A Practical Guide to Sous Vide Cooking

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Preface

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

This guide attempts to distill the science of sous vide cooking to provide anyone with the tools needed to safely realize their 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 necessary for sous vide cooking.

Introduction

Sous vide is a method of cooking in vacuum sealed plastic pouches at low temperatures for long times. Sous vide differs from conventional cooking methods in two fundamental ways: (i) the raw food is vacuum sealed in 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 cooking fish, meat and poultry. Consider the problem of cooking a thick-cut steak medium-rare. Cooking the steak on a grill at over 1 000°F (500°C) until the center comes up to 120°F (50°C) will result in everything but the very center being overcooked. A common solution is to sear one side of the steak in a pan, flip the steak over, and place the pan in a 275°F (135°C) oven until the center comes up to 131°F (55°C). For sous vide, the steak is vacuum sealed in a plastic pouch, cooked in a 131°F (55°C) water bath for a couple hours, and then seared in a smoking hot pan or with a blowtorch; the result is a medium-rare steak with a great crust that is the same doneness at the edge as it is at the center. Moreover, the flavorful flat iron steak can be cooked (very safely) in a 131°F (55°C) water bath for 24 hours and will be both medium-rare and as tender as filet mignon.

Part I

Technique

1. Safety

Our goal is to maximizing taste while minimizing the risk of food pathogens. Although pathogenic microorganisms can be controlled with the addition of acids, salts and some spices, sous vide prepared foods rely heavily on temperature control (Rybka-Rodgers, 2001).

Background

The myth of the "danger zone" of 40°F to 140°F (4°C to 60°C) is absurd. It is well known that food pathogens can multiply between 29.3°F and 127.5°F (–1.6°C and 53°C), while spoilage bacteria begin to multiply at 23°F (–5°C) (Snyder, 2006). Moreover, contrary to popular belief, most food pathogens and toxins cannot be seen, smelt or tasted.

All sous vide prepared foods can be divided into three categories: (i) raw or unpasteurized, (ii) *pasteurized*, and (iii) *sterilized*. Pasteurization means heat treating the food to reduce the number of *vegetative* pathogens to a safe level. Vegetative pathogens are simply active bacteria that are growing and multiplying. Some bacteria are also able to form *spores* which are very resistant to heat and chemicals. Heat treating food to reduce both the vegetative microorganisms and the spores to a safe level is called sterilization[1].

Pasteurized foods 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 populations. Even for immune competent individuals, it is 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 (Anon., 2005b, 3-501.19.B).

Pasteurization is a combination of both temperature *and* time. Consider the common food pathogen *Salmonella spp.* At 140°F (60°C), all the *Salmonella* in a piece of ground beef does not 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. Beef is considered safe after 6.5 decimal reductions of *Salmonella* (Anon., 2005a) or after $6.5D_{60}^{6.0} = 35.6$ 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 vegetative 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 spp.* and *Bacillus cereus* (Aran, 2001; Rybka-Rodgers, 2001).

[1]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). Sterilized foods are shelf stable, but are grossly overcooked and taste similar to canned foods.

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; while tough cuts of beef can be cooked and held in a 130°F (54.4°C) water bath for 24–48 hours, most food products can only be held for 8–10 hours before becoming unacceptably tender.

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 on the following page.

For cook-chill sous vide, it is important that cooking achieves at least a six-decimal reduction in *Listeria monocytogenes*; *Listeria* is the most heat-resistant non-spore forming pathogen and is able to grow at refrigerator temperatures (Nyati, 2000b; Rybka-Rodgers, 2001). Moreover, while keeping the 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

(i) below 36.5°F (2.5°C) for up to 90 days,
(ii) below 38°F (3.3°C) for less than 31 days,
(iii) below 41°F (5°C) for less than 10 days, or
(iv) 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-time combinations which can reduce non-proteolytic *C. botulinum* to a safe level; specifically, a 6D 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). If there was no oxygen in the bag, then the food could be stored at below 50°F (10°C) indefinitely—the minimum temperature at which proteolytic *C. botulinum* and *C. perfringens* can grow (Rybka-Rodgers, 2001). However, O'Mahony et al. (2004) found that the majority of pouches after vacuum packaging had high levels of residual oxygen.

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

Thickness mm	131°F 55°C	141°F 60.5°C	176°F 80°C
5	1	1	1
10	4	4	5
15	10	10	11
20	17	18	20
25	27	28	30
30	38	40	43
35	52	54	59
40	1:07	1:10	1:17
45	1:25	1:28	1:37
50	1:45	1:49	1:59
55	2:07	2:11	2:24
60	2:30	2:36	2:51
65	2:56	3:03	3:21
70	3:24	3:31	3:53

Table 1.1: Approximate cooling times (HH:MM) for the core temperature of meat to reach 41°F (5°C) in an ice water bath which is at least half ice.

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 2.3 and 2.4 on page 8).

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 finishes 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.

Above the shrinking temperature of collagen, it loses its structure, is soluble in water, and is called gelatin. While the peak temperature of denaturation of intact collagen is 144–145°F (62–63°C) [in fish, the shrinking temperature is 113°F/45°C], enzymatic denaturation by collagenase peaks at 131–135°F (55–57°C) (Beltran et al., 1991).

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!

While there is no consensus as to what temperatures rare, medium-rare and medium correspond to, I use the temperatures in Table 2.2 on the following page. 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 2.3 on the next page and 2.4 on the following page. For a complete discussion on how these times were computed, please see Appendix A.

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 is as tender as 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 2.3 or 2.4 on the next page 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

	Rare	*Medium-Rare*	*Medium*
Meat	125°F (51.5°C)	130°F (54.5°C)	140°F (60°C)
Fish	110°F (43.5°C)	120°F (49°C)	140°F (60°C)

Table 2.2: Temperatures corresponding to rare, medium-rare and medium in meat and fish.

	Heating Time from 38°F (3°C)				
Thickness	111°F	121°F	126°F	131°F	141°F
mm	44°C	49.5°C	52°C	55°C	60.5°C
5	2	2	2	2	2
10	7	8	8	8	8
15	17	17	17	18	18
20	30	30	31	31	32
25	46	47	48	48	49
30	1:06	1:08	1:09	1:09	1:11
35	1:30	1:32	1:33	1:34	1:36
40	1:57	2:00	2:02	2:03	2:06
45	2:28	2:32	2:34	2:35	2:38
50	3:02	3:07	3:10	3:12	3:16
55	3:40	3:46	3:49	3:51	3:56
60	—	—	—	4:35	4:41
65	—	—	—	5:23	5:30
70	—	—	—	6:15	6:23

Table 2.3: Approximate cooking times (in HH:MM) for thawed meat (at 38°F/3°C) when the temperature of the water bath is 1°F (0.5°C) above the desired core temperature of the meat.

	Heating Time from 0°F (–18°C)				
Thickness	111°F	121°F	126°F	131°F	141°F
mm	44°C	49.5°C	52°C	55°C	60.5°C
5	2	2	2	2	2
10	9	9	9	9	9
15	21	21	21	21	21
20	37	37	37	37	38
25	58	58	58	58	58
30	1:23	1:23	1:23	1:24	1:24
35	1:52	1:53	1:53	1:54	1:54
40	2:27	2:27	2:28	2:28	2:29
45	3:05	3:07	3:07	3:08	3:09
50	3:48	3:50	3:51	3:51	3:53
55	4:36	4:38	4:39	4:40	4:42
60	—	—	—	5:33	5:35
65	—	—	—	6:31	6:33
70	—	—	—	7:33	7:36

Table 2.4: Approximate cooking times (in HH:MM) for frozen meat (at 0°F/–18°C) when the temperature of the water bath is 1°F (0.5°C) above the desired core temperature of the meat.

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 cooking 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 3.5 on the following page (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.

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 3.5 on the next page.

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 on page 4) 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 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 food borne 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

Pasteurization Time from 41°F (5°C)

	Lean Fish			Fatty Fish		
Thickness	131°F	136°F	141°F	131°F	136°F	141°F
mm	55°C	57.5°C	60.5°C	55°C	57.5°C	60.5°C
5	2:18	50	16	4:30	1:27	27
10	2:22	55	21	3:59	1:32	32
15	2:31	1:04	30	4:08	1:40	41
20	2:42	1:16	41	4:20	1:52	53
25	2:58	1:31	56	4:35	2:07	1:08
30	3:16	1:50	1:12	4:53	2:26	1:25
35	3:38	2:11	1:31	5:15	2:48	1:45
40	4:03	2:35	1:52	5:40	3:13	2:08
45	4:31	3:01	2:14	6:09	3:40	2:32
50	5:02	3:29	2:39	6:40	4:10	2:58
55	5:36	4:00	3:05	7:15	4:43	3:27
60	6:12	4:32	3:33	7:52	5:18	3:57
65	6:51	5:07	4:03	8:33	5:55	4:29
70	7:33	5:44	4:35	9:16	6:34	5:03

Table 3.5: Pasteurization times (HH:MM) for a 6D reduction of *Listeria monocytogenes* in finfish. Lean fish (such as cod) has $D_{60}^{5.59}$ = 2.88 minutes, while fatty fish (such as salmon) has $D_{60}^{5.68}$ = 5.13 minutes (Embarek and Huss, 1993).

24 hours) to kill the parasites or pasteurizing the fish using the times and temperatures in Table 3.5.

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 easily prevented by brining the fish in a 10% salt water solution for 10 minutes.

Fresh Wild Salmon
Olive Oil
Salt and Pepper
Garlic Powder (Optional)

Set the temperature of the water bath to 101°F (38.5°C) for very rare salmon, 116°F (47°C) for rare-medium-rare salmon, or 126°F (52°C) for medium-medium-rare 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 brine the salmon in the refrigerator for 10 minutes.

If cooking the salmon medium or medium-rare, 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.

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).

Cook the salmon for the times listed in Table 3.6 on the facing page, garnish with crisped salmon skin and serve immediately.

Heating Time from 41°F (5°C)			
Thickness	101°F	116°F	126°F
mm	38.5°C	47°C	52°C
5	2	2	2
10	7	7	7
15	15	16	16
20	26	28	28
25	41	43	44
30	59	1:02	1:03
35	1:20	1:24	1:25
40	1:44	1:49	1:51
45	2:11	2:18	2:21
50	2:42	2:49	2:53
55	3:16	3:25	3:30

Table 3.6: Cooking times for thawed salmon cooked very rare, rare-medium-rare and medium-medium-rare in HH:MM. These times and temperatures do not pasteurize the salmon, and should never be served to immune compromised individuals.

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 4.7 on page 16. [After cooking, the breasts may be rapidly cooled in ice water (see Table 1.1 on page 4) 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 using either a very hot pan (with just smoking oil) or a blowtorch. Serve immediately (garnished with crisped skin).

Turkey, Duck or Goose Leg 'Confit'

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

If brining, 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.

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 on page 4) 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 on the facing page, we observe that the denaturing of the protein ovotransferrin at 144°F (62°C) causes the egg white to coagulate (This, 2006, Chap 3).

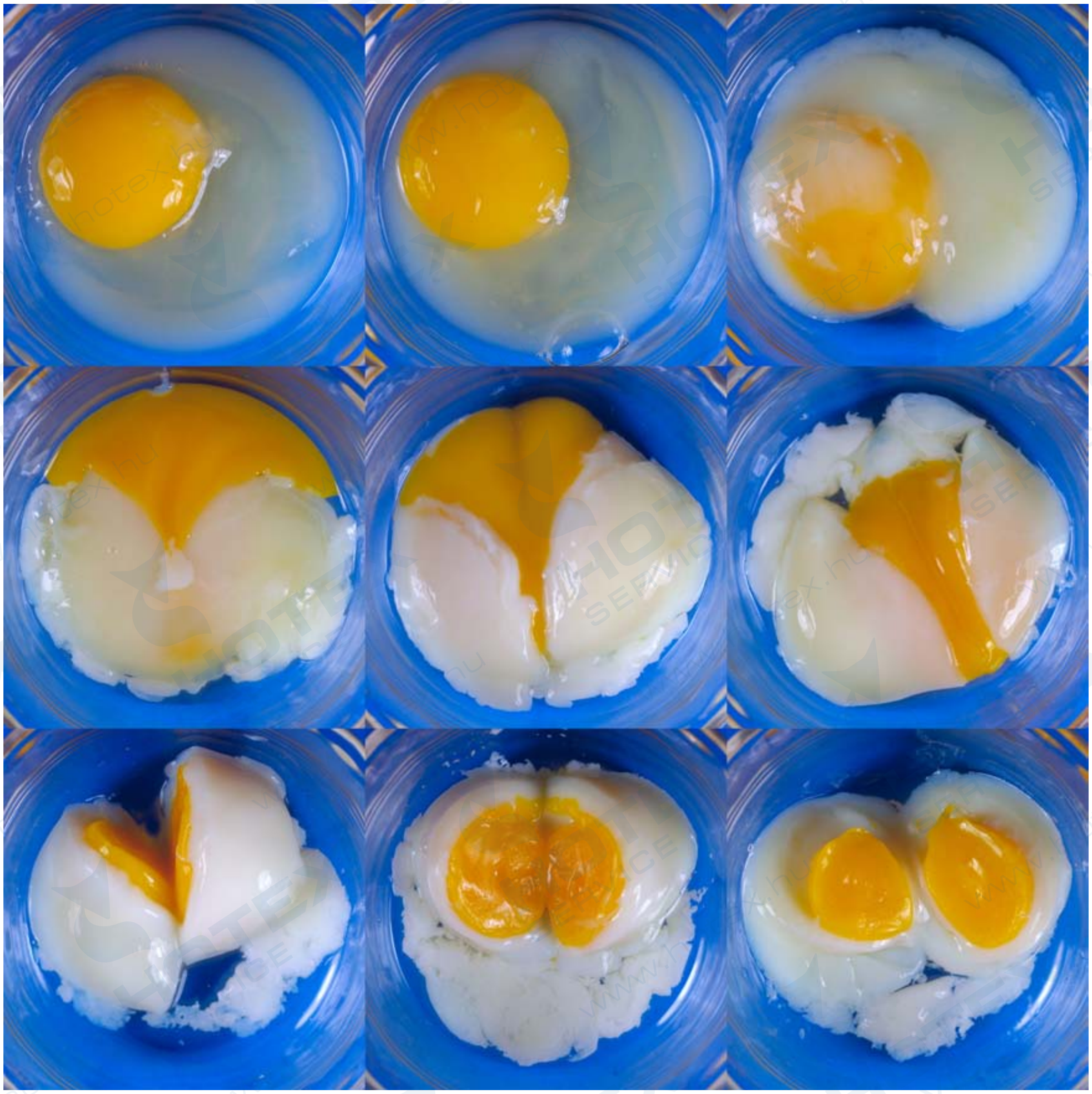

Figure 4.1: Pictures of intact eggs cooked in a water bath for 75 minutes at temperatures ranging from 136˚F (57.8˚C) to 152˚F (66.7˚C). From left-to-right and top-to-bottom, the water bath temperature was 136.0˚F (57.8˚C), 138.0˚F (58.9˚C), 140.0˚F (60.0˚C), …, 152˚F (66.7˚C).

Pasteurization Time from 41°F (5°C)

Thickness	136°F	141°F	146°F	151°F
mm	57.5°F	60.5°C	63.5°F	66°C
5	1:40	31	10	5
10	1:45	36	15	10
15	1:53	44	23	17
20	2:04	55	34	26
25	2:18	1:09	46	38
30	2:35	1:25	1:01	51
35	2:55	1:44	1:17	1:05
40	3:18	2:05	1:36	1:22
45	3:44	2:28	1:56	1:40
50	4:12	2:54	2:17	1:59
55	4:43	3:20	2:41	2:20
60	5:16	3:49	3:06	2:43
65	5:52	4:20	3:32	3:07
70	6:29	4:52	4:01	3:33

Table 4.7: Time required for a 6D reduction of *Listeria monocytogenes* in poultry. These times are computed using log D-value = 11.37 – 0.1766T°C which is equivalent to $D_{60}^{5.66}$ = 5.94 minutes (calculated using linear regression from Table 2 of (O'Bryan et al., 2006)). For more information on calculating log reductions, see Appendix A.

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

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 2.3 on page 8. 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 5.8 on the following page. 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).

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 24 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 on page 4) 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 on page 4) 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

Pasteurization Time from 41°F (5°C)

Thickness mm	131°F 55°C	136°F 57.5°C	141°F 60.5°C	146°F 63.5°C
5	1:17	42	21	10
10	1:21	46	25	15
15	1:28	53	32	22
20	1:37	1:02	41	31
25	1:49	1:14	53	41
30	2:03	1:29	1:06	54
35	2:20	1:45	1:21	1:07
40	2:40	2:03	1:38	1:23
45	3:01	2:23	1:56	1:39
50	3:24	2:45	2:16	1:57
55	3:49	3:08	2:37	2:16
60	4:16	3:33	2:59	2:36
65	4:44	3:59	3:23	2:58
70	5:14	4:26	3:48	3:21

Table 5.8: Time (HH:MM) required for a 6D reduction of *Listeria monocytogenes* in thawed meat. Here we used the log D-value = 7.07 − 0.1085T°C ($D_{60}^{9.22}$ = 3.63 minutes), which was calculated using linear regression from (O'Bryan et al., 2006, Table 1) as well as (Bolton et al., 2000, Table 2) and (Hansen and Knøchel, 1996, Table 1). For more information on calculating log reductions, see Appendix A. *Note: 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).*

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 on page 4) 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 medium-rare), 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 5.8 on the facing page. [The chop may be rapidly cooled in ice water (see Table 1.1 on page 4) 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 on page 4) 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 on page 4) 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 on page 4) 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 (m²/sec), k is thermal conductivity (W/m-K), ρ is density (kg/m³), 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

$$\begin{cases} \rho C_p(T) T_t = k(T)\{T_{rr} + \beta T_r/r\}, \\ T(r,0) = T_0, \qquad T_r(0,t) = 0, \\ k(T) T_r(R,t) = h\{T_{\text{Water}} - T(R,t)\}, \end{cases} \qquad (*)$$

where $t \geq 0$, $0 \leq r \leq R$ is the distance from the core, $0 \leq \beta \leq 2$ is a geometric factor, $T_t = \partial T/\partial t$, $T_r = \partial T/\partial r$, $T_{rr} = \partial^2 T/\partial r^2$, 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/m²-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.2 on the next page.

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

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/m³ at 41°F (5°C) and 1067 kg/m³ at 86°F (30°C). This is much less than the difference between beef sirloin ($\alpha = 1.24 \times 10^{-7}$ m²/sec) and beef round ($\alpha = 1.11 \times 10^{-7}$ m²/sec) (Sanz et al., 1987). Therefore, we can model the temperature of thawed foods by

$$\begin{cases} T_t = \alpha\{T_{rr} + \beta T_r/r\}, \\ T(r,0) = T_0, \qquad T_r(0,t) = 0, \\ T_r(R,t) = (h/k)\{T_{\text{Water}} - T(R,t)\}, \end{cases}$$

for $0 \leq r \leq R$ and $t \geq 0$. Since h is large (500–700 W/m²-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.

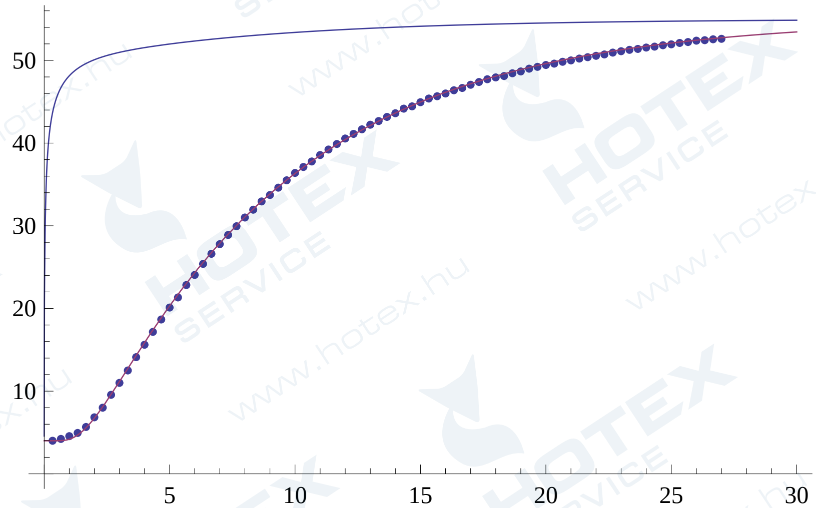

Figure A.2: Plot of temperature (°C) verse time (minutes) of a 27 mm thick piece of Mahi-Mahi cooked in a 131°F (55°C) water bath. The blue dots are the core temperature measured using a ThermoWorks MicroTherma2T with a needle probe. The red line is the calculated core temperature and the blue line is the calculated surface 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 600 W/m^2-K).

Most foods have a thermal diffusivity between 1.2 and 1.6×10^{-7} m^2/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 $\alpha = 0.995\times10^{-7}$ m^2/s in all my tables because it is lower than the thermal diffusivities reported in the literature (see Table A.9 on the following page). 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.

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

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

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*.

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

B. Equipment

Digital Thermometers

Accurate temperature control is important for safe sous vide cooking. Pasteurization times depend critically on temperature. Many PID controlled water baths are off by 2°F (1°C) or more; so if a water bath is set at 141°F (60.5°C) it might only really be 139°F (59.5°C), and would mean a chicken breast needs 15 minutes more than expect to be considered safe. It is highly recommended that any chef interested in sous vide invest in a high quality digital thermometer.

On the low end, I would highly recommend ThermoWorks' Super-Fast Thermapen. Interchangeable probes are very useful in sous vide, so you may want to invest in a ThermoWorks MicroTherma 2T.

Vacuum Sealers

For short cooking times, it is often possible to wrap the food in a high quality plastic wrap; however, it is difficult to keep the liquid released by the food in and the liquid from the water bath out. Any air trapped in the plastic wrap will balloon during heating and insulate the food (since air is a very poor conductor of heat); ballooning might also cause the food to float to the surface of the water bath and result in unevenly cooked food.

If you do not have (and do not want to buy) a vacuum packaging system, the best solution is to use the inexpensive Reynolds Handi-Vac; the vacuum is not as strong as clamp or chamber style vacuum sealers, but it is inexpensive and the bags have been tested and work well for everything from salmon to pork shoulder.

Most home cooks use clamp style vacuum sealers, such as FoodSaver and Seal-A-Meal. 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. The easiest solution for vacuum sealing liquids is to freeze them before sealing; for instance, freezing a small ice cube tray filled with extra virgin olive oil is especially convenient.

Some advanced home and many professional cooks use 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.

Water Baths and Steam Ovens

Temperature Controlled Rice Cookers, Steam Tables, Slow Cookers and Electric Burners

For short cooking times (such as when cooking fish), a pan of water on the stove can be used if the cook is 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 simplest (and least expensive) digital controllers used for sous vide are on-off (or bang-bang) controllers, such as the Ranco ETC. When tested with a steam table, I found that the Ranco ETC kept the water bath within ± 2.1°F (± 1.2°C). This level of temperature control is sufficient for nearly all sous vide applications.

A particularly popular digital control for sous vide cooking is the PID controllers by Auber Instruments and Fresh Meals Solutions. Unlike an on-off controller, it must be tuned to the cooking device being used; I found that after tuning that an Auber PID controller kept my steam table water bath to within ±0.7°F (±0.4°C).

With all these digital controllers, I highly recommend setting the temperature offset (measured near the temperature at which you wish to cook) using a high quality digital thermometer. Indeed, at the default settings the thermistors used in the above controllers can easily be off 2–4°F (1–2°C).

These temperature controllers are often used with either a a counter top food warmer (or steam table), commercial rice cooker, a electric (induction) burner, a slow cooker (or crock pot), or a 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 use a rice cooker, steam table or electric burner 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, steam tables and electric burners 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, it is highly recommended that a circulator be used in conjunction with the temperature controller. The most popular options for circulating the water is an aquarium air bubbler—aquarium pumps which must be submerged in the water are not designed to operate at sous vide temperatures and quickly fail. Another popular options for circulating the water is a swamp cooler pump because it is not submerged in the water and is designed for continuous operation.

Laboratory Immersion Circulators

Circulating laboratory water baths are extremely popular because they are able to keep a large volume of water (often up to 50 liters) to ±0.1°F (±0.05°C). Many were purchased used on eBay for $100–$200, but because of the increased demand from sous vide are now selling for $350–$500. A significant problem with buying used laboratory water baths is that they may have been used in conjunction with carcinogens and pathogens; it is recommend that they first be cleaned with bleach, then cleaned with vinegar, and finally rinsed with a 70% (140 proof) alcohol. With the rising price of used circulating water baths, many are buying new immersion circulators from PolyScience and Techne.

While some cooks purchase specially designed stainless steel or acrylic tanks for their immersion circulators, most use either a large stock pot or a steam table pan. I find that a countertop food warmer (designed to hold a full size steam table pan) to be especially convenient; these food warmers are insulated, hold about 20 liters of water, and if set at a temperature just below the cooking temperature will insure that if the circulator fails the food will not be ruined.

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 ovens 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.

Basic Equipment Suggestions

The table below is meant to give an idea of the approximate cost of various sous vide setups.

Cost	Vacuum Sealer	Heating System
$10	Reynolds Handi-Vac	Stock pot on stove
$70–$110	—	Ranco ETC controlled large rice (or slow) cooker (with an aquarium air pump for circulation)
$110–$150	—	PID controlled large rice (or slow) cooker (with an aquarium air pump for circulation)
$220–$260	FoodSaver V2840	—
$450–$600	—	Used eBay immersion circulator
$1 100	—	New immersion circulator (e.g., PolyScience 7306C) in a large stock pot or steam table pan
$1 350	—	New immersion circulator used in a counter top food warmer
$2 500	VacMaster SVP-10	—
$3 000	MiniPack MVS-31	—
>$3 000	Large Chamber Vacuum Sealer	Multiple new immersion circulators or convection steam oven(s)

C. Government Pasteurization Tables

The pasteurization times for beef, lamb and pork are listed in Table C.10. Table C.11 on the facing page 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.10: Pasteurization times for beef, corned beef, lamb, pork and cured pork (Anon., 2005b, 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.11: Pasteurization times for a 7D reduction in *Salmonella* for chicken and turkey (Anon., 2005a).

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