Teagasc
Agriculture and Food Development Authority

FINAL REPORT

Project RMIS No. 4875

Developing *Sous Vide*/Freezing Systems for Ready-Meal Components

The National Food Centre
RESEARCH & TRAINING FOR THE FOOD INDUSTRY
RESEARCH REPORT NO 70

DEVELOPING *SOUS VIDE*/FREEZING SYSTEMS FOR READY-MEAL COMPONENTS

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ISBN: 1 84170 403 2
April 2005

Teagasc Oakpark Carlow Co. Carlow

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SUMMARY

Sous vide cooking involves sealing raw or par-cooked food in a vacuumised laminated plastic pouch or container, cooking by controlled heating, rapid chilling and then re-heating for consumption. The chilled storage period is up to 21 days at 0 to 3°C. The recommended thermal process for *sous vide* products is 90°C for 10min or its time-temperature equivalent. Concerns about the safety of *sous vide* products, mainly due to the potential for temperature abuse in the chill chain, has prevented the widespread use of this technology. The role of the current project, therefore, was to investigate *sous vide* cooking followed by freezing, as a safe alternative to *sous vide*/chilling for 10 ready-meal components *i.e.* carbohydrates (potatoes, pasta, rice), vegetables (carrots, broccoli) and muscle foods (salmon, cod, chicken, beef and lamb).

A survey conducted on the quality of 36 samples of commercially-produced *sous vide* ready-meals indicated that 14 products received scores of 8/10 or higher [samples scored from 0 (unacceptable) to 10 (highly acceptable)] while eight samples scored 5/10 or lower. A review was also conducted on production technologies for *sous vide* ready-meals embracing ingredients, vacuum packing/sealing, cooking/cooling equipment, labelling/storage/reheating, and finally computer-aided manufacturing.

A P-SV-F system for *sous vide* processing of the 10 ready-meal components embracing pre-treatments (P), *sous vide* cook time/temperature (SV), and freezing (F) post-*sous vide* cooking was developed and validated. There was a particular focus on the effects of the P-SV-F system on product texture. However, taste panels were unable to detect a significant difference between the *sous vide* frozen *vs* chilled samples indicating that freezing was having a minimal adverse effect, if any, on texture. Rate of freezing or long term (up to 8 months) frozen storage had only a small effect on *sous vide* product characteristics.

Research on the safety of the P-SV-F system indicated that a *sous vide* cook time of 10 min at 90°C (core temperature) delivered safe *sous vide* frozen products. However, the possibility of increased pathogen thermotolerance via stress responses resulting from the P-SV-F system needs to be recognised.

The enterprise planning for setting up a world-class ready-meal manufacturing system based on *sous vide* technology was reviewed. The manufacturing steps (unit operations) of a *sous vide* system for ready-meal production were addressed and organisational implications analysed for each case. Recommendations are given on the best practices for production management and product logistics.

Industry participated in the project, including one large company, one SME and three start-up companies. Over 60 companies received project results.

INTRODUCTION

Sous vide, also known as *cuisine en papillote sous vide*, is an interrupted catering system in which raw or par-cooked food is sealed in a vacuumised laminated plastic pouch or container, heat-treated by controlled cooking, rapidly chilled and then reheated for service after a period of chilled storage (SVAC, 1991). The chilled storage period is up to 21 days at 0 to 3°C. The recommended thermal process for *sous vide* products is 90°C for 10 min or its time-temperature equivalent (SVAC, 1991). This thermal process will ensure a minimum 6-log reduction in psychrotrophic *Clostridium botulinum* spores as well as a 6-log reduction in vegetative pathogens such as *Listeria*, *Salmonella* and *Escherichia coli*.

Sous vide has been used mostly in the catering and food service sectors (Creed and Reeve, 1998) but more recently it is being used in the ready-meals sector. Concerns about the safety of *sous vide* products, mainly due to the potential for temperature abuse in the chill chain, has prevented its widespread use (Betts, 1992). If temperature abuse does occur at chill, the botulinum spores could grow in the product to produce a potentially lethal toxin.

An alternative to chilling *sous vide* products is freezing. Freezing has two advantages: (i) it minimises the risk of growth of *Clostridium botulinum* spores and (ii) it extends product shelf-life. The main disadvantage is that it could negate some of the potential quality advantages of the *sous vide* process, especially product texture, due to structural damage by ice crystals.

The current project was novel in at least two respects. Firstly, the use of *sous vide* cooking followed by freezing instead of chilling allows the recommended process to be reduced significantly as there is little risk of botulinum growth. However, such a product could only be reheated from frozen for immediate consumption. Secondly, the use of consumer-size portions as opposed to catering-size portions is a relatively new innovation. Ten different foods were studied in three groups; carbohydrates (potatoes, pasta and rice), vegetables (carrots and broccoli) and muscle foods (salmon, cod, chicken, beef and lamb). The project involved the optimisation of pre-treatments, *sous vide* cooking times/temperatures, and post-*sous vide* treatments to deliver frozen *sous vide* foods with acceptable textural quality as well as microbiological safety. Supply chain and logistics aspects were also studied. The project partnership of The National Food Centre (NFC), University of Limerick (UL) and University College Cork (UCC) resulted in the ideal blend of expertise to deliver the 11 project elements. These were:

1. Survey on the quality of commercially produced *sous vide* ready-meals (NFC)
2. Review of production technologies for *sous vide* ready-meals (NFC)
3. Determining ideal texture (NFC)
4. Evaluation of pre-treatments (NFC)
5. *Sous vide* cooking (NFC)
6. Retention of nutrients (β-carotene, thiamine and vitamin C) (NFC)
7. Freezing *vs* chilling (NFC, UCC)
8. Effect of freezing rate and storage time (UCC, NFC)
9. Safety aspects (UL)
10. Logistics of *sous vide* manufacturing (UCC)
11. Industrial applications (NFC, UCC)

The collective outcomes from the 11 project elements provide a key platform of scientific and technical information on the *sous vide* processing of ready-meal components coupled with freezing which will aid the Irish prepared foods sector involved with ready-meals to continue its dynamic growth and to further realise its commercial potential (PCFG, 2003).

MATERIALS AND METHODS

Sous vide/freezing tests were conducted on carbohydrates (sliced potatoes, pasta, rice), vegetables (sliced carrots, broccoli florets) and muscle foods (salmon portions, cod portions, chicken, beef and lamb pieces/cubes). All samples received pre-treatments (see below and Table 3) prior to *sous vide* cooking. This was carried out using a Barriquand Steriflow cooker (Barriquand Steriflow, Roanne, France). Samples (150-170g) were packed in *sous vide* bags (Packex Industries, Wicklow, Ireland), sealed with vacuum (machine setting 1.5 - 3.0) and cooked at temperatures between 80 and 90°C for a set time to give a product which received either the standard *sous vide* process of 10 min at 90°C ($P_{90} \geq 10$ min) or a pasteurisation process of 2 min at 70°C ($P_{70} \geq 2$ min); these temperatures are product core values. Cooking time varied from food to food due to variation in heat transfer rates and the size of the food pieces. Pasteurisation values (P values) were recorded using an Ellab time-temperature recorder (Ellab Ltd., Norfolk, UK). Product was then blast frozen (2 h at -30°C) or chilled (+4°C) and tests conducted for shear, colour, gravity drip, centrifugal drip and moisture as well as specific tests such as β-carotene levels (carrots), vitamin C levels (broccoli) and thiamine levels (salmon and cod). Shear tests were conducted with a Kramer shear press fitted with a standard test cell (100g samples), colour with a D25A Hunter meter (Lab) (2.5 or 5cm aperture) and gravity drip, centrifugal drip and moisture as described by Fagan *et al.* (2004). The experimental design for the mainstream factorial trials was the same for each of the 10 products and embraced pre-treatments (factor 1), short *vs* long *sous vide* cook times (factor 2) followed by freezing *vs* chilling (factor 3) with 3 replicates.

Comparisons between the carotene content of carrots from the different treatments were made on the basis of Hunter ‘a’ values in view of the high correlation of this index with extracted β-carotene (Hussey and Gormley, 1994). Vitamin C content of broccoli was measured using the 2,6-dichlorophenolindophenol procedure while thiamine in salmon and cod was quantified using the method described by Tansey *et al.* (2002).

Most of the sensory tests were paired comparisons (20-30 tasters) but the ideal target textures for *sous vide*/frozen products were determined by a specialised panel (see below). Details of other and more specific tests or procedures are given in the results and discussion section.

RESULTS AND DISCUSSION

Survey on the quality of commercially-produced sous vide ready-meals

The purpose of the survey was to assess the range and quality of *sous vide* products on the market. Thirty-six chilled ready-meal products prepared by *sous vide* cooking were sourced; 24 were obtained in Ireland, nine from France and three from Germany. The items included rice and pasta dishes, sweet and sour items, vegetable pies and lasagnes; many contained beef, pork, chicken or seafood components. The samples were scored out of ten (0=unacceptable; 10=very acceptable) for the appearance of the box/outer sleeve, for the appearance of the products themselves, and in some cases the finger-feel (*i.e.* tactile texture). Seven judges familiar with the evaluation of ready-meals were used. The samples were not tasted as the cold chain could not be guaranteed based on the logistics of sample shipment to The National Food Centre.

The scores for the outer boxes/sleeves were generally high with a mean value of 8.1/10 and a standard deviation of 0.93. One outer box received a score of 5/10, three 7/10, one 10/10 and the remainder 8 or 9/10. The consensus was that most of the outer boxes were attractive and would encourage purchase (the judges were told to ignore brand names). The mean values for the appearance and finger-feel scores of the products themselves were both 6.7 with a standard deviation of 1.55. Eight samples were awarded scores of 5/10 or less and typical comments relating to these were 'too little product in tray', 'sauce too runny or pale', 'visually poor', 'too little meat', 'sausage meat too pale' and 'rice looks overcooked'. Fourteen products received scores of 8/10 or above. Comments on these were highly positive, such as 'very appetising', 'good balance of components', 'large chunks of chicken and meat visible', 'well-layered lasagne' and 'looks freshly-made'. High or low scores did not follow any particular brand or product line. The tabulated findings have been published (Tansey and Gormley, 2002b).

Review of production technologies for sous vide ready-meals

There has been an increase in consumer demand for ready-meals over the past decade mainly due to lifestyle changes. *Sous vide* ready-meals are regarded by the trade as being of better sensory and nutritional quality than conventional ready-meals. Irish ready-meal companies are responding to market demands and are producing an ever-increasing range of ready-meals. *Sous vide* cooking represents an attractive option for ready-meals and this review of production technologies was aimed at alerting interested companies to the procedures and equipment involved. The topic was addressed under the following headings: ingredients, vacuum-packing and sealing, large-scale cooking and cooling equipment, small and medium-scale cooking and cooling equipment, labelling/storage/reheating and, finally, computer-aided manufacturing. The findings have been published as a 6-page industry-friendly pamphlet (Tansey and Gormley, 2002c).

Determining ideal texture

Good textural properties in food products are a key requirement for acceptance, hence the importance of determining ideal texture ranges for the 10 products in the current study. This was determined by sensory analysis and measuring shear values. The method involved conventional steaming or boiling of each food in water. A set amount (2-3kg) of each was prepared and added to a steamer/pot. Samples were removed at intervals between 5 and 120 min depending on the food, followed by immediate sensory analysis by eight trained panellists. This involved marking a 6cm line with end-points of too soft (0) and too hard (6) with the mid-point (3) representing the ideal texture. Duplicate samples were removed for hot shearing (immediate) and cold shearing (after 24 h at 4°C) using a Kramer shear press with a standard cell. The ideal texture range for carrots is shown in Figure 1 and a summary for the 10 foods is presented in Table 1. These texture ranges became the target textures for the products following pre-treatment, *sous vide* cooking and freezing. The vegetable and carbohydrate components started hard but gradually became very soft on cooking. However, the muscle foods toughened slightly and either gradually softened or remained consistently tough with cooking. The ideal texture for pasta was achieved quickly after 10 min boiling

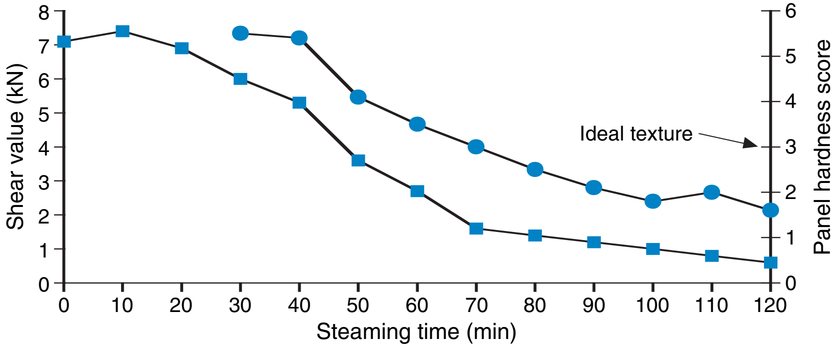

Figure 1: Effect of steaming time (min) on shear values (kN; cold samples) and taste panel texture scores in carrots (hot samples). Panel hardness scores (●) (0 = too soft; 3 = ideal; 6 = too hard). Shear values (■).

Table 1: Ideal texture range (shear values; kN) for 10 foods with corresponding steaming / boiling times.

Component	Ideal texture (hot shear) (kN)	Ideal texture (cold shear) (kN)	Steaming/boiling time to ideal texture (min)
Carrots	0.8-2.2	1.3-2.6	25-30
Broccoli	0.6-1.0	0.8-1.2	15
Potatoes	0.3-0.5	0.5-0.8	20-25
Pasta	0.8-1.2	1.3-2.0	10
Rice	0.4-0.7	0.9-1.5	15-20
Salmon	1.8-2.1	1.9-2.2	25-35
Cod	1.9-3.5	2.4-4.2	20-50
Chicken	2.0-3.0	3.0-4.0	40-120
Beef	4.0-4.6	4.8-6.2	120-180
Lamb	3.7-4.3	4.5-5.5	60-90

whereas that for beef was achieved after 120 min and was maintained at 180 min (Table 1).

Evaluation of pre-treatments and starting materials

Pre-treatments were used to firm up texture in carrots, broccoli and sliced potato in order to counteract the texture-softening effects of *sous vide* processing followed by blast freezing. A range of other pre-treatments was used for the other seven products ranging from chilled *vs* frozen starting material, to water soaking or to pan searing. The influence of pre-treatments on selected quality attributes of the 10 *sous vide* products is given below.

Carrots: Samples *sous vide* cooked from raw had a firmer texture than those cooked from blanched or blanched/frozen (Tansey and Gormley, 2002a, 2002d; Gormley and Tansey, 2004) (Table 2). The use of blanched or blanched/frozen carrots for *sous vide* cooking is highly likely as processors may

Table 2: Effect of starting material and *sous vide* (SV)[a]/freezing on shear, colour (Hunter meter) and soluble solids values of carrots.

	Starting material (carrots)				
	Raw	Blanched	Blanched + frozen	F-test	LSD[b]
Shear (Kn)					
Pre-SV/freeze	7.18	2.61	1.96	P < 0.001	0.46
Post-SV/freeze	2.69	1.58	1.36	P < 0.001	0.48
Hunter L (lightness)					
Pre-SV/freeze	8.3	6.3	5.9	P < 0.001	0.90
Post-SV/freeze	8.2	5.8	5.8	P < 0.001	1.66

[a] Cook time = 11 min at 85°C (core temperature)

[b] Least significant difference.

[c] Not significant.

buy-in prepared (*e.g.* blanched) or blanched/frozen product for convenience and to avoid the washing/peeling/slicing operations associated with raw carrots. The results (Table 2) show the texture softening effect of both heat treatment (blanching and *sous vide* cooking) and the freezing process. Blanching reduced carrot lightness values but follow-on *sous vide* cooking had no further darkening effect (Table 2). Both blanching and blanching followed by freezing caused a loss of soluble solids from the carrots. However, *sous vide* cooking had only a minimal effect on solids loss especially when using raw carrots (Table 2). This has positive implications for carrot sweetness and sensory acceptability.

Broccoli: The florets were given three pre-treatments [(i) full blanch at 90°C for 2 min, (ii) mild blanch at 50°C for 15 min + full blanch, and (iii) mild blanch at 50°C for 30 min + full blanch], vacuum-packed in *sous vide* bags (150g portions) and subjected to two mild *sous vide* cook treatments (10 or 25 min at 90°C) followed by two post-cook treatments (blast freezing or chilling). Shear values of *sous vide* broccoli were influenced ($P < 0.01$) by pre-treatment with values of 1.5, 2.2 and 2.3kN respectively. Taste panel tests on boiled broccoli indicated that the ideal texture was in the range 0.8 to 1.2kN. The firming effect of the mild blanch pre-treatments was most likely due to the activation of pectin methylesterase which interacts with the methylester groups of the pectin chain to produce free carboxyl groups which are then cross-linked by either calcium or magnesium ions (Fuchigami *et. al.*, 1995).

Sliced potato: A mild heat pre-treatment increased the shear values of raw potato slices, presumably via the pectin methylesterase pathway (see broccoli above). A sulphur dioxide pre-treatment (2 min in 3% sodium metabisulphite solution) gave a whiter *sous vide* sliced potato product (74.1 *vs* 67.7 Hunter L) which was also firmer (0.88 *vs* 0.55kN) compared with a pre-dip in water. In the mainstream factorial trial (see Materials and Methods), a pre-treatment of 30 min/50°C + 2 min/90°C was used throughout prior to *sous vide* cooking.

Pasta: Only one pre-treatment was used *i.e.* simmering in water at 90°C for 4 min.

Rice: The effect of pre-treating with different amounts of water *i.e.* rice/water 1:2 vs 1:2.5 on the quality of the *sous vide* product was investigated. The lower water regime gave a less white *sous vide* product (6.76 vs 7.02 Hunter L/b ratio) than the higher water regime but had no influence on the shear, drip or moisture values of the *sous vide* rice.

Cod: The effect of using fresh (chilled) *vs* frozen (thawed) cod as starting material for *sous vide* cooking was investigated. Neither starting material had an effect on the texture, colour, drip loss or moisture content of the *sous vide* samples.

Salmon: As for cod, the use of fresh (chilled) *vs* frozen (thawed) salmon portions was investigated. Frozen (thawed) starting material resulted in less gravity drip (11.1 vs 1.7%) in the *sous vide* product than fresh (chilled) starting material. This may be due to the loss of gravity drip in the initial thawing step on the frozen starting material. Neither starting material influenced product texture, colour, centrifugal drip or moisture content.

Chicken: The pre-treatments were searing *vs* not searing (Table 3). *Sous vide* chicken that was seared was firmer (2.88 *vs* 2.45kN), less white (72.4 *vs* 76.0 Hunter L), yellower (12.5 *vs* 10.2 Hunter b; 5.89 *vs* 7.46 Hunter L/b) and with lower gravity (13.5 *vs* 26.1%) and centrifugal drip (1.4 *vs* 1.7%) values and a lower moisture content (65.4 *vs* 66.8%) than chicken that was not seared prior to *sous vide* cooking.

Beef: The pre-treatments were searing *vs* not searing (Table 3). *Sous vide* beef that was seared had a lower gravity drip (21.8 *vs* 41.2%) than unseared *sous vide* samples. Searing *vs* not searing had no influence on beef texture, colour or moisture content.

Lamb: The pre-treatments were searing *vs* not searing (see Table 3). *Sous vide* lamb that was seared was firmer (3.63 *vs* 3.55 kN), darker (44.2 *vs* 46.6 Hunter L) and less yellow (10.9 *vs* 11.2 Hunter b) than unseared samples.

Optimised sous vide process

The ideal texture ranges for the 10 products (Table 1) became the target textures for the optimised *sous vide* process for each product. This embraced

Table 3: Optimised pre-treatments and *sous vide* cooking process for ready - meal components which were blast frozen or chilled (4°C) and were within the ideal texture range.[a]

Component *(150g in sous vide bags)*	Pre-treatment	Cooking time and temperature[b]	Pasteurisation values (P values min)	Storage	Sensory tests[c] *(frozen vs chill)*
Carrot slices (5mm)	Blanch at 50°C for 15 min, then blanch at 90°C for 2 min with 0.1% salt and cool.	10 min 90°C	$P_{70} > 2$	Frozen	10/10
		30 min 90°C	$P_{90} > 10$	Chilled	Not significant
Broccoli florets (10-50g heads)	Blanch at 50°C for 15 min, then blanch at 90°C for 2 min with 0.1% salt and cool.	30 min 90°C	$P_{90} > 10$	Frozen	6/14
		40 min 90°C	$P_{90} > 10$	Chilled	Not significant
Potato slices (5mm)	Blanch at 50°C for 15 min, then blanch at 90°C for 2 min with 0.1 % salt and cool.	20 min 90°C	$P_{90} > 10$	Frozen	10/10
		20 min 90°C	$P_{90} > 10$	Chilled	Not significant
Salmon fillet (150g portions)	None.	20 min 90°C	$P_{90} > 10$	Frozen	8/12
		40 min 90°C	$P_{90} > 10$	Chilled	Not significant
Cod fillet (150g portions)	None.	20 min 90°C	$P_{90} > 10$	Frozen	8/12
		30 min 90°C	$P_{90} > 10$	Chilled	Not significant
Pasta shells (Roma)	Simmer for 4 min in water with 2% vegetable oil, drain and wash. Soak in water with 2% vegetable oil and drain.	15 min 90°C	$P_{90} > 10$	Frozen	11/9
		20 min 90°C	$P_{90} > 10$	Chilled	Not significant
Long grain rice (Uncle Ben's long grain)	Soak 3 parts water : 1 part rice for 3 h, add 2% vegetable oil and drain.	40 min 90°C	$P_{90} > 10$	Frozen	11/9
	Soak 2 parts water : 1 part rice for 3 h, add 2% vegetable oil and drain.	30 min 90°C	$P_{90} > 10$	Chilled	Not significant
Beef (diced shoulder)	Sear for 5 min in frying pan with vegetable oil.	200 min 90°C	$P_{90} > 10$	Frozen	13/7
		200 min 90°C	$P_{90} > 10$	Chilled	Not significant
Lamb (diced shoulder)	Sear for 5 min in frying pan with vegetable oil.	200 min 90°C	$P_{90} > 10$	Frozen	8/12
		200 min 90°C	$P_{90} > 10$	Chilled	Not significant
Chicken (diced breast)	Sear for 5 min in frying pan with vegetable oil.	90 min 90°C	$P_{90} > 10$	Frozen	9/11
		90 min 90°C	$P_{90} > 10$	Chilled	Not significant

[a] See Table 1

[b] 2nd phase of Barriquand retort cycle

[c] Paired comparison; 20 tasters

a combination of pre-treatment, *sous vide* cook time, and freezing or chilling post-*sous vide* cooking. The optimised process, based on three factors, for each product is shown in Table 3 together with the time/temperature values for each thermal process. All were in excess of 10 min at 90ºC (*i.e.* $P_{90} > 10$) with the exception of carrots processed for 10 min at 90ºC which had a value of $P_{70} > 2$. The cook time/temperature values (Table 3) are not product core temperatures but refer to the holding times/temperatures in the middle (2nd) phase of the Barriquand retort cycle; the other phases are come-up (1st) and cooling (3rd). Beef and lamb required much longer cooking times than the other products. Samples to be frozen after *sous vide* cooking received a shorter process than those to be chilled in the case of carrots, broccoli florets, salmon/cod fillets and pasta shells (Table 3). Paired comparison taste panel tests indicated no statistically significant preference for frozen *versus* chilled *sous vide* products (Table 3). This is a key finding as freezing post-*sous vide* cooking gives additional product safety without seriously impairing product quality.

The optimised conditions (Table 3) are an output of many pre-trials on the effects of short *versus* long *sous vide* cook times on the quality of the 10 products. The short cooks were mild pasteurisation treatments [pasteurisation value ($P_{70} \geq 2$ min)] and were lethal to *Listeria*, *Salmonella* and *E. coli*. The long cooks ($P_{90} \geq 10$ min) were lethal to these and to psychrotrophic, spore-forming *Clostridia*. Chilled *sous vide* samples from the pre-trial pasteurisation treatments were not tasted for safety reasons. Results from these trials have been published in the case of carrots (Tansey and Gormley, 2002d; Gormley and Tansey, 2004), cod and salmon (Gormley *et al.*, 2003). A summary of the effects of short *vs* long *sous vide* cook times on a range of quality parameters for the 10 products is given below. These data were obtained from the factorial trials on the product range embracing pre-treatments, *sous vide* cook times, and freezing *vs* chilling post *sous vide* cooking (see Materials and Methods). Only statistically-significant effects are listed.

Carrots: Carrots cooked by the short *sous vide* process were firmer (2.34 *vs* 0.92kN), lighter (44.6 *vs* 43.3 Hunter L), redder (26.7 *vs* 25.7 Hunter ‘a’) and had a higher centrifugal drip (2.6 *vs* 2.1%) than samples from the long *sous* *vide* cook. However, soluble solids values were highest (7.1 *vs* 6.6%) in samples receiving the longer cook. This was unexpected as more leaching of solids would be expected in these samples.

Broccoli: The short cook gave a product which was firmer (3.01 *vs* 1.01kN), greener (8.5 *vs* - 6.1 Hunter 'a'; and 128 *vs* 117° hue angle) and with lower gravity (4.9 *vs* 5.9%) and centrifugal drip values (10.7 *vs* 16.2%) than the samples given the long cook. Mean vitamin C content was 29.8mg/100 g (see more detail under 'nutrient retention' below) and moisture content was 88.1%.

Sliced potato: Short cook slices were firmer (1.80 *vs* 1.00kN), less moist (79.9 *vs* 81.3%) and with higher gravity (9.1 *vs* 5.5%) and lower centrifugal drip values (9.0 *vs* 11.2%) than the long cook samples. Mean Hunter L/b ratio was 10.6.

Pasta: Short cook shells were firmer (3.55 *vs* 1.17kN) than those receiving a long cook but showed no other differences. Mean Hunter L/b value was 2.83, centrifugal drip 0.8%, and moisture content 45.4%.

Rice: Short cook samples were softer (2.66 *vs* 2.83kN) than the long cook ones but showed no other differences; this finding was unexpected. Mean Hunter L/b value was 6.89, centrifugal drip 1.41% and moisture content 58.3%.

Cod: Short cook samples had a higher Hunter L/b ratio (9.92 *vs* 8.22), were less yellow (7.5 *vs* 9.0 Hunter 'b') and had a lower hue angle (5.9 *vs* 7.0°) than long cook samples. Gravity drip was also lower for the former (20.2 *vs* 22.4%). Mean shear value was 1.76 kN, Hunter L 73.6, centrifugal drip 14.5% and moisture content 80.4%. Data for thiamine content are given under 'nutrient retention' below.

Salmon: Samples from the short cook were softer (shears of 1.36 *vs* 1.78kN), redder (Hunter 'a' 12.9 *vs* 10.9), darker (5.1 *vs* 6.2 Hunter L/a and had lower gravity drip (8.9 *vs* 14.9%) than those from the long cook. Mean moisture content was 61.8% and centrifugal drip 15.2%. Data for thiamine content are given under 'nutrient retention' below.

Chicken: Short cook samples had higher shear values (2.84 *vs* 2.49kN), less gravity drip (18.9 *vs* 20.6%), were brighter (7.00 *vs* 6.36 Hunter L/b) and less yellow (10.8 *vs* 11.9 Hunter 'b') than long cook samples. Mean moisture content was 66.1% and centrifugal drip 1.58%.

Beef: Short cook beef was tougher (7.48 *vs* 5.22kN), lighter in colour (3.73 *vs* 3.38 Hunter L/b), less red (6.3 *vs* 7.9 Hunter 'a'), less yellow (11.4 *vs* 12.3 Hunter 'b') and had less gravity drip (30.0 *vs* 33.0%) than the long cook *sous vide* samples. Mean moisture content was 60.3% and centrifugal drip 1.2%.

Lamb: Short cook lamb samples were tougher (4.28 *vs* 2.45kN) with a lower gravity drip (25.2 *vs* 27.6%) and a higher moisture content (62.3 *vs* 57.7%) than those receiving a long cook. Mean Hunter values were L = 45.4, 'a' = 5.6, 'b' = 4.7 and L/b = 4.14; mean centrifugal drip was 1.2%.

Nutrient retention

Retention of nutrients is a key requirement in any thermal process and tests were conducted on *sous vide* frozen carrots (β-carotene), broccoli (vitamin C) and on cod & salmon (thiamine). The Hunter colour meter was used to get an indication of β-carotene content. Hunter 'a' (redness) values were not influenced by *sous vide* heat treatments or by freezing and the mean 'a' value was 26.2. Hunter a values are highly correlated with β-carotene content (Hussey and Gormley, 1994) which in turn indicates that the pro-vitamin A status of the carrots in the current study was maintained. In addition, heat treatment of carrots may result in higher bioavailability of β-carotene (Nicoli *et al.*, 1999).

Broccoli requires a heat pre-treatment and/or blanching before *sous vide* cooking in order to firm texture (see above) and to stop enzyme activity. This reduced vitamin C content from 51mg/100g in fresh broccoli to *circa* 30mg/100g in the pre-treated samples. The reducing effect was the same for the three pre-treatments, i.e. 90°C/2 min, 50°C/15 min + 90°C/2 min and 50°C/30 min + 90°C/2 min. The vitamin C content of 30mg/100g was not affected by follow-on *sous vide* treatments or by subsequent chilled or frozen storage of the *sous vide* broccoli. In tests where broccoli florets were *sous vide* treated without heat pre-treatments, the vitamin C content of the fresh broccoli (50mg/100g) fell to 48 mg/100g (*i.e.* 96% retention) during *sous vide* cooking. However, if the *sous vide* bag was punctured with a needle to allow entry of oxygen, then the retention of vitamin C was reduced to 45%.

The effects of short (80°C/11 min) *versus* long (80°C/104 min) *sous vide* cook times on the thiamine content of cod and salmon were also investigated. In cod the values were 0.07 and 0.06mg/100g for the short and long cooks respectively ($P < 0.01$) and in salmon 0.17 and 0.18mg/100g ($P < 0.001$). While the values were different statistically, they were similar in practical terms. The thiamine contents of the fresh fish were 0.08 and 0.20 mg/100g for cod and salmon respectively. These data indicate a high level of thiamine retention in *sous vide* cooked cod and salmon (Gormley *et al.*, 2003). Freezing *vs* chilling post-*sous vide* cooking did not influence the thiamine content of cod but freezing resulted in a higher ($P < 0.001$) thiamine content (0.19mg/100g) than chilling (0.17mg/100g) in salmon.

Effect of freezing vs chilling

The main focus of the current project was to investigate the use of freezing post-*sous vide* cooking as a safer alternative to chilling for consumer size portions of ready-meal components. However, it is important to determine if freezing post-*sous vide* cooking delivers a lower quality product than chilling. The sensory data for the optimised *sous vide* processes (see Table 3) indicate no statistically significant difference in acceptability between the *sous vide*/frozen and the *sous vide*/chilled products (a 15/5 preference ratio is required from 20 tasters for a statistically-significant effect). However, it is also important to study effects on the physico-chemical quality parameters of the 10 products. This information was obtained from the 3-factor trials (pre-treatments x *sous vide* cook times x freezing/chilling) (see Materials and Methods) on the 10 products and is summarised below.

Carrots: Samples frozen post-*sous vide* cooking were softer (1.34 *vs* 1.99kN), redder (26.5 *vs* 25.9 Hunter 'a'; 1.01 *vs* 0.97 Hunter a/b; 44.8 *vs* 45.9° hue angle) and had a higher centrifugal drip value (2.5 *vs* 2.0%) than chilled *sous vide* samples.

Broccoli: Frozen *sous vide* broccoli samples were softer (1.63 *vs* 2.39kN), more yellow (12.5 *vs* 10.4 Hunter 'b'; 2.08 *vs* 2.53 Hunter L/b) and had a higher centrifugal drip (18.5 *vs* 8.4%) than their *sous vide* chilled counterparts.

Potato: The frozen *sous vide* samples were softer (1.10 *vs* 1.70kN), less white (55.9 *vs* 60.7 Hunter L), more yellow (8.0 *vs* 4.5 Hunter 'b'; 7.2 *vs* 14.0 Hunter L/b) and with more gravity (9.0 *vs* 5.6%) and centrifugal drip (10.9 *vs* 1.4%) than *sous vide* samples that were chilled.

Rice: Samples frozen post-*sous vide* cooking were whiter (66.2 *vs* 59.5 Hunter L), more yellow (9.9 *vs* 8.4 Hunter 'b'; 6.68 *vs* 7.09 Hunter L/b) and had less centrifugal drip (0.9 *vs* 1.9%) than *sous vide* chilled samples.

Pasta: Samples frozen post-*sous vide* cooking were softer (1.97 *vs* 2.75kN), whiter (60.9 *vs* 58.5 Hunter L; 2.89 *vs* 2.77 Hunter L/b), less moist (44.3 *vs* 46.5%), and had less centrifugal drip (0.58 *vs* 1.07%) than their chilled counterparts.

Cod: The frozen *sous vide* samples were tougher (1.94 *vs* 1.58kN), less white (72.6 *vs* 74.7 Hunter L) and had less gravity drip (20.1 *vs* 22.5%) than the chilled *sous vide* samples.

Salmon: Frozen *sous vide* samples were tougher (1.78 *vs* 1.36kN), lighter in colour (65.0 *vs* 63.1 Hunter L), less red (11.1 *vs* 12.8 Hunter 'a'; 6.1 *vs* 5.1 Hunter L/a), and had lower gravity (11.2 *vs* 12.5%) and higher centrifugal drip (16.3 *vs* 14.1%) values than the chilled samples.

Chicken: Frozen *sous vide* samples were less yellow (11.9 *vs* 11.8 Hunter 'b'), brighter (6.9 *vs* 6.5 Hunter L/b) and had less gravity drip (19.4 *vs* 20.2%) than their chilled counterparts.

Beef: Frozen *sous vide* samples were tougher (6.50 *vs* 6.19kN), lighter (43.6 *vs* 40.3 Hunter L) and more yellow (12.3 *vs* 11.4 Hunter 'b') than the chilled samples. There were no differences in gravity or in centrifugal drip values.

Lamb: Frozen *sous vide* lamb was less tough (3.41 *vs* 3.77kN) and was darker in colour (44.8 *vs* 46.0 Hunter L) than the chilled samples. There were no differences in gravity or centrifugal drip values for the frozen *vs* chilled samples.

Effect of freezing rate

The effect of freezing rate on the texture (shear values), colour and gravity/centrifugal drip values of *sous vide* samples (200g lots) was investigated. Rapid freezing is usually associated with high product quality (Gormley, 1971) and in this regard *sous vide* samples of the 10 products were frozen by cabinet (-20°C), air blast (-30°C for 2h) and liquid nitrogen (-196°C) freezing methods. These procedures represent slow, intermediate and fast freezing rates respectively. The liquid nitrogen (LN) freezing was conducted in a cryogenic environmental chamber (CM 2000, Carburas Metalicos, Madrid, Spain) supplied by Air Products Ltd. Typical times to traverse the freezing plateau (0 to –5°C) for *sous vide* carrots were *circa* 3h (cabinet), 1h (blast) and 40min (liquid nitrogen). The efficacy of LN as a rapid freezing medium was attenuated on account of the large unit size of the *sous vide* packs (*i.e.* 200g). The impact of the different freezing methods on the quality parameters was small and statistically-significant effects are listed in the order cabinet, air blast and LN for the product range.

Freezing rate had no effect on the texture, colour or drip loss in *sous vide* broccoli, sliced potatoes, pasta, cod, salmon, beef or lamb. In *sous vide* carrots, cabinet freezing gave a lower centrifugal drip loss than air blast or LN (44.0 *vs* 52.6 *vs* 54.2%). This result was unexpected and may be due to the large unit size of the samples which tended to equalise the three freezing procedures. In *sous vide* rice, the cabinet frozen samples were firmer (6.05 *vs* 5.63 *vs* 5.15kN), less white (5.1 *vs* 5.5 *vs* 5.5 Hunter L) and had more centrifugal drip (0.9 *vs* 0.7 *vs* 0.6%). In the case of chicken, cabinet freezing gave a darker product compared to the other procedures (84.1 *vs* 87.6 *vs* 87.6 Hunter L).

Research in UCC showed that high pressure shift freezing is the only technology that gives frozen cooked potatoes which are similar to just-cooked ones, particularly in terms of texture (Carbonell and Oliveira, 2004). The result is likely to be widely-applicable to vegetables in general. This enables the production of frozen products with a freshly - cooked quality. However, the technology is expensive to acquire and to run and at the moment there are still questions about its robustness in an industrial environment. Companies that decide to invest in this technology need to assess the experience of the equipment manufacturer in producing high pressure units specifically for freezing, not high pressure units in general, and to obtain feedback from users on the robustness of the system. A simpler, low-cost, fast-freezing method which has application to *sous vide* packs is to immerse product in an ethylene glycol solution. The pack avoids uptake of the chemical by the food.

Further research in UCC has demonstrated that guar gum is a cheap and effective ingredient to protect the texture of potatoes against freezing stress (Carbonell and Oliveira, 2004). The gum is impregnated into the vegetable tissue by blanching in a hot aqueous solution of gum (5g/L). The recommended blanching process is 2-step in which the food is immersed in a gum solution at 70°C for 12 min, removed, cooled to room temperature and then immersed in another solution at 97°C for 2 min. Although the research was only performed for potatoes, there are scientific reasons to believe that the result will also be helpful for vegetables in general.

Effect of long-term frozen storage

The purpose of the long-term frozen storage trial was to determine the deleterious effects, if any, of frozen storage on selected quality parameters of the *sous vide* products. Long-term frozen storage has the potential to adversely affect product quality due to ice crystal growth, moisture migration and oxidation (Gormley *et al.*, 2002). The *sous vide* packs (produced by the optimised process; $P_{90} > 10$ min) for the 10 products used in the trial were blast frozen (-35°C for 2.5h), stored at -20°C and tested after 0, 3, 6 and 9 months. Colour measurements were conducted to study changes in appearance; shear values to reflect the effects on texture; centrifugal drip to assess structural damage and water-binding capacity; vitamin C content (broccoli and potato slices) to reflect nutrient retention.

Length of storage time at -20°C had a statistically-significant effect on the colour parameters (Hunter Lab values and their ratios) of some of the 10 *sous vide* products. However, the magnitude of these effects was small in practical terms and would be unlikely to have a major effect on visual appearance as sensed by the consumer. Length of storage time at -20°C had no effect on the texture (shear values) of *sous vide* cooked broccoli, cod, salmon, chicken, beef or lamb. Pasta and rice samples became progressively firmer with storage time as indicated by shear values of 3.11, 3.35, 3.44 and 3.66 (pasta), and 4.11, 4.67, 5.13 and 5.60 kN (rice) at the 0, 3, 6 and 9 month test dates. There was no pattern in the shear data for carrots and potatoes. The unusual pattern observed for the centrifugal drip values (*i.e.* the values peaked at the 6-month test date and fell again at the 9-month stage) in *sous vide* cooked carrots, broccoli, potato, cod, salmon, beef and lamb is difficult to explain and needs further research including histological tests.

Safety aspects of sous vide processing

The traditional microbiological concern associated with *sous vide* processing is that a mild heat treatment in conjunction with vacuum packaging and extended storage in chill may pose a risk for the survival and growth of *Clostridium botulinum* and toxin production. In this project, a freezing step was introduced to the process which, if properly controlled, will overcome this risk. The microbiological objectives were to assess the effects of *sous vide* processing and post-processing storage conditions on the survival of food pathogens. The research focused on the effects of different thermal treatments, pre-treatments and preparation steps, stress conditions and combined thermal, freezing and frozen storage on the survival of a range of pathogens.

Strain effects on thermal resistance properties of Listeria spp: In the literature, there is some degree of strain variation reported concerning thermal resistance properties of *Listeria monocytogenes*. D-values (time in minutes required to destroy 90% of a bacterial population) for a number of strains of *L. monocytogenes* were compared with *L. innocua* in *sous vide* processed sliced potatoes (Table 4). At 50°C, *L. innocua* had a higher D- value than *L. monocytogenes* NCTC 11994 only. However, at 55° and 60°C, *L. innocua* had a greater heat resistance than all other *L. monocytogenes* strains examined. From this initial test, further work on *Listeria* spp. concentrated on *L. innocua*.

Comparison of thermal resistance of E. coli O157:H7 and Salmonella spp.: A non-toxigenic strain of *E. coli* O157:H7 was used and *Salmonella senftenberg* was selected as a representative of *Salmonella spp.* as it is reported to have high thermal resistance properties. The D-values for these were compared with *L. innocua* in a *sous vide* processed chicken breast model. *L. innocua* had D-values almost double those of *E. coli* O157:H7 and *S. senftenberg*. As a result,

Table 4: D-values for *Listeria monocytogenes* NCTC 11994, *Listeria innocua* NCTC 11288, *Listeria monocytogenes* NCTC 7973 and *Listeria monocytogenes* Scott a in a *sous vide* sliced potato model.

Temperature (°C)	Medium	NCTC 11994 *L. monocytogenes*	NCTC 11288 *L. innocua*	NCTC 7973 *L. monocytogenes*	Scott a *L. monocytogenes*
50°C	LSA[a]	52.1	57.5	66.2	70.2
55°C	LSA	5.2	7.8	6.5	6.9
60°C	LSA	0.4	1.2	0.7	0.9

[a] LSA: Listeria selective agar

further work on *sous vide* food models concentrated on the control or elimination of *L. innocua* as a representative pathogen.

Effects of stress conditions on the thermal resistance of L. innocua: Heat stress conditions may arise due to slow or uneven heating of a product and can generate a heat shock response; this can manifest itself as increased heat resistance of a contaminating pathogen. A range of stresses was examined for effects on heat resistance and included prior heat stress at 46°C for 30 min. Processing treatments such as acid dipping or low pH product formulation may also contribute to acid stress conditions and an acid adaptive response may lead to increased heat resistance. Acid adaptation was carried out by exposure to pH 5.5 for one hour. Starvation conditions may arise from inadequate cleaning practices leaving pathogens on surfaces with little or no nutrient availability. Starvation conditions were simulated by holding inoculum in phosphate buffered saline for 48 hours. All applied stresses led to significant increases in the heat resistance of *L. innocua* (Table 5) as indicated by D-values. Acid adaptation and prior heat stress resulted in the greatest increase in heat resistance compared to controls. Prior heat stress (*i.e.* that applied to the inoculum prior to inoculation) had the most significant effect in the salmon and beef model products. This is probably the prior stress of

Table 5: D-values for *L. innocua* at 55°C exposed to prior stress conditions in four *sous vide* food models.

Treatment	Medium	Potato	Broccoli	Beef	Salmon
Control	LSA[a]	7.8	6.9	13.3	16.5
	TSA-YE[b]	7.9	8.3	14.6	23.7
Acid adapted	LSA	8.2	8.6	23.1	22.0
	TSA-YE	12.8	10.3	30.9	26.6
Heat stress	LSA	7.6	8.3	18.7	25.3
	TSA-YE	12.3	10.7	34.7	38.0
Starvation	LSA	-	-	24.4	21.9
	TSA-YE	-	-	26.0	25.8

[a] Listeria selective agar

[b] Tryptone soya agar - yeast extracted

most practical significance as it is easily encountered during commercial processing, when the come-up time to the required core temperature may be as much as 30 min.

Effects of heat pre-treatments on product safety: Heat pre-treatments are often used in *sous vide* processing to enhance or to thicken sauces. However, such heat pre-treatments may increase the survival rate of bacteria. The effect of a pre-treatment regime of 50°C for 30 min followed by 90°C for 2 min on the survival of *L. innocua* in a *sous vide* sliced potato model was examined and the products were challenged with either a minimal (70°C for 2 min) or a recommended process (90°C for 10 min) prior to analysis and freezing. The samples were examined for presence of *L. innocua* at two stages *i.e* following thermal processing and after frozen storage at – 40°C for 1 week. There was greater recovery of *L. innocua* from samples given the 70°C for 2 min treatment than from those heated to 90°C for 10 minutes regardless of time of analysis (Table 6). From this study two main conclusions can be reached. If using a heat pre-treatment that incorporates a heat stress profile such as 50°C

Table 6: The effects of heat pre-treatments (50°C for 30 min and then 90°C for 2 min) on product safety in a sliced potato model.

Heat process	70°C / 2 min (P_{70}=2.4)[a]	90°C / 10 min (P_{90}=10.5)[a]
Prior to freezing		
Standard procedure	9/12[b]	0/12
Enriched	12/12	12/12
Post defrosting		
Standard procedure	0/12	0/12
Enriched	4/12	0/12

[a] Pasteurisation value

[b] Number of samples containing viable bacteria

for 30 min, a process in excess of 70°C for 2 min should be used. Freezing of the product reduced recovery levels of *L. innocua* even after a minimal heat treatment, with no *L. innocua* detected from frozen samples given the higher process of 90°C for 10 min. This study was also carried out on a broccoli model product in which enhanced survival of *L. innocua* was observed even after a heat pre-treatment of 50°C for 15 min.

Survival of L. *innocua in a sous vide beef model:* Beef samples were inoculated with either control or acid-adapted populations of *L. innocua* and challenged with three *sous vide* thermal treatments: 70°C for 2 min, 85°C for 11 min or 90°C for 4.5 min. Following thermal processing, the effects of storage on recovery of *L. innocua* in beef samples that were refrigerated for 1 week at 8°C were compared to samples stored at -40°C for 1 week. Of the thermal treatments applied, 90°C for 4.5 min was the most effective (Table 7). *L. innocua* was recovered without enrichment procedures following the minimal process of 70°C for 2 min but a 6-log reduction was achieved. Acid adaptation of *L. innocua* contributed to a higher recovery rate only in product subjected to the lower thermal process. There was a lower rate of *L. innocua* recovery from the 70°C for 2 min and 85 °C for 11 min processes if the beef samples were frozen rather than chilled.

Table 7: Recovery of *L. innocua* in beef: effects of *sous vide* process, storage and stress conditions.

	70°C / 2 min		85°C / 11 min		90°C / 4.5 min	
Time	Control	Acid adapted	Control	Acid adapted	Control	Acid adapted
Time 1 (Prior to freezing)	4/12	1/12	2/12	1/12	0/12	0/12
Enriched	12/12	12/12	2/12	2/12	0/12	0/12
Time 2 (1 wk at 8°C)	1/12	1/12	0/12	0/12	0/12	0/12
Enriched	10/12	12/12	2/12	2/12	0/12	0/12
Time 3 (1 wk at -40°C)	0/12	0/12	0/12	0/12	0/12	0/12
Enriched	0/12	4/12	0/12	2/12	0/12	0/12

In summary, the microbiological safety of *sous vide* products can be optimised by using an adequate heat treatment *e.g.* 90°C for 4.5 min. The possibility of increased pathogen thermotolerance resulting from any steps during processing where a stress response may be activated should be taken into account.

Logistics of sous vide manufacturing

This section reviews the enterprise planning and organisational implications of setting up a world-class ready-meal manufacturing system based on *sous vide* technology. The manufacturing steps (unit operations) of a *sous vide* system for ready-meal production are considered and the organisational implications analysed for each case. Recommendations are given on the best practices for production management and product logistics. There is special focus on supply chain management (SCM) which incorporates methodologies to manage the flow of materials, information and decisions in the company. This management goes from the acquisition of even the smallest of components from suppliers to the delivery of the final products to the clients, with the objective of optimising the services rendered by the company (value) and the operating profit (overall cost minimisation). Two major flows compose the logistics chain; (a) the physical flow of materials from the raw materials coming from suppliers to the end-product going to the clients, and (b) the demand flow of orders coming from the clients and then translated into orders to the suppliers.

Three other concepts/procedures are used in a logistics approach and are the so-called 5S procedure, the single minute exchange of dies (SMED), and the Kanban method. The 5S is a sequential procedure with 5 steps, all of which start with the letter S in Japanese, which ensures quality and lean operation (Arnould and Renaud, 2002). It seeks to organise the workplace to make it highly productive. These can be described as: remove (all unnecessary elements), sort (all elements necessary), keep clean, standardise and sustain. Various other terms have been proposed in English to maintain the 5S capitals, such as "sort, set in order, shine, standardise and sustain". The catchphrase for 5S is that once it operates, there is "a place for everything and everything in its place".

SMED also originated in Japan, proposed by Shigeo Shingo. Its application in food manufacturing requires a new approach to cleaning and sanitation of the process equipment. Each piece of machinery which delivers an ingredient subject to a changeover between batches contains two (at least) chambers instead of only one. The chambers can rotate and the idea is that while one is being used in the processing line, dispensing the ingredient/material for that particular batch, the other is being cleaned and loaded with the material that will be required for the next batch. The idea is to minimise, even eliminate, the time needed for cleaning and changeovers between batches.

The Kanban method for Just-In-Time is again a Japanese concept which organises production to deliver the exact amount required of a material at the exact time it is required (Arnould and Renaud, 2002). Kanban works in terms of a pull-material replenishment system; that is, materials are pulled along the factory chain instead of pushed from one workplace to the next. In Kanban, when a workpost uses one item it sends the corresponding "kanban card" to the workpost that delivers it and only that gives the order to produce a new item.

The production of ready-meals by *sous vide* cooking is a semi-continuous process with batch and continuous phases. The preparation and assembly of ingredients is batch, the *sous vide* process is semi-continuous while the preparation of final product prior to distribution is batch. Recommendations for a logistics approach to production management are as follows:

Supply: The perishability of materials and ingredients is a major factor and there are four categories: (i) no preservation problems - can be stored indefinitely; (ii) low risk in preservation - likely to store for a long time without deterioration; (iii) perishable - cannot be stored for a long time, may require chilling/freezing; and (iv) very perishable - use as soon as possible, requires special storage conditions. Different stock management techniques are therefore recommended and one-size-fits-all may not give the best results. For example, potatoes/rice (stock-to-order); canned materials (stock-to-order-to replenish); fresh salads (daily supply, close to zero stock); non-perishable ingredients and materials (stock regularly).

Preparation of materials: Each ingredient or raw material is prepared according to the use required by the formulation. The preparation room must comply with the highest hygienic standard and preparation time is minimised to limit quality loss due to perishability of raw foods. The industrial management technique recommended is the 5S method complemented by HACCP (European Directive 93/43) at the level of the workposts. Cleaning, sanitation and hygienic procedures need to be suitably incorporated in the operating procedure.

Assembly: The assembly of *sous vide* ready meals is similar to assembly of any type of industrial product and follows the specificities of the particular recipe. The various ingredients and raw materials previously prepared are brought together in the specified amounts and order, usually into the primary package. The ingredients must be available in convenient, suitable locations for assembly in the easiest and fastest way for the operators and/or machines. The 5S and HACCP procedures apply here and it is recommended to use a 4-stage 5S process, consisting of: replenish, organise optimally, visualise and proceed. In addition, productivity and flexibility are maximised by implementing the SMED (Single Minute Exchange of Dies) method. The Kanban method is implemented for managing the materials in just-in-time fashion.

Sous vide processing: It is necessary to manage this step as a bottleneck in overcapacity, noting its batch/manual lead-time nature. The rate of *sous vide* processing controls the rate of overall product manufacturing. Generally, the planning mirrors the manufacturing orders. The Method of Time Measurement (MTM) or planning using man-machine charts may be suggested. Cooling time is managed in sequence with the cooking step.

Preparation for transport and distribution: Hygienic handling must be of the highest standard. The assembly of primary packages into secondary packaging and palettes depends on the type of transport and distribution, namely intermediate storage. The requirement for cold storage throughout the whole chain means (i) minimising the number of intermediate storage points between manufacturing and final point of sale, (ii) grouping products in order to minimise the number of transportations required, and (iii) full traceability *i.e.* identification of product and distribution chain.

Transport and distribution: In terms of chain logistics, this is the most crucial step. It does not add value while significantly increasing costs (usually varies between 30 and 60% of the final product cost). Road transport is the norm and has the advantage of door-to-door transport within the time constraints of the product shelf-life. Generally, the transport is sub-contracted to a specialist company. Stockage time should be as short as possible. Ideally, products should be shipped as they are being manufactured. The following options can be considered:

- One truck per client, if the quantity is sufficient
- One truck for various (small) clients
- One truck per manufacturing company to a central distribution warehouse of a large retailer who then distributes various products to individual shops.

Trucks and warehouses must have good chilled facilities, with suitable control, to ensure the low temperature required for quality and shelf-life at all times. Loading and unloading are the most critical times when this requirement will be jeopardised and must, therefore, be simple and efficient.

In the case of warehouse storage, the geographical location should be selected to minimise overall transport and storage times. However, in many cases this will be a decision of large clients regarding the locations of their own buying or distribution centrals.

Full details of this logistics approach to *sous vide* manufacturing are given in *Sous Vide* Technical Bulletin No. 4 (Renaud *et al.*, 2003) which is available from the authors.

Industrial applications

One large company, one SME and three start-up companies were intimately involved and utilised project results and outcomes. Pilot-scale *sous vide* processing tests were conducted for these companies at The National Food Centre and also in-factory. Over 60 other companies received project results *via* industry workshops and technical bulletins/digests.

CONCLUSIONS

- A P-SV-F system for the *sous vide* cooking of ready-meal components (10 products) embracing pre-treatments (P), *sous vide* cook times/temperatures (SV), and freezing (F) post-*sous vide* cooking has been designed, optimised and validated. There was particular focus on product texture and how it was influenced by the P-SV-F system.

- Taste panellists were unable to detect a difference between *sous vide* products that were frozen *vs* chilled after *sous vide* cooking. This is a key result as the former ensures safety and is easily managed (*i.e.* frozen storage) while the latter requires a carefully-controlled chill chain.

- Rate of freezing or long-term frozen storage had a minimal effect on the quality attributes of the 10 *sous vide* cooked products.

- The technological aspects of the P-SV-F system were underpinned by extensive microbiological tests. These focused on the effects of product preparation, pre-treatments, thermal treatments and also on the stress conditions generated by combined thermal, freezing and frozen storage treatments on the survival of a range of pathogens.

- The enterprise planning and organisational implications of setting up a world-class ready-meal manufacturing system based on *sous vide* technology have been documented. The manufacturing steps (unit operations) of a *sous vide* system for ready-meal production have been listed and the organisational implications analysed for each case. Recommendations are given on the best practice for production management and product logistics.

RECOMMENDATIONS TO INDUSTRY

- *Sous vide* cooking followed by freezing is a safer alternative than *sous vide*/chilling and gives an extended shelf-life to ready-meal components and ready-meals. The relationships between pre-treatments, *sous vide* cook time/temperature and post-*sous vide* freezing must be optimised for each product application in order to deliver an acceptable product texture.

- The safety of frozen *sous vide* products can be optimised by using an adequate heat treatment *e.g.* by achieving a product core temperature of 90°C for 10 min. The possibility of increased pathogen thermotolerance resulting from steps during processing where a stress response may be activated should be taken into account.

- A logistics approach facilitates the achievement of a world-class ready-meal manufacturing system based on *sous vide* technology.

- Technical bulletins have been prepared on a number of project outputs and are available from the authors.

OTHER RESEARCH ON *SOUS VIDE* COOKING AT THE NATIONAL FOOD CENTRE

Tests have been conducted on the effect of *sous vide* cooking with freezing on selected quality parameters of seven fish species in a range of 12 savoury sauces (Fagan and Gormley, 2004). Sensory results showed that *sous-vide*-cooked albacore tuna, cardinal fish and blue ling were the most acceptable species and tikka, tomato-and-pesto, arrabbiata and hollandaise the preferred sauces. Greenland halibut and roundnose grenadier were too soft after *sous vide* cooking. Freezing post-*sous vide* cooking did not influence product quality and gave additional benefits over chilling of an extended shelf life and greater flexibility in relation to product safety. The pH of the sauces has an influence on lethality and was in the range 3.96 (cajun) to 5.42 (bearnaise). Mean pH values fell from 4.66 before *sous vide* cooking to 4.38 after cooking. Sauce colour also became lighter during *sous vide* cooking of fish portions as indicated by Hunter Lab colour values. The results of the research have been disseminated to seafood companies and scale-up trials are in progress.

ACKNOWLEDGEMENTS

Thanks are extended to Claudia Duelk, Anne Sainlot and Tanja Budde who conducted elements of the project, to Tony Hegarty for the statistical analyses, to the food companies and start-up companies who participated in the project and to the Department of Agriculture and Food for funding the project under the Food Institutional Research Measure (FIRM) as part of the Irish National Development Plan.

LIST OF PUBLICATIONS FROM THIS PROJECT

There are 21 publications to date including four peer-reviewed papers (submitted) from University College Cork. A further 10 peer-reviewed papers (six from The National Food Centre and four from the University of Limerick) are in preparation as are two Ph.D. theses.

Bourke, P. and O'Beirne, D. 2002. Effects of acid adaptation and acid stress on the thermal inactivation of *L. innocua* in *sous vide* processed potato slices and broccoli florets. *Proceedings of the 32nd Annual Food Science and Technology Research Conference*, University College Cork, Cork, 130.

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Carbonell, S. and Oliveira, J.C. 2004. Effect of blanching, vacuum infusion, additive impregnation and freezing on the resistance of core potato tissue to a freeze-thaw cycle. *International Journal of Food Science and Technology,* Submitted.

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Carbonell, S. and Oliveira, J.C. 2004. Preservation of the texture quality of cooked potato tissue using high-pressure shift freezing. *Innovative Food Science and Emerging Technologies,* Submitted.

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