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Quality Improvement and Process Feasibility of Quick-Frozen Vacuum-Packed Tuna Steaks

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SUMMARY

Vacuum-packed Yellowfin tuna steaks were individually frozen in either liquid freon or in an air storage freezer, and evaluated for keeping quality after 1, 3, and 6 months of frozen storage (-27°C). The resulting freezing rates were used to project the economic feasibility of a small scale commercial processing plant. Regardless of freezing method the vacuum-packed steaks demonstrated keeping quality comparable to fresh control samples handled as in normal distribution channels. The estimated cost to manufacture allowed sufficient profit at competitive selling prices to generate a rate of return of 132%. This would pay back the estimated cost of plant and equipment in less than one 6-month season of operation at full capacity.

1. INTRODUCTION

The growing demand for premium grade raw tuna in the United States combined with the traditional demand from Japanese markets has prompted Florida fishermen to view recent tuna catches as more than just incidental to their swordfish operations. As more tuna is landed, so is more found not to meet the premium quality grade associated with foreign and domestic Sushi restaurants. Frustrated by less than predictable grading practices, Florida wholesalers welcome the opportunity to introduce tuna as broiled steaks on a premium restaurant menu or prepared at home much like a broiled swordfish steak.

Market distribution of fresh tuna is limited because tuna is a fatty fish and deteriorates rapidly through chemical oxidation to produce rancid off-flavors and discoloration in spite of refrigeration to reduce microbial and enzymatic spoilage (Hobbs /1/ and Karmas /2/). Flavor and color deterioration continues under frozen storage in the presence of oxygen (Fenema et al. /3/, Heen /4/, and Persson /5/). Textural quality is lost because of moisture migration across cell membranes and membrane damage from ice crystal formation caused by slow freezing rates as explained by Love /6/ and Reid /7/. To counter these problems Yu et al. /8/, Strasser et al. /9/, and Josephson et al. /10/ have shown that chemical oxidation and surface dehydration can be minimized by vacuum packaging with commercially available high barrier films. In addition, the faster freezing rates that are necessary to minimize textural damage can be achieved by reducing the size of the piece to be frozen (i.e. individual steaks), and by increasing surface heat transfer rates through liquid immersion freezing rather than traditional freezing in air (FAO /11/ and Mead /12/).

The purpose of this study was to demonstrate the quality consequences of individually quick-frozen (IQF), vacuum-packed tuna steaks and use the resulting freezing rates and costs to project the economic feasibility of a proposed processing plant for producing IQF, vacuum-packed tuna.

2. METHODOLOGY

Freezing Rates: Laboratory experiments were performed with fresh tuna steaks cut approximately 1 cm. thick. Thermocouples (36-gauge copper constantan type T) were imbedded near the slab center with sufficient lead wire retained within the fish flesh to minimize errors due to heat conduction. The instrumented steaks were then vacuum sealed in Cryovac® type B barrier film bag (30X40 cm) with provision to avoid leakage around thermocouple leads. Part of the samples prepared in this way were frozen by direct immersion in liquid freon at - 30°C, while the remaining samples were placed in an air storage freezer at -27°C. Temperatures were continuously recorded using an Esterline Angus data logger model PD-2064. Freezer residence times were taken as the time required for the product center temperature to reach -18°C from an initial temperature of 4°C. Data from these experiments were then used to calibrate a mathematical model for predicting freezer residence times with other heat exchange media (Hung and Thompson /13/ and Heldman and Singh /14/) and for steaks of different thickness.

Quality Evaluation: Additional vacuum-packed samples frozen by both methods were placed under long term frozen storage (-27°C) for keeping quality evaluations. At the same time, samples cut from the same tuna chunks that had never been frozen were subjected to a zero-time evaluation to serve as a reference for fresh quality. All frozen samples were cut, vacuum packed, and frozen in either air or freon from fresh tuna chunks kept on ice for 5 days after catch. Control samples were cut from the same chunks kept on ice 6 days longer to more fairly represent the age of fresh tuna reaching the retail trade through normal distribution channels. Frozen samples were thawed and evaluated after 1, 3, and 6 months of storage for chemical, physical, and sensory quality. Chemical tests consisted of measuring thiobarbituric acid (TBA) as an index of oxidative rancidity. Physical tests included free and expressible drip losses according to the method of Siang et al. /15/, and cooking yield loss as determined from weight loss after cooking. Sensory quality was measured by a taste panel pretrained to judge meat color, flavor, odor, texture, and overall acceptance on both raw and cooked samples. Samples were cooked in their vaccum barrier bags by immersion in boiling water for approximately 4 minutes to reach a standard internal temperature of 71°C.

Process Economics: As a basis for estimating process economics, a flow diagram was developed describing the sequence of unit operations required to convert the raw material to the finished product. The next step required specifying the plant capacity, and carrying out energy and mass balance calculations in order to estimate energy and product flow rate requirements for each unit operation. This information led to the identification, specification and sizing of all major items of processing and handling equipment as well as associated labor requirements and facilities.

A process flow diagram showing sequence of unit operations and material balance is given in Figure 1. Based on the yellowfin tuna catch rate of Florida fishermen, the potential number of vessels that can supply a wholesale distributor, an average turn around time of 10 days per

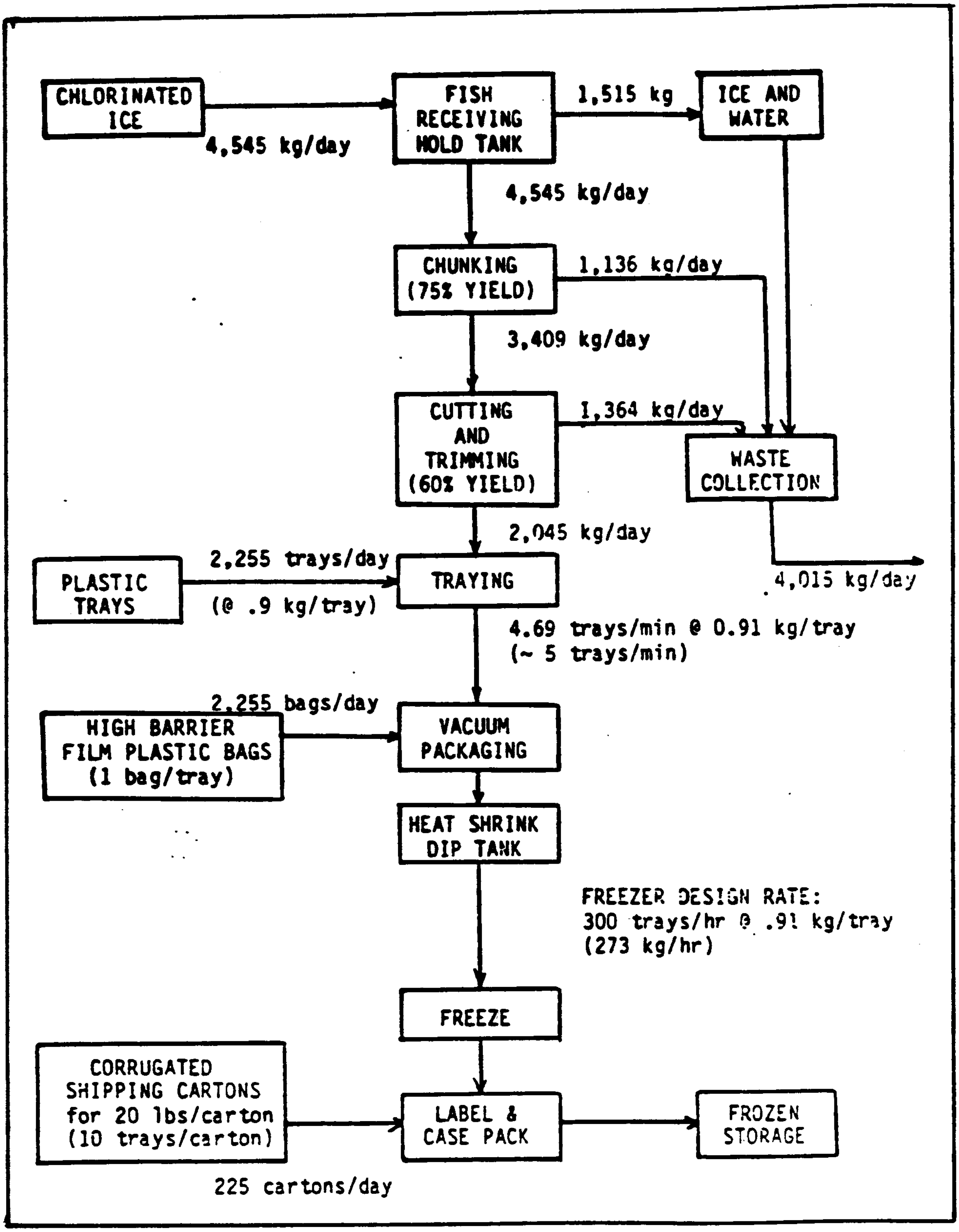

Fig. 1 - Process flow diagram showing sequence of unit operations and material balance for proposed frozen tuna steak line.

vessel and a season of 125 days (6 months), a useful plant should have the capacity to process 4545 kg (~10,000 lb) of tuna daily.

The tuna would be received as iced, deheaded and gutted carcasses from the vessels and placed in tote bins with newly made cracked ice at a mass ratio of 1:3 ice:fish per bin, sufficient to keep the carcasses chilled at 1.67°C (35°F) for a period of at least 2 hours. These carcasses would be cut into chunks and then sliced into approximately 1.27 cm (0.5 inch) thick steaks on a band saw followed by trimming and inspection prior to arranging on shallow trays for vacuum packaging and freezing. These trays (30 x 40 cm) would hold 4 to 5 steaks lying flat and totaling 0.91 kg (~2 lb). These trays are very thin and should not change the required freezer residence time. Once the steaks are arranged in this fashion, the trays would be vacuum-packed using Cryovac type B-barrier bags and equipment, followed by a heat shink treatment, which would require the dipping of each tray in 95°C (203°F) water for 2 seconds immediately after vacuum packaging.

The trays would undergo freezing in a flume conveyor of recirculating chilled brine, kept at -21.1°C (-6°F), with overhead sprays to assure contact with refrigerant (brine) from all sides as packages float down the flume for the 30-minute resident time. The frozen vacuum-packed trays would then be conveyed to a check weigher and labeled prior to case packing in 10-pack shipping cartons for frozen storage at -29.9°C (-20°F). All unit operations, except the freezing storage, would be carried out in a 12.8°C (55°F) processing area. The labor requirement for each unit operation is shown in Figure 2.

Equipment costs were estimated through discussion with equipment suppliers for major items and reference to food processing handbooks for common handling equipment. Building and facilities costs were based on estimated area requirements for each unit operation along with provision for utilities, office space, personnel facilities, laboratory, shop, storage and warehousing. Unit construction costs appropriate for the type of construction planned in each area were then applied to arrive at a total building cost.

Operating costs were based on estimated costs for raw materials, energy, and labor. The cost for the single major raw material (tuna) was determined through discusssions with independent Florida fishing vessel captains and wholesale seafood distributors who buy directly from these independent fishermen. Packaging material costs were obtained from discussions with suppliers (Cryovac Division, W.R. Grace). Energy costs were based on estimated refrigeration requirements, steam and hot water usage and water and sewage requirements. Labor requirements were based on estimates established from observing commercial fish handling and processing operations during field visits to New England fish processing plants; and selling prices were determined from discussions with national seafood brokers and marketing specialists experienced in dealing with fresh and frozen tuna for the restaurant and retail trade.

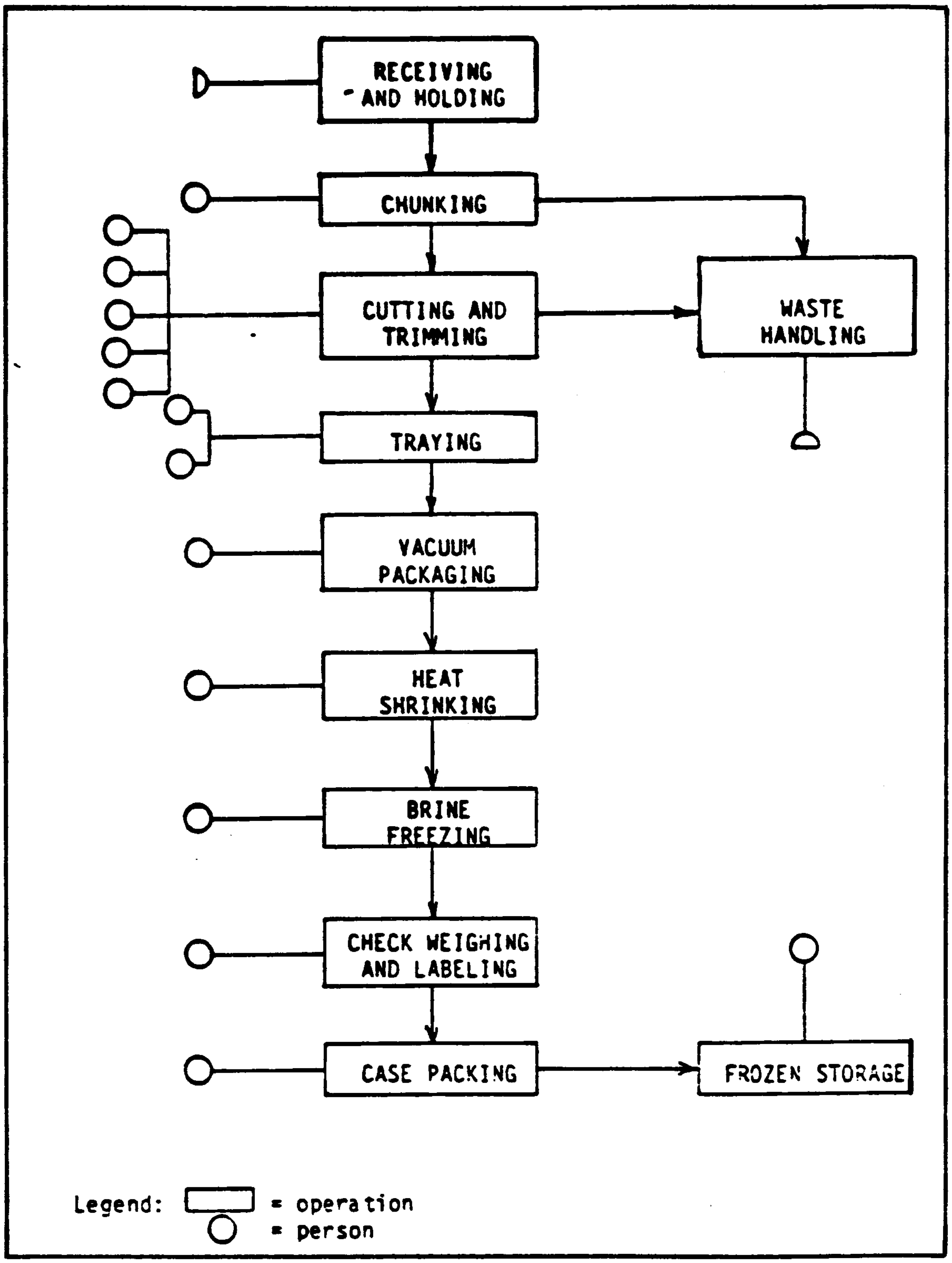

Fig. 2 - Proposed frozen tuna steak line showing estimated labor requirement.

3. RESULTS AND DISCUSSION

Freezing Times: Typical temperature response curves for samples frozen in liquid freon and in air are shown in Figure 3. The results show that samples frozen in liquid freon required only 12 minutes to reach a final temperature of -18°C, while samples frozen in an air storage freezer required nearly 100 minutes to reach this same temperature. Although this difference dramatizes the effect of different heat exchange media on surface heat transfer coefficient, it can only be appreciated when the tuna is frozen in individual thin steaks (about 1 cm thick) which minimizes the time required for internal heat transfer from the center of the steak to the surface. When tuna is traditionally frozen in large (10 Kg) chunks, internal heat transfer dictates freezing times of several hours, thus minimizing the significance of the 1 or 2 hours difference that can be saved by improving the surface heat transfer coefficient through liquid immersion freezing.

For a small scale processing plant such as that proposed for this study, the shorter residence time possible by liquid immersion freezing has significant impact on choice of commercially available freezing equipment systems and costs. Liquid immersion systems using refrigerated heat exchange fluids such as propylene glycol or brine solutions of either sodium or calcium chloride are commercially available for small scale plants, and a system based on the use of a 30% sodium chloride brine maintained at -21°C was chosen as a basis for cost estimates. Under these conditions a freezer residence time in the order of 30 minutes was predicted from the mathematical freezing rate models used in this study for steaks averaging 225g (1/2 lb.) in weight.

Frozen Quality Evaluations: Data on chemical, physical, and sensory keeping quality of fresh and frozen tuna steaks after 1, 3, and 6 months of frozen storage are shown in Tables I-a and I-b. The TBA test results show how vacuum packaging retarded rancidity development to only half the level found in the control samples after 1 month of storage, while just reaching the control level after 3 months of storage. Cooking yield loss was considerably reduced in all frozen samples from that shown by the control, suggesting that control samples may have undergone some dehydration over the extra six days of holding. Free and expressible drip losses were indicative of moisture migration across cell membranes and damage to membranes respectively. Results showed less moisture migration from the faster freezing rate achieved in freon as expected, but no difference in cell membrane damage between freezing methods. Taste panel evaluation of texture, color, aroma, and flavor of cooked samples showed that all frozen samples at all time frames were rated essentially comparable to fresh controls in all respects.

Process Economics: A list of equipment and facilities with estimated costs for each of three different levels of investment is given in Table II. The first level of investment represents a processor who already has equipment and facilities in place for packaging fresh fish fillets and needs only to upgrade by adding the freezing and vacuum packaging equipment. The second level of investment represents a wholesaler with basic building and cold storage facilities in-place who would plan to install a processing line for the first time. The third level of investment is for

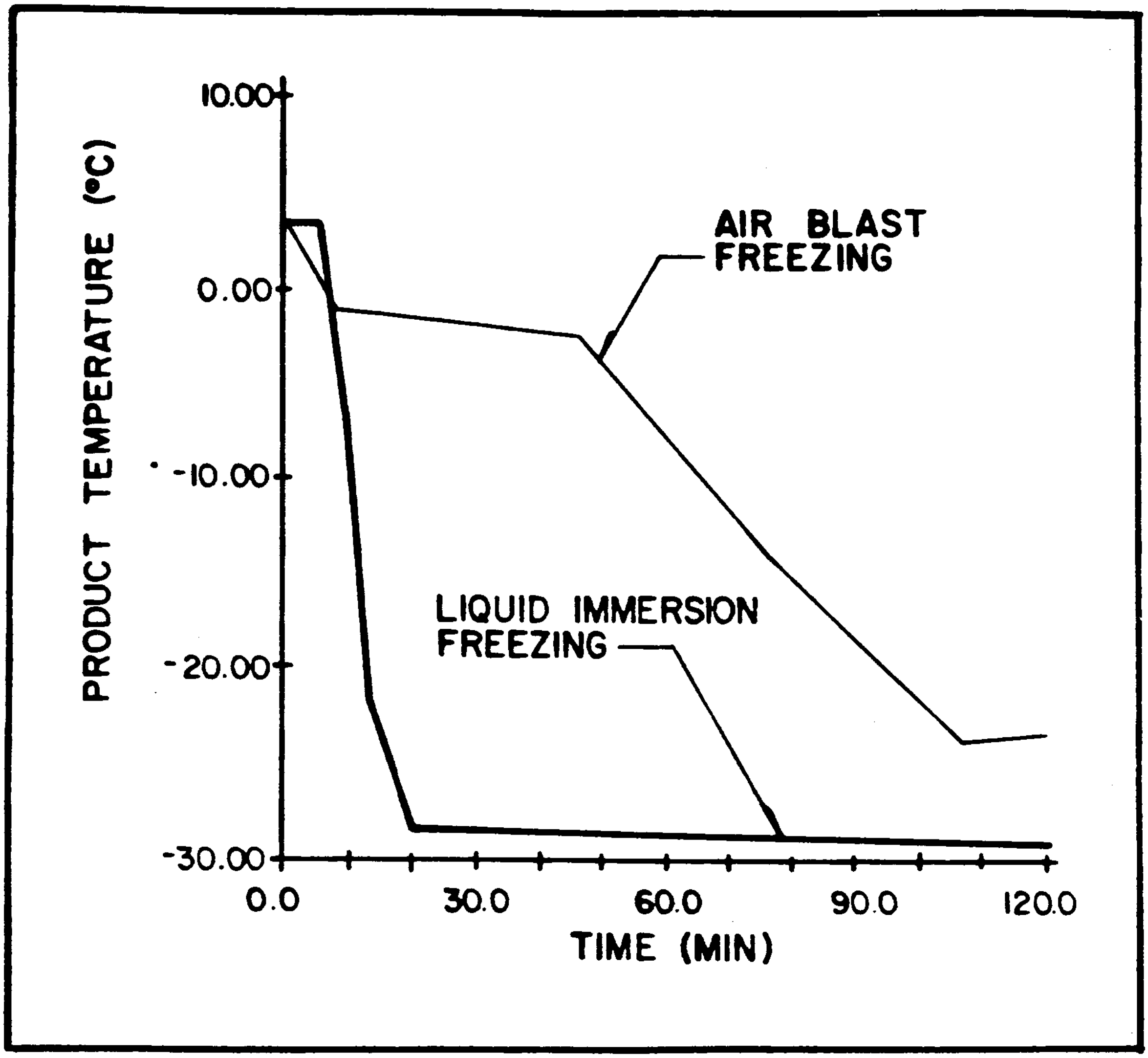

Fig. 3 - Freezing curves for vacuum-packed tuna steaks (1 cm. thick) showing internal product temperature over time when immersed in liquid freon at -30°C or frozen in air at -27°C.

the start up of a complete processing plant where no prior facility exists.

The estimated seasonal operating costs and unit cost to manufacture are shown in Table III. Fixed overhead costs are based on the level 3 investment for start up of a new plant. The breakdown of these costs for packaging materials, energy, labor and overhead show that these combined processing costs amount to one-tenth the total cost of manufacture, and are over-shadowed by the cost of raw tuna reflected in the 45% yield in processing.

A final economic summary of the proposed process is shown in Table IV. The selling price for the frozen tuna steaks of $13.20/kg. was based on discussions with seafood brokers in the restaurant and retail trade who explained that tuna is currently handled in either fresh chunks at $13.22 to 15.43/kg. or frozen chunks at $8.82 to 11.02/kg. Thus, if vacuum-packed quick-frozen steaks can rival the quality of fresh tuna reaching the market place while offering added convenience in ready - steak form, the projected selling price of $13.20/kg would appear reasonably competitive. The results summarized in Table IV show that the process is capable of generating a simple rate of return of 132%. This would pay back the estimated cost of plant and equipment in less than one season of operation at full plant capacity.

CONCLUSION

The results of this study suggest that individually quick-frozen vacuum-packed tuna steaks, that have been stored up to 6 months at -29°C (-20°F), can rival the quality of fresh grade 2 or 3 tuna. Furthermore, the technology for making such a product, using a brine freezer, is readily available, making its manufacture technically feasible. The study also shows that a processing plant capable of handling 4545 kg (10,000 lb) of tuna carcasses daily, paying the fisherman $4.40/kg ($2.00/lb), could generate sufficient profit to allow the processor to pay back the investment in less than one season (< 6 months) provided the plant operated at full capacity during the entire length of the season, and that the processor received $13.22/kg ($6.00/lb) for the finished product.

To the extent that the economic feasibility of the project analyzed in this study was based on costs of production and estimates on the price the consumer is willing to pay for similar products, the production of individually quick-frozen, vacuum-packed tuna steaks could be an important value-added industry for the Florida fisheries and merits further marketing studies.

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Table I-a. Physical and Chemical Quality Scores of Fresh and Both Air- and Freon-Frozen Vacuum-Packed Tuna Steaks After 1, 3 and 6 Months of Storage at -30°C

Storage Time (months)	Sample History and Method of Freezing[a]	TBA (mg/kg)	Cooking Yield Loss (% loss)	Free Drip (% loss)	Expressible Drip (% loss)
0	Control Samples Never Frozen	0.44±0.07	24.33±4.54	N/A	N/A
1	Air Frozen	0.21±0.03	12.40±0.89	7.04±2.28	20.6±1.9
	Immersion Frozen	0.24±0.03	13.38±0.93	3.29±1.72	22.1±1.6
3	Air Frozen	0.421±0.027	12.81±1.17	7.40±3.35	22.9±1.4
	Immersion Frozen	0.519±0.075	15.74±2.89	3.19±1.11	24.6±2.2
6	Air Frozen	N/A	16.24±3.45	5.05±3.13	31.2±4.0
	Immersion Frozen	N/A	18.08±2.62	2.04±0.95	30.6±2.6

a All frozen samples were vacuum packaged and frozen from fresh tuna chunks kept on ice for 5 days after catch, while control samples were kept on ice 6 days longer to more fairly represent age of fresh tuna reaching retail trade.

Table I-b. Sensory Scores of "Cooked" Tuna from Fresh and Both Air- and Freon-Frozen Vacuum-Packed Tuna Steaks Stored at -30°C

Storage Time (months)	Sample History and Method of Freezing[a]	Organoleptic Characteristics (Scale of 1-5, where 1 = poor, 5 = excellent)				
		Texture	Color	Aroma	Flavor	Acceptance
0	Control Never Frozen	4.0±0.9	4.7±0.5	3.7±1.2	3.8±0.9	3.7±1.0
1	Air Frozen	3.9±1.6	5.0±0.0	4.1±1.1	3.6±1.2	3.4±1.1
	Immersion Frozen	3.6±1.2	4.5±0.5	3.9±0.6	3.5±0.9	3.4±0.9
3	Air Frozen	3.3±1.0	4.7±0.5	4.3±0.5	4.3±0.8	3.3±1.0
	Immersion Frozen	4.0±1.1	4.2±0.4	3.7±0.5	3.5±1.0	3.2±1.2
6	Air Frozen	3.4±1.5	4.4±1.1	4.4±0.8	4.6±0.8	4.3±0.8
	Immersion Frozen	3.3±0.8	4.4±0.8	3.7±0.5	3.6±1.0	3.3±1.0

[a] All frozen samples were vacuum packaged and frozen from fresh tuna chunks kept on ice for 5 days after catch, while control samples were kept on ice 6 days longer to more fairly represent age of fresh tuna reaching retail trade.

TABLE II

List of Equipment and Facilities with Estimated Costs for Proposed Frozen Tuna Steak Processing Plant at Three Levels of Investment

Equipment/Facility	Level of Investment 1st	2nd	3rd
Stainless steel work tables (6 @ $1,000)	$ -	$ 6,000	$ 6,000
Plastic heavy tote bins (20 @ $500)	-	10,000	10,000
Food process band saw	-	3,000	3,000
Vacuum packaging machine	13,700	13,700	13,700
Heat shrink dip tank and basket	3,200	3,200	3,200
Liquid brine freezer flume and converyor	30,000	30,000	30,000
Check weigher and labeler	6,000	6,000	6,000
Finished product storage freezer	-	-	10,000
Refrigeration system and equipment	30,000	30,000	62,300
Boiler and fuel tank	-	10,000	10,000
Insulated plant building (260 m2 @ $326)	-	-	84,870
Office and laboratory Equipment	-	12,000	12,000
Shop and janitorial equipment	-	10,000	10,000
TOTAL ESTIMATED COST for plant and equipment	$82,900	$133,900	$261,070
Engineering design & Installation (40% of Total Estimated Cost)	33,160	53,560	104,428
TOTAL INSTALLED COST	$116,060	$187,460	$365,498

TABLE III

Estimated Seasonal Operating Costs and Cost to Manufacture Per Kilogram of Product for a Frozen Tuna Steak Processing Plant, Based on $4.40/kg ($2.00/lb) Paid to Fishermen

Operating Cost Category	Estimated Seasonal Cost	Cost to Manufacture ($/kg)
Raw Materials		
Tuna (568,125 kg @ $4.40)	$2,499,750	9.78*
Plastic trays (281,250 @ $0.20)	56,250	0.22
Vacuum bags (281,250 @ $0.12)	33,750	0.13
Shipping cartons (28,125 @ $0.27)	7,594	0.03
Total Raw Materials Cost	$2,597,344	10.16
Energy and Utilities		
Electricity for refrigeration and accessories (162,068 kwh @ $0.08/kwh)	12,965	0.051
Boiler fuel (3,000 gal @ $1.17/gal)	3,510	0.014
Water and sewer ($1x10^6$ gal @ $1.50/1000 gal)	1,500	0.006
Total Energy and Utility Cost	$17,975	0.070
Labor		
Hourly workers (15 @ $10,000/6 mos.)	150,000	
Maintenance technician	15,000	
Supervisor	20,000	
Total Labor Cost	$185,000	0.73
Overhead		
Taxes, insurance, maintenance and repair (10% of Total estimated cost of plant and equipment)	26,107	0.10
Depreciation on Plant & Equipment (10% of Equipment and 3% of Plant)	20,160	0.08
Cost of Capital (12% Total Installed Cost)	43,860	0.17
TOTAL OVERHEAD COST	90,127	0.35
TOTAL PLANT OPERATING COSTS AND COST TO MANUFACTURE	**$2,890,446**	**11.31**

* Based on 45% yield taken from material balance shown on Figure 1.

TABLE IV

Summary of Economic Feasibility for Proposed Frozen Tuna Steak Processing Plant at Three Levels of Investment

Seasonal revenue from sale of product (255,625 kg @ $13.20/kg)	$3,374,250
Seasonal operating costs	$2,890,446
Seasonal profit (revenue less cost)	$483,864
Estimated Installed cost of plant and equipment	$365,498
Rate of Return (profit/investment)	132.38%