion Circulators

There are several good options for both home cooks and restaurant chefs.

For home cooks, there are several good immersion circulators available for \$200–\$400. I've tried the models from Anova, Nomiku, Sansaire, and PolyScience; any of them will work great in a home kitchen. I especially like the latest models from Anova. The Creative series from PolyScience is also a good choice.

While restaurant chefs can use immersion circulators designed for home cooks, most restaurant chefs prefer heavier-duty models. I have used models from both Julabo and PolyScience. I was impressed by the Julabo FusionChef Diamond series because of its premium build quality and features, but it comes at premium price. Most restaurants will find that the PolyScience Chef series, PolyScience Classic series, and Julabo FusionChef Pearl series will meet their needs just as well at half the price. Which is good, because you'll probably want to have three or four going at different temperatures.

In the past, many sous vide enthusiasts bought use circulators off eBay from lab equipment resellers. The popularity of sous vide cooking has significantly increased the price of these used circulators and I can no longer recommend getting one. Most laboratory water baths are used around the clock and the remaining usable life per dollar is much less than a new consumer immersion circulator. Moreover, a significant problem with buying used laboratory water baths is that they may have been used in conjunction with carcinogens and pathogens; it's recommend that they first be cleaned with bleach, then cleaned with vinegar, and finally rinsed with a 70% (140 proof) alcohol.

Most restaurants use a 20 liter clear plastic food box (Cambro) with their immersion circulators. While a large stock pot is an acceptable option, a polycarbonate food box provides better insulation and it's easy to see the food cooking inside it. When cooking a large amount of food, a large cooler is a great option when you cover the top with plastic wrap to limit evaporation.

Convection Steam Ovens

Convection steam ovens are able to cook large quantities of food, but gas models can have temperature swings of up to 10°F (5°C) and electrical models of around 5°F (2.5°C). Moreover Sheard and Rodger (1995) found that none of the convection steam ovens they tested heated sous vide pouches uniformly when fully loaded. Indeed, it took the slowest heating (standardized) pouch 70%–200% longer than the fastest heating pouch to go from 68°F to 167°F (20°C to 75°C) when set to an operating temperature of 176°F (80°C). They believe this variation is a result of the relatively poor distribution of steam at temperatures below 212°F (100°C) and the oven's dependence on condensing steam as the heat transfer medium. Therefore, the tables in this guide cannot be used and needle temperatures probes must be used to determine cooking and pasteurization times.

But while a water bath does a better job at sous vide cooking, modern ovens can do a lot more than sous vide cooking and can cook huge quantities of food. I strongly recommend reading the Chapter 8, Volume 2 of Myhrvold, Young, and Bilet's *Modernist Cuisine* (2011) to learn all about modern ovens like the Rational combi oven or Winston CVap.

Vacuum Sealers

Resealable pouches, such as Ziploc heavy-duty freezer bags, work very well for sous vide cooking below about 195°F (90°C) – above that temperature, the plastic softens and the bag might fail. When using a resealable pouch, it's important to remove as much air as possible so it doesn't insulate the food from the water (since air is a very poor conductor of heat). I do this by adding liquid to the pouch with the raw food and then submerging the pouch in cool water to displace the air; for detailed instructions see pages 250–251 in Sous Vide for the Home Cook or watch my chicken breasts video. You can also just drop the bottom of the pouch, with the food and liquid inside, into the hot water bath, leave the top open, and clamp the open top to the side of the water bath.

Some home cooks use clamp-style vacuum sealers, such as a FoodSaver or the SousVide Supreme vacuum sealer. The problem with clamp- or edge-style vacuum sealers is that it is difficult to get a strong vacuum, the bags are expensive (compared to those used in chamber machines), and liquids tend to get sucked into the machine. If your recipe calls for liquid to be in the pouch, I'd recommend using a resealable pouch instead of your clamp-style vacuum sealer. If you do want to use your clamp-style vacuum sealer, you can either

- freeze the liquid before putting it into the pouch; for instance, freezing a small ice cube tray filled with extra virgin olive oil is quite convenient.
- cut the pouch long, hang the edge over the counter (so the liquid is below the level of the vacuum channel), and push the "seal" or "stop and seal" button just before the liquid reaches the vacuum sealer.

Some advanced home and many professional cooks use a chamber-style vacuum sealers (such as the Minipack MVS31). These machines are able to pull a much stronger vacuum than clamp-style vacuum sealers, use less expensive bags ($0.12 per square foot verse $0.42 per square foot), and are able to package liquids without freezing. However, chamber vacuum sealers are much larger and heavier than clamp style vacuum sealers and cost more than ten times as much.

Regardless of how you vacuum seal your food, I recommend adding liquid to keep the food's edges from getting crimped while cooking. The more delicate the food, the more liquid you should add; for example, you might put the same weight of oil as scallops in the bag to keep them from getting deformed.

Digital Thermometers

Accurate temperature control is important for safe sous vide cooking: pasteurization times depend critically on temperature. I recommended that anyone interested in precision cooking – sous vide or traditional – invest in a good digital thermometer. For everyday cooking, the Comark PDQ400 is a great entry-level thermocouple thermometer – I keep one in my backpack just in case I find myself cooking at a friend's house. If you have the money, ThermoWorks' Thermapen is much faster than the PDQ400 and even easier to use.

If you like doing science experiments, you might consider getting several interchangeable probes and a thermometer that can read them. I have several K- and T-type probes from ThermoWorks and I'm very happy with them, especially the needle probes which respond very quickly.

Basic Equipment Suggestions

$25–100

Heavy-duty Ziploc freezer bags and a large pot on a stove using a good digital thermometer.

$200–450

Heavy-duty Ziploc freezer bags and a consumer immersion circulator or SousVide Supreme.

$600–3,000

Heavy-duty Ziploc freezer bags and one or more heavy-duty immersion circulators.

$4,000–10,000

Large chamber vacuum sealer and two or more heavy-duty immersion circulators.

$20,000+

Large chamber vacuum sealer, several heavy-duty immersion circulators, and a Rational combi-oven.

C. Government Pasteurization Tables

The pasteurization times for beef, lamb and pork are listed in Table C.1. Table C.2 lists the pasteurization times for chicken and turkey.

Temperature °F (°C)	*Time (Minutes)*	*Temperature °F (°C)*	*Time (Seconds)*
130 (54.4)	112 min	146 (63.3)	169 sec
131 (55.0)	89 min	147 (63.9)	134 sec
132 (55.6)	71 min	148 (64.4)	107 sec
133 (56.1)	56 min	149 (65.0)	85 sec
134 (56.7)	45 min	150 (65.6)	67 sec
135 (57.2)	36 min	151 (66.1)	54 sec
136 (57.8)	28 min	152 (66.7)	43 sec
137 (58.4)	23 min	153 (67.2)	34 sec
138 (58.9)	18 min	154 (67.8)	27 sec
139 (59.5)	15 min	155 (68.3)	22 sec
140 (60.0)	12 min	156 (68.9)	17 sec
141 (60.6)	9 min	157 (69.4)	14 sec
142 (61.1)	8 min	158 (70.0)	0 sec

143 (61.7)	6 min
144 (62.2)	5 min
145 (62.8)	4 min

Table C.1: Pasteurization times for beef, corned beef, lamb, pork and cured pork (FDA, 2009, 3-401.11.B.2).

Temperature °F (°C)	*Time 1% fat*	*Time 3% fat*	*Time 5% fat*	*Time 7% fat*	*Time 9% fat*	*Time 12% fat*
136 (57.8)	64 min	65.7 min	68.4 min	71.4 min	74.8 min	81.4 min
137 (58.3)	51.9 min	52.4 min	54.3 min	56.8 min	59.7 min	65.5 min
138 (58.9)	42.2 min	42.7 min	43.4 min	45.3 min	47.7 min	52.9 min
139 (59.4)	34.4 min	34.9 min	35.4 min	36.2 min	38.3 min	43 min
140 (60.0)	28.1 min	28.5 min	29 min	29.7 min	30.8 min	35 min
141 (60.6)	23 min	23.3 min	23.8 min	24.4 min	25.5 min	28.7 min
142 (61.1)	18.9 min	19.1 min	19.5 min	20.1 min	21.1 min	23.7 min
143 (61.7)	15.5 min	15.7 min	16.1 min	16.6 min	17.4 min	19.8 min
144 (62.2)	12.8 min	12.9 min	13.2 min	13.7 min	14.4 min	16.6 min
145 (62.8)	10.5 min	10.6 min	10.8 min	11.3 min	11.9 min	13.8 min
146 (63.3)	8.7 min	8.7 min	8.9 min	9.2 min	9.8 min	11.5 min
148 (64.4)	5.8 min	5.8 min	5.9 min	6.1 min	6.5 min	7.7 min
150 (65.6)	3.8 min	3.7 min	3.7 min	3.9 min	4.1 min	4.9 min
152 (66.7)	2.3 min	2.3 min	2.3 min	2.3 min	2.4 min	2.8 min
154 (67.8)	1.5 min	1.5 min	1.5 min	1.5 min	1.5 min	1.6 min
156 (68.9)	59 sec	59.5 sec	1 min	1 min	1 min	1 min
158 (70.0)	38.8 sec	39.2 sec	39.6 sec	40 sec	40.3 sec	40.9 sec
160 (71.1)	25.6 sec	25.8 sec	26.1 sec	26.3 sec	26.6 sec	26.9 sec
162 (72.2)	16.9 sec	17 sec	17.2 sec	17.3 sec	17.5 sec	17.7 sec
164 (73.3)	11.1 sec	11.2 sec	11.3 sec	11.4 sec	11.5 sec	11.7 sec
166 (74.4)	0 sec	0 sec	0 sec	0 sec	0 sec	0 sec

Table C.2: Pasteurization times for a 7D reduction in Salmonella for chicken and turkey (FSIS, 2005).

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Version History: I posted the first version of my guide, then called “A Short Guide to Sous-Vide,” on 22 February 2008. I posted version 0.3a on 10 March 2008 and this version had most the content that’s in the current version; I changed the name to “A

Practical Guide to Sous Vide Cooking” in 0.3b on 16 July 2008. I made a major revision and rewrote most the chapters for version 0.4a, which I posted on 1 September 2008, and made small improvements up until version 0.4f on 28 November 2008. This is the version that was translated into French and German. On 26 March 2009, for version 0.4g, I added the section on the Maillard reaction.

Then I wrote my cookbook, “Sous Vide for the Home Cook”: I started writing in earnest on 27 July 2009; submitted my first complete draft for editing on 3 November 2009; second draft on 3 January 2010; final draft for typesetting on 11 February 2010—it was officially published on 12 April 2010.

I updated the equipment chapter (to include most the new equipment that’s been released since 0.4g) in version 0.4h on 8 February 2011. On 18 June 2011, for version 0.4i, I updated the food safety chapter and most of the heating, cooling, and pasteurization tables. On 25 December 2014, for version 0.4j, I again updated the equipment section to reflect the new equipment that's become available.

If you have any specific update requests, please email me. In my next updates I plan to: update the egg section to link to my work with ChefSteps.com, add a chapter on cooking fruits and vegetables, update the equipment section, and revise the basic techniques chapter to improve readability and add some new results.