NAFO Sci. Coun. Studies, 13: 7–25

Experiments to Determine Split Fish Equivalent Factor for Salted Codfish in Bulk

G. R. Peters
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, Newfoundland, Canada A1B 3X5

L. A. Strowbridge
Resource Management Division, Fisheries and Habitat Management
Department of Fisheries and Oceans, St. John's, Newfoundland, Canada A1C 5X1

and

L. W. Penney
Resource Management Division, Fisheries and Habitat Management
Department of Fisheries and Oceans, St. John's, Newfoundland, Canada A1C 5X1

Abstract

The split codfish equivalent of salted codfish in bulk at various stages of the curing process was investigated by isolating the salting ratio, bulk height and salting rate. The salt to fish weight ratio which controls the initial value of the split fish equivalent (conversion) factor, is calculated by a mathematical equation. In addition the moisture fraction and salt content also affect the final or equilibrium value of the factor. This equilibrium value is calculated from another equation.

The variation from initial to final values is predictable, and the addition of new fish tends to reduce the factor. A set of equations has been derived and combined in a simple computer program which enables the calculation of conversion factors consistent with three experiments, and permits generalization of the results.

The effect of compression in the bulk is to slightly increase the conversion factor predicted by theory for pile depth greater than about 1 m. The difference is approximately 5%.

The values of the parameters are quantified, it is now possible to calculate a definitive conversion factor within the range of 600–1,500 kg/m^3.

Introduction

Background

During the early 1980s a large number of foreign vessels fishing inside Canadian waters were salting codfish. In order to determine round weight of catches from the salted product, a procedure was needed to convert salted codfish volumes to split and round weight equivalents. The experiment was designed to simulate the salting and curing practices in the offshore fishing fleets and some significant effects of identified variables were investigated.

The principal objective of this study was to determine a split codfish equivalent of salted codfish in bulk at various stages of the curing process, isolating the following variables: (a) the quantity of salt per hundredweight of split codfish (salting ratio); (b) the bulk height (compression); and (c) high catch rates (continuous salting).

Materials and Methods

Three experiments were undertaken to isolate the aforementioned variables. Measured quantities of split codfish were salted into six enclosed pallets and studied in the following three experiments between 18 July and 13 October 1983.

Experiment 1. Effect of salt to fish ratio

Experiment 1 used three of the six enclosed pallets, which were labelled A, B, and C. To measure the effects of varying percentages of salt-per-hundredweight of split fish, daily quantities of between 250–300 kg of split codfish were salted into each pallet at ratios of 0.5, 0.6 and 0.7, respectively. These daily additions of split codfish and salt were continued for 9 days until pallet C (greatest percentage of salt) attained a height of approximately 2.0 m. The other pallets, A and B, were approximately 1.6 and 1.8 m high upon completion of the 9 days' salting (Fig. 1).

Experiment 2. The effect of bulk height (compression)

Experiment 2 used two pallets, labelled D and E, together with pallet B from the first experiment. To measure the effects of compression due to bulk height, daily quantities of 250-300 kg of split codfish were salted into each of the pallets D and E until the bulks reached heights of 0.85 and 1.35 m. Data were obtained for these pallets and for pallet B, which was approximately 1.8 m high in bulk of salt and fish. The three pallets had been salted with the same percentages (60%) of salt to fish (Fig. 2).

Experiment 3. Simulated high catch rate (continuous salting)

Experiment 3 used one of the six enclosed pallets, labelled F. Split codfish was salted at a ratio of 60 kg of salt to 100 kg of split fish in one continuous period of approximately 9.5 hr, to a measured height of 2 m, and

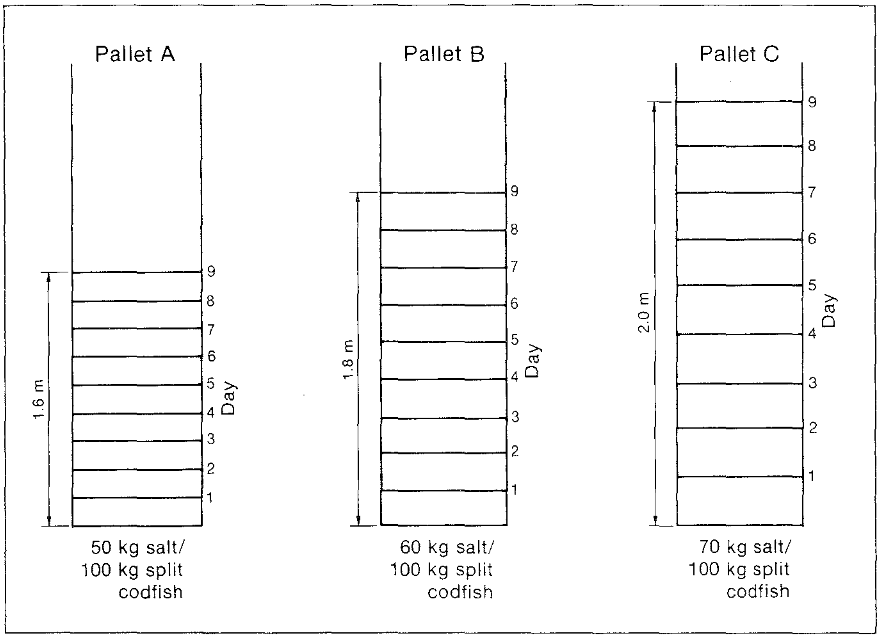


Fig. 1. Three pallets (A, B and C) showing daily quantities of split codfish and salt added during the first nine days.

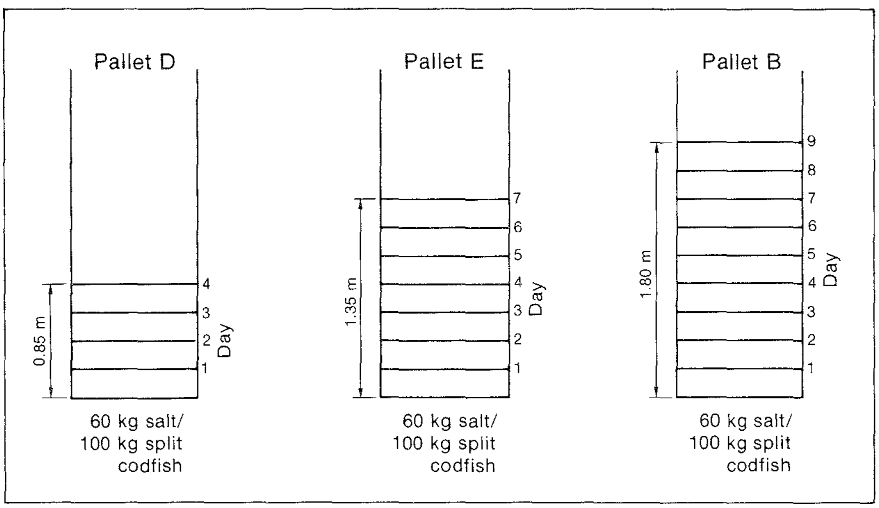


Fig. 2. Two pallets D and E compared with pallet B of experiment 1 showing daily quantities of split codfish and salt added during the first nine days.

was allowed to cure. The data obtained from this experiment were compared with the data from Experiments 1 and 2.

Data collection

Prior to salting each day's allotment into pallets A to E, the heights of all previous daily allotments were measured for volume changes. Each daily layer of fish and salt was separated from other layers by a sheet of burlap. Each pallet was also weighed to obtain the net weight loss for each bulk. The brine runoff was collected in containers and weighed to verify the weight loss of each bulk and to enable calculation of a complete mass balance.

These measurements and weighings were performed throughout the salting and curing phases until the bulk volumes and weights had not changed significantly for a period of 2 weeks. At this time, each daily layer of salted codfish and excess salt was removed from the pallets A to F by hand, and fish and salt were separated.

Facilities and equipment

The facilities and equipment used to complete the experiments were as follows: (a) a 84 m^2 chillroom with average temperature 12°C and relative humidity 75% (variation from these was very slight); (b) six enclosed pallets as shown in Fig. 3; (c) forklift — lift capacity of 5 tons; (d) volumentric container — base 1 m^2 and height 0.5 m; e) Cardinal scale (SN 40828) — weight limit 4 tons and a Dove scale — weight limit of 7 kg; (f) Baader 440 fish splitting machine; (g) barometer; (h) sling psychrometer; (i) thermometer; and (j) salometer.

Pallet design

Six enclosed pallets were designed by Newton Engineering and Associates Limited* to specified dimensions (Fig. 3) having sufficient strength to withstand experimental stresses. The pallets were designed to allow adequate brine drainage and visual access to individual daily levels of split codfish and salt.

Outline of Project Activities

Preparation

Day 1, 18 July. Activities involved the completion of such last-minute details such as: checklisting, labelling and certifying all equipment; arranging the daily delivery of fresh codfish; and finalizing the procedures to be followed in carrying out the experiments.

The procedures from the initial delivery of round codfish to daily salting into pallets are outlined in Fig. 4.

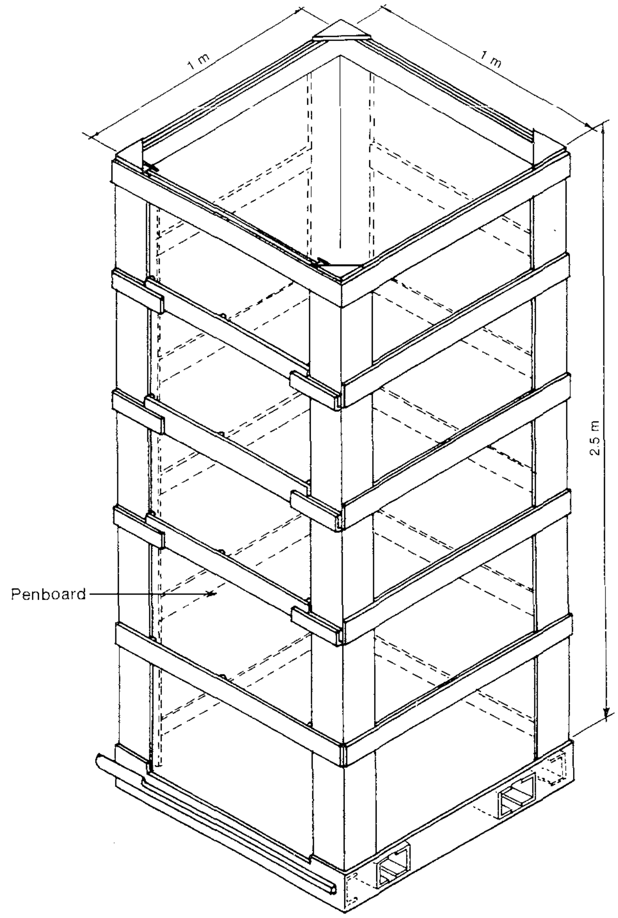


Fig. 3. Isometric view of experimental pallet. General specifications are: (a) the entire pallet constructed of aluminum welded together, except for the pallet penboards; (b) penboards made of plexi-glass; (c) exact inside dimension of 1 m^2 and a height of 2.5 m.

All handling of codfish including splitting was completed in a processing area and the split fish were then transported to the chillroom for salting. A chillroom was specifically secured for the experiments.

Salting phase

Day 2, 19 July. Experiment 3 simulated conditions when fishing recorded high catch-rates (approximately 2 tons of split fish were salted into pallet F in a period of 9.4 hr) and did not require the separation of daily quantities of fish. It was decided to proceed first with this experiment since it provided an opportunity to streamline the entire processing operation.

The experiment began with the delivery of approximately 3,400 kg of fresh round codfish. Length frequency mesurements were taken on 25% of the total, and three medium-sized fish were extracted for moisture analysis. The round codfish was then weighed in lots of approximately 350 kg for ease in handling, and

* Exact details of specifications are contained in blueprints No. 83-181, obtainable from Newton Engineering and Associates Limited, 51 O'Leary Avenue, St. John's, Newfoundland, Canada A1C 6C4.

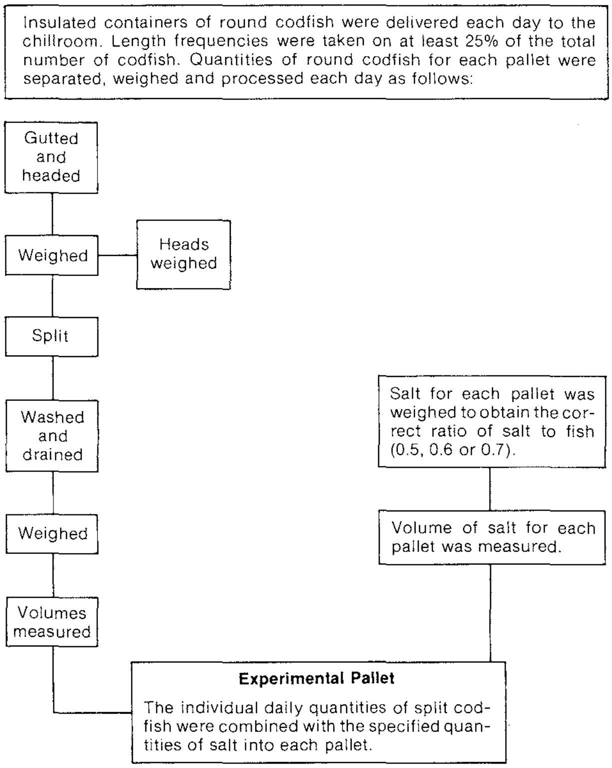


Fig. 4. Flow chart of daily procedures of fish salting.

after heading and gutting the lot was weighed again. The heads removed during processing were also weighed to distinguish between percentages of head and gut content. The total gutted, head-off fish was then processed by a Baader 440 splitting machine. Split fish were washed, drained and weighed before salting. The weighings between each step in processing were taken to obtain yield factors for the various types of product. Volumes of split fish were also measured in a volumetric container to determine split fish density.

The salt necessary to obtain a 60% by weight for pallet F was weighed and its volume determined before the salting process began. From 1800 hr on 19 July to 0330 hr on 20 July a total of 1,895.2 kg of split fish was salted with 1,137.2 kg of salt. Upon completion of salting, the total volume of the bulk was recorded. During the initial 48 hr after salting, brine runoff was collected at 3-hr intervals. For the remainder of the curing phase of the experiment, brine was collected at the time of each daily weighing and volume calculation in order to verify mass balance.

Day 3, 20 July. With the salting phase of Experiment 3 completed, work began on Experiment 1 (the effects of salt per hundredweight of split fish) and Experiment 2 (the effects of bulk height).

Experiments 1 and 2 involved placing of approximately equal quantities of split fish with predetermined percentages of salt in pallets A to E over a 4- to 9-day period. Each daily layer of split fish and salt was separated by a sheet of burlap, so that data could be obtained on daily changes of volume in the layer. Each pallet was weighed on the Cardinal scale daily, to obtain data on the weight of each new layer of salt and fish as well as the changes in weight of the bulk as a whole.

Day 3 began with the delivery of approximately 2,300 kg of round codfish. Length frequencies were conducted on 25% of the total, and three medium-sized fish were taken for moisture analysis. The round codfish was then weighed in five lots of 450 kg each (individual pallet allotment), and headed and gutted. The resulting product was weighed. The heads were weighed (as in Experiment 3) in order to distinguish between percentages of head and gut content. The volume was determined after the gutted, head-off fish were split, washed and drained.

The five allotments of split fish were salted and placed in pallets A to E with the percentages of salt as follows:

Pallet	% salt	Experiment
A	50	1
B	60	1, 2
C	70	1
D	60	2
E	60	2

Volumes and weights of each bulk were taken upon completion of salting as described in Experiment 3. During the initial 24 hr of the curing phase, brine runoff was collected at 3-hr intervals. Until the curing phase was completed, brine was collected at the time of each daily weighing and volume measurement.

Day 4 to Day 9, 21-29 July. The processing and salting procedures outlined in the preceding section were followed during this period. The only additional procedure involved the volume determination of each daily layer of split fish and salt (height between sheets of burlap).

Table 1 provides a summary of amounts of fish and salt used in the three experiments.

Curing phase

Day 10 to Day 76, 30 July to 3 October. Weights and volumes were taken until there were no significant changes for a period of 2 weeks. Throughout the curing phase, the temperature and humidity of the chillroom were monitored. These varied only slightly from the averages of 12° C and 75% respectively.

In the first week of the curing phase, individual pallet weighings and volume calculations, as well as brine sampling, were taken daily. As the curing phase progressed, weight loss in the bulk and brine runoff diminished to the point that data collection was necessary only twice a week. These twice-weekly measurements continued for a periof of 4 weeks, after which data collection was necessary only every 2 weeks.

By Day 70 (28 September) changes in the weights and volumes of individual pallets were insignificant, thus removal from salt was scheduled for the following week.

Removal from salt

Day 76 to Day 86, 4-13 October. Once the final bulk weight and volume of pallet F (Experiment 3) were recorded, the removal of fish and salt from pallets A to E commenced. On 4 and 5 October, the split fish was removed from the bulk by hand, shaken vigorously over the pallet to dislodge the particles of salt adhering to the fish, and weighed. The salt remaining in the pallet was weighed. Three samples from the top, middle, and bottom of the bulk, comprised of three medium-sized fish in each sample (for a total of nine fish from the whole bulk) were removed. These samples were sent to the Inspection Laboratory, Department of Fisheries and Oceans, Newfoundland, for salt and moisture analyses. The same procedure as for pallet F was followed, except that three medium-sized fish were removed from each layer for salt and moisture analyses.

The removal of fish and salt began on 4 October and completed on 13 October.

Results

Data

Of the large original data base, in this paper, only summaries of data are presented where necessary to clarify and support the main conclusions drawn. Tables 2, 3 and 4 contain some of these basic data.

Mass of split fish per unit bulk volume

A major objective was to obtain a split fish equivalent factor which could be used to convert directly from a measured volume of salted fish to the mass of split fish originally salted in the bulk. The factor was expected to depend on several variables, including the original ratio of salt to fish, the height of the bulk and the stage of curing process.

In each of the five pallets A through E, approximately 250–300 kg of split fish was salted each day for 9 days while in pallet F, salting was continuous over a 9.4 hr period, simulating a high catch-rate. The value of split fish equivalent factor (E) at any time can be calculated by dividing the original split fish weight (in a layer of bulk, as appropriate) by the corresponding volume.

TABLE 1. Total amounts of fish, split fish and percentage of salt by individual pallets in the three experiments. (Processing or salting of codfish in experiment 2 and 3 did not occur on 24 July due to the unavailability of fresh codfish.)

Experiment	Pallet	Total round weight (kg)	Total split weight (kg)	Total salt (kg)	% of salt	Total No. of days (layers)
1	A	4,119.8	2,461.5	1,234.1	50.1	9
	B	4,113.8	2,507.9	1,504.9	60.0	9
	C	4,121.9	2,514.1	1,759.4	69.9	9
2	D	1,816.1	1,068.1	640.9	60.0	4
	E	3,075.9	1,854.6	1,113.0	60.0	7
	B	4,113.8	2,507.9	1,504.9	60.0	9
3	F	3,302.9	1,895.2	1,137.2	59.9	1
	Mean	—	—	—	60.1	—

TABLE 2. Weights of fish and results of salt treatment in each pallet. Average moisture content of fish before salting = 81.1 % ± 0.6 (mean of 30 fish taken from the experiment during 19–29 July.

	Pallet						
	A	B	C	D	E	F	Mean
Total round weight (kg)	4,120	4,114	4,122	1,816	3,076	3,303	
Total split wieght (kg)	2,462	2,508	2,514	1,068	1,855	1,895	
Total salt (kg)	1,234	1,505	1,759	641	1,113	1,137	
Moisture content at end of experiment*	51.1(±1.1)	51.1(±0.7)	50.9(±0.8)	51.5	51.4(±0.8)	53.2	51.5%
Salt content at end of experiment*	18.3(±0.6)	19.1(±0.8)	18.8(±0.5)	19.4	19.3(±0.4)	18.6	18.9%
Weight of salted fish (kg)	1,485	1,498	1,485	673	1,128	1,143	
Weight of excess salt (kg)	487	745	1,004	319	555	568	

* Standard deviation given within brackets when more than 4 samples were taken.

For any one layer, this value increases monotonically with time from a value E_o (which depends on the original salt to fish ratio) to E_f, which depends on the salt to fish ratio and several other variables. The addition of a quantity of new fish to a bulk will have the effect of reducing E.

Table 5 gives the volume and weight measurements as the pallets were filled. E was calculated as explained above and bulk density D is simply the ratio of the mass of the bulk to its volume. Figure 5 shows graphs of E with time for the six pallets.

TABLE 3. Measurements of split fish bulk density taken in experiment 3 on 19 July and experiments 1 and 2 on the following 9 days.

Date	Pallets	Weight of split fish (kg)	Volume (m^3)	Bulk density (kg/m^3)
19 Jul	F	1,895	1.92	987
20 Jul	A–E	1,289	1.35	955
21 Jul	A–E	1,329	1.37	970
22 Jul	A–E	1,348	1.29	1,045
23 Jul	A–E	1,320	1.37	964
25 Jul	ABCE	1,122	1.12	1,002
26 Jul	ABCE	1,116	1.13	988
27 Jul	ABCE	1,167	1.12	1,042
28 Jul	ABC	844	0.83	1,017
29 Jul	ABC	873	0.87	1,003
Mean				997±3%

Experiment 1. Effect of salt per kilogram of split fish

Pallets A, B and C contained fish salted with 50, 60

TABLE 4. Measurement of salt bulk density for the three experiments.

Salt weight (kg)	Volume (m^3)	Bulk density (kg/m^3)
1,137.1	0.850	1,338
129.3	0.094	1,376
154.7	0.112	1,381
178.3	0.130	1,372
155.6	0.122	1,275
155.6	0.122	1,275
773.5	0.580	1,334
131.1	0.098	1,338
161.9	0.118	1,372
188.7	0.139	1,358
162.4	0.118	1,376
155.6	0.121	1,286
799.7	0.593	1,349
132.9	0.098	1,356
161.0	0.120	1,342
185.9	0.139	1,337
479.8	0.356	1,348
Mean		1342±2.5%

TABLE 5. Split fish equivalent (E) and bulk density (D) resulting from the volume and weight recordings as the six pallets were filled.

		50 kg/100 kg Pallet A		60 kg/100 kg Pallet B		70 kg/100 kg Pallet C			Pallet D		Pallet E		Pallet F		
Date	Day	E kg/m^3	D kg/m^3	E kg/m^3	D kg/m^3	E kg/m^3	D kg/m^3	Remarks	E	D	E	D	E	D	Remarks
20 Jul	0	759	1,139	696	1,114	670	1,140	Salting approximately 270 kg.	721	1,153	719	1,152	862	1,378	End salting pallet F.
21 Jul	1	897	1,164	824	1,162	818	1,221	Split fish each day.	840	1,179	808	1,132	1,036	1,236	
22 Jul	2	1,005	1,221	912	1,209	849	1,192		911	1,206	877	1,160	1,149	1,229	
23 Jul	3	1,039	1,202	946	1,184	904	1,213		971	1,205	964	1,188	1,207	1,242	End salting pallet D.
24 Jul	4	1,179	1,195	1,089	1,209	1,006	1,214	No salting.	1,709	1,212	1,101	1,230	1,247	1,245	
25 Jul	5	1,096	1,180	1,021	1,195	963	1,214		1,136	1,204	1,029	1,210	1,263	1,249	
26 Jul	6	1,132	1,202	1,058	1,224	967	1,208			1,211	1,055	1,225	1,281	1,249	
27 Jul	7	1,152	1,201	1,058	1,204	989	1,223		1,187	1,206	1,072	1,230	1,294	1,249	End salting pallet E.
28 Jul	8	1,162	1,188	1,091	1,230	1,005	1,230		1,200	1,204	1,166	1,231	1,303	1,250	
29 Jul	9	1,201	1,217	1,110	1,229	1,026	1,235	Last day salting, A, B, C.	1,207	1,202	1,212	1,234	1,303	1,244	
30 Jul	10	1,289	1,218	1,185	1,241	1,088	1,243		1,214	1,203	1,228	1,231	1,307	1,243	
31 Jul	11	1,338	1,217	1,235	1,240	1,127	1,240		1,221	1,203	1,253	1,238	1,307	1,241	
1 Aug	12	1,368	1,219	1,254	1,234	1,143	1,234		1,221	1,196	1,262	1,233	1,312	1,240	
2 Aug	13	1,383	1,215	1,273	1,237	1,153	1,231						1,316	1,241	
3 Aug	14	1,391	1,210	1,286	1,238	1,169	1,237		1,235	1,201	1,279	1,232			
4 Aug	15												1,316	1,235	
5 Aug	16	1,407	1,207	1,299	1,235	1,180	1,236		1,242	1,203	1,292	1,234			
6 Aug	17												1,325	1,237	
8 Aug	19	1,423	1,206	1,313	1,234	1,192	1,236		1,249	1,200	1,306	1,237			
9 Aug	20												1,335	1,239	
11 Aug	22	1,439	1,210	1,327	1,237	1,203	1,238		1,257	1,200	1,320	1,241			
12 Aug	23												1,335	1,236	
15 Aug	26	1,457	1,213	1,334	1,235	1,209	1,236		1,272	1,209	1,329	1,243			
16 Aug	27												1,339	1,235	
19 Aug	30	1,465	1,214	1,341	1,235	1,215	1,236		1,272	1,203	1,329	1,235			
20 Aug	31												1,344	1,234	
26 Aug	37	1,474	1,212	1,348	1,233	1,220	1,233		1,272		1,344	1,241			
27 Aug	38												1,354	1,238	
9 Sep	51	1,492	1,214	1,363	1,235	1,232	1,234		1,279		1,354	1,239			
22 Sep	64	1,501	1,213	1,370	1,242	1,238	1,233		1,287		1,354	1,232			
3 Oct	75	1,510	1,210	1,378	1,235	1,251	1,239								

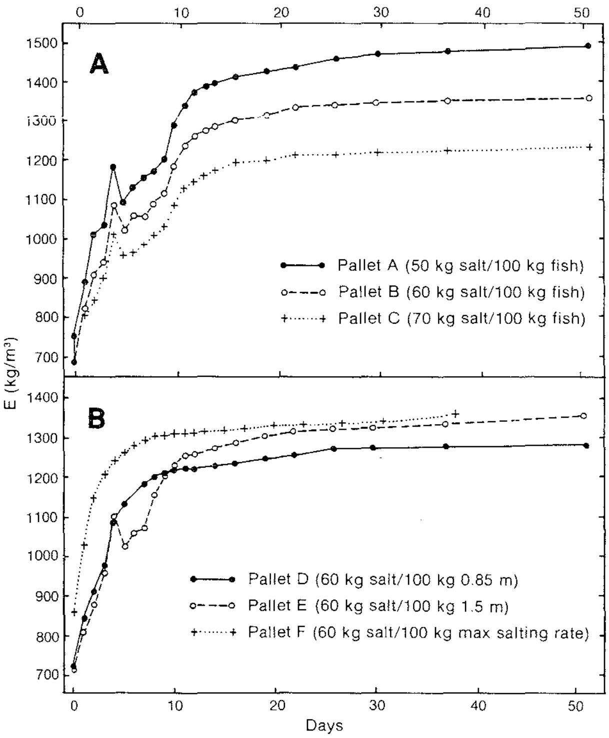


Fig. 5. Change in split fish equivalent factor (E) with time in the six experimental pallets.

and 70 kg of salt per 100 kg of split fish, respectively. In each case, one layer of fish was salted per day (except on day 4) until there were nine layers. All the curves had the same general shape, but clearly had different final values of E (E_f). The initial value of the split fish equivalent factor, E_o, also depends on the original salt/fish ratio. Table 6 gives the values of E_o and E_f estimated from Experiment 1. (Pallets D and E from Experiment 2 have also been included in Table 6).

Experiment 2. Effect of bulk height

Pallets B, D, E were loaded to different total heights, all other variables being kept constant. The percentage of salt used was 60% for all three pallets. The main effect was on the value of E_f, and the results are summarized in Table 7.

The effect of different bulk height was only noticeable between the lowest pile (0.85 m) and the next highest (1.35 m), and the change in E_f was just over 5%. This was presumed to be the effect of compression on the lower layers of the pile due to the weight above. Observations also suggested that the compression effect is most pronounced at the start of the process of building a bulk. The amount of additional compression of a layer of fish rapidly approaches zero as the pile of fish above it increases, and once the layer had been compressed by a meter or so of fish, it was very difficult to compress it further. This was a reasonable explanation of why there was no noticeable difference between the 1.35 and 1.8 m high pallets.

TABLE 6. Initial (E_o) and final values (E_f) of split fish equivalent factor for each pallet.

Pallet	Original salt to fish ratio	E_o (kg/m³)	E_f (kg/m³)
A	50	760	1,480
B	60	690	1,350
D	60	720	1,280
E	60	720	1,350
F	60	862	1,350
C	70	660	1,220

TABLE 7. Effects of bulk height on the final split fish equivalent factor (E_f) in experiment 2.

Pallet	Final height	E_f
D	0.85	1,280
E	1.35	1,350
B	1.8	1,350

Experiment 3. High catch rate

Pallet F was salted with 60 kg of salt per 100 kg split fish in one continuous pile to a total height of about 2 m over a 9.4 hr period. This was intended to simulate a period of high catch-rates. This experiment also provided basic information from which the variation of E during intermittent salting and afterwards can be predicted.

Figure 5 shows the split fish equivalent factor (E) in relation to time. In this case E rises quickly to a final value of about 1,350 kg/m³. This value is consistent with pallets B and E, with the same salt to fish ratio and similar height. After 2 days in salt, the value of E reached 1,150 kg/m³ or 81% of its final value, and has reached 96% of its final value in 8 days.

Mass balance for salt

It was important to do an overall mass balance for salt in order to check experimental accuracy and to obtain certain experimental constants useful in later analysis. The amount of salt initially used was measured, as were brine volume and density, the final amount of undissolved salt, and the final salt content of the fish. Table 8 summarizes the results. Measurements of specific gravity showed that the brine draining from the bulk of fish was saturated. The amount of salt unaccounted for was quite small (between 2 and 5% for the six pallets).

Analysis

Initial value of E

An attempt was made to predict the initial or "instantaneous" value (E_o) immediately after a layer of fish was salted. This simple model neglected any compression effect, and also ignored voids. Considering

TABLE 8. Mass balance for salt through the saturation treatment of fish in each pallet.

	Pallet					
	A	B	C	D	E	F
Salt taken from bulk (kg)	486.6	744.9	1,003.6	318.6	554.8	568.1
Measured salt content (average) %	18.3	19.1	18.8	19.4	19.3	18.6
Salt in fish (kg)	271.7	286.1	279.1	130.5	217.7	212.5
Volume of brine collected (liter)	1,677	1,684	1,687	642	1,214	1,143
Mass of salt lost in saturated brine (kg)	436	438	439	167	316	297
Total salt accounted for (kg)	1,194	1,469	1,722	616	1,089	1,078
Salt originally used (kg)	1,234	1,515	1,759	641	1,113	1,137
% of salt accounted for (mass balance)	97	98	98	96	98	95

the situation before any solution of salt has occurred, the total volume of a fish and salt bulk can be obtained by summing the volumes of fish and salt. A straightforward analysis then shows that

$$E_o = \frac{d_{sf}\, d_s}{d_s + r\, d_{sf}} \qquad (1)$$

where d_{sf} = bulk density of split fish,

d_s = bulk density of salt,

r = ratio of salt to fish.

See Appendix II for development of equation.

Table 9 shows theoretical values according to equation (1) as well as the measured values of E for the first layers salted for each pallet. These values of E_o are reasonably close to the initial measurements, keeping in mind that by the time the measurement was made, some solution of salt had taken place and the value of E was already rising as shown in Fig. 5.

In addition to the experimental data for the first layers on each pallet (Table 9), it is possible to use all the layers, noting the time it took to build them, and then extrapolate linearly to zero time to obtain another experimental estimate of F_o. However, the thickness of a pile of fish is not easy to define precisely; there is a scatter in the data, and not a high correlation with time. A plot of the data in Table 9 for pallets B, D, E and F nevertheless gives very good agreement with the value of E_o from equation (1).

In conclusion, equation (1) gives a very reasonable estimate of E_o, and has the advantage of simplicity. The estimate is slightly conservative, and if it were used to calculate the amount of split fish in a vessel, the estimate would likely be slightly below the actual weight. This is due to certain assumptions which are discussed below. Figure 6 shows E_o for various salt to fish ratios, based on equation (1).

TABLE 9. Theoretical initial value of split fish equivalent factor (E_o) calculated after one layer of fish was salted.

Pallet	Salt to fish ratio (r)	E_o equation (1)* (kg/m^3)	First measured F_o (kg/m^3)	Time to salt first layer (hr)
A	0.50	727	759	1.0
B	0.60	690	696	1.3
C	0.70	656	670	2.5
D	0.60	690	721	2.6
E	0.60	690	719	1.2
F	0.60	690	862	9.4

* Split fish density = 997 kg/m^3; salt density = 1,342 kg/m^3.

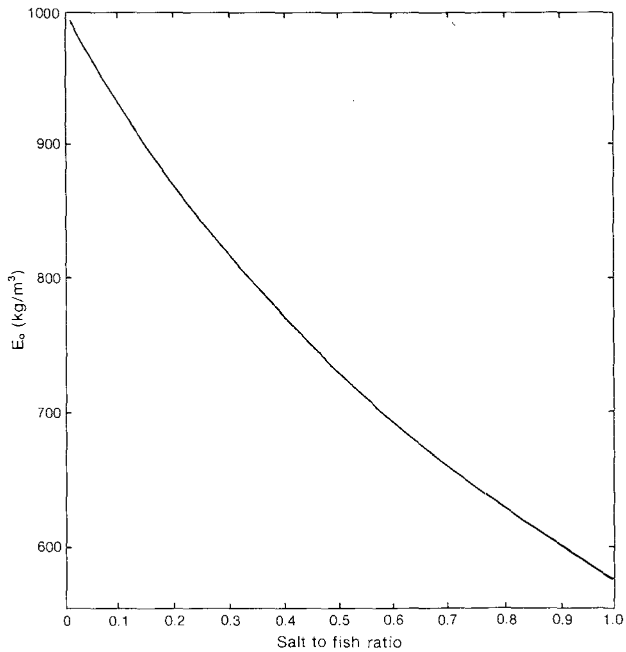


Fig. 6. Theoretical initial split fish equivalent factor (E_o) plotted against salt to fish ratio based on equation 1.

Equilibrium value of E

The graphs of E against time (Fig. 5) show that after a certain period, E approaches what appears to be an equilibrium or final value for E_f. As with E_o, it is possible to predict a theoretical value for E_f, but the process is somewhat more complex, and involves several other variables such as moisture content, salt content, and the density of fully cured salt fish. Again, certain simplifying assumptions were made. In particular the compression in the pile is neglected, it is assumed that there are no voids, small loss of protein through solution in the brine is neglected, and it is assumed that the brine which flows away is fully saturated with salt. These simplifications are not unreasonable in the light of experimental measurements, but it is necessary to recognize them when the theoretical model is interpreted.

The model starts by equating the volume of the final bulk to the sum of the volume of the salted fish and the remaining salt in the pile. The weight of fish is clearly determined by the original amount of split fish, its initial and final moisture content, and the salt content. The weight of salt remaining is determined by the original amount used, the amount absorbed by the fish and the amount drained away in the brine. After some algebra (see Appendix II), the following equation results:

$$E_f = \frac{d_{cf}d_s}{d_s\left(\frac{1-M_o}{1-M_f-S}\right) + d_{cf}\left[r - \frac{S(1-M_o)}{1-M_f-S} - 0.36\left(\frac{M_o(1-S)-M_f}{1-M_f-S}\right)\right]} \qquad (2)$$

where d_{cf} = bulk density of cured fish (kg/m^3),
d_s = bulk density of salt (kg/m^3)
M_o = original moisture content of fish (fraction of wet weight)
M_f = final moisture content of fish (fraction of wet weight),
S = salt content of fish (fraction of wet weight),
r = ratio of weight of salt used to weight of split fish,
E_f = final split fish equivalent factor (kg/m^3).

All of the variables in equation (2) except for d_{cf}, have already been discussed or established by direct measurement. This final variable can also be estimated from experimental data since the weight and volume of the total bulk and the salt were measured at the end of the experiment. If the effect of any voids is neglected, an effective bulk density for cured fish can be calculated. Table 10 gives the data and the estimated values of d_{cf}. These values show reasonable consistency from pallet to pallet, and have a mean value of 1,176 kg/m^3.

It is now possible to produce a comparison of experiment and theory for each pallet. Since all the fish received similar treatment however (in that the result should be heavysalted saltbulk), it is perhaps more realistic to take the average values of the variables in equation (2) (e.g. final salt and moisture contents, which vary slightly from pallet to pallet) and compute theoretical values for E_f for comparison with experimental results. The set values were as follows:

$M_o = 0.811$ (Table 2); $M_f = 0.515$ (Table 2),
$S = 0.189$ (Table 2); $d_s = 1{,}342$ (Table 4),
and $d_{cf} = 1{,}176$ (Table 10).

Allowing r to take values from 0.3 to 1, a set of values for E_f are given in Table 11, which includes the experimental values.

Apart from pallet D, the experimental values are only slightly higher (up to approximately 4%) than the theoretical ones, showing excellent agreement. Both the compression of the bottom layers and the loss of protein through solution have been neglected in the model, and these assumptions should lead to errors which compensate each other. It was noted that the only experiment which gave a lower value of E_f than the theoretical model in equation (2) was one in which the pile was lowest, and therefore the effect of compression was least (pallet D, height 0.85 m).

Figure 7 shows graph of E_f with r for two different final moisture contents. In the experiments M_f was

TABLE 10. Theoretical values of bulk density of cured fish calculated for each pallet.

Pallet	Final volume (m^3)	Weight salt remaining (kg)	Volume salt (m^3)	Weight cured fish (kg)	Density cured fish (kg/m^3)
A	1.63	487	0.36	1,485	1,169
B	1.82	745	0.56	1,498	1,189
C	2.01	1,004	0.75	1,485	1,179
D	0.83	319	0.24	673	1,141
E	1.36	555	0.41	1,128	1,187
F	1.38	568	0.42	1,143	1,191
Mean					1,176

TABLE 11. Calculated and experimental equilibrium values of E_f.

Salt to fish ratio*	E_f from equation (2) (kg/m^3)	Experimental: Pallet	Experimental: (see Table 6)
0.3	1,827		
0.4	1,608		
0.5	1,436	A	1,480
0.6	1,297	B	1,350
0.6	1,297	D	1,280
0.6	1,297	E	1,350
0.6	1,297	F	1,350
0.7	1,183	C	1,220
0.8	1,087		
0.9	1,006		
1.0	936		

* If this ratio is less than approximately 0.30, there will not be sufficient salt to saturate all the water present, and fully salted fish will not be obtained.

measured to be about 52% (wet basis), which is a little below what one normally expects for salt bulk fish. This may have been due to a slight loss of moisture in the lab before analysis. It is also possible that previous experience was based on cured fish washed prior to drying, probably resulting in slightly higher moisture content. Similar variations in initial moisture content and salt content also affect E_f. Equation (2) can easily be used to investigate these effects. More importantly, it provides the means of generalizing results to other moisture contents, salt contents, and salt-to-fish ratios. The ability to predict E_o and E_f is thus of some significance, and when combined with the results from Experiment 3, the prediction of the value of E as it changes from E_o to E_f in the salting process is possible.

Variation of E with time

Figure 5 shows E rising from E_o to E_f for the bulk as a whole. As each layer is added, the value of E begins at E_o and follows the pattern shown by pallet F, to eventually approach E_f. This variation from E_o to E_f happens simultaneously at all levels in the bulk, and the value of E for any layer depends on the length of time it has been salted. The overall value of E is a combination of the values of E for the various layers, as each layer decreases in thickness. Analysis shows that at any given time the overall value of E for the bulk is the weighted average of E of all the layers, where the "weights" in the average are related to the layer thicknesses. A more detailed discussion of this variation is found in Appendix II.

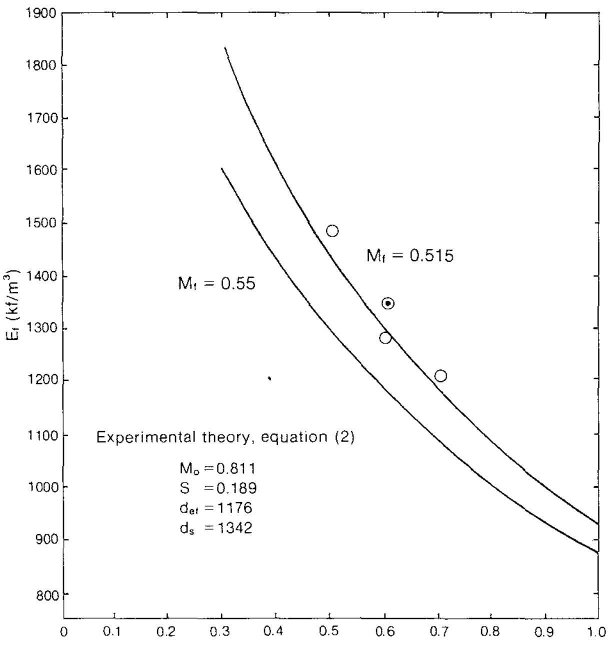


Fig. 7. E_f plotted against r to obtain two relationships for final moisture contents.

The dimensionless ratio R (see also Appendix II) is defined by:

$$R = \frac{E - E_o}{E_f - E_o} \tag{3}$$

As E varies from E_o to E_f, R varies from 0 to 1. Thus, if there is a bulk consisting of N layers, each having values of E corresponding to the period in salt, such that for each layer R takes values R_1, R_2...R_n, then the result of the mathematics is that

$$\bar{R} = \frac{\sum \frac{F_n R_n}{1+(E_f/E_o-1)R_n}}{\sum \frac{F_n}{1+R_n(E_f/E_o-1)}} \tag{4}$$

where the summation is over all the N layers, and

$R_n = \dfrac{E_n - E_o}{E_f - E_o}$ for layer n,

E_f = equilibrium value of E,

E_o = initial value of E, and

F_n = fraction of total bulk in layer n.

When $\bar{R}$ has been found, E for the whole bulk can be calculated from reversing the process in equation (3), i.e.

$$\bar{E} = (E_f - E_o)\,\bar{R} + E_o \tag{5}$$

The value of R for any layer depends on the time it has been in salt. For the purpose of this analysis, time is measured in days. In Experiment 3 salting was as fast as possible, and there was essentially one layer. A model is now constructed in which the variation of E with time for this pallet is used to simulate each layer in a bulk of fish. All the layers are then combined using equation (4) to obtain a model for the whole bulk.

A graph of R with time for pallet F is shown in Fig. 8. To construct this curve the value of E_o has been taken as 690 kg/m^3, as given by equation (1), but the value of E_f is the experimental estimate, i.e. 1,350 kg/m^3. This final value is not critical to the simulation, but it is convenient and realistic not to have R exceed 1. After passing a smooth curve through the experimental points of Fig. 8 and interpolating where necessary, Table 12 is constructed of model values of R with time.

The values of F_n in equation (4) are determined by the fraction of total split fish originally put in each layer (i.e. the fraction of split fish which will be of a particular age). These data are shown in Table 13 for all pallets except F (pallet F had only one layer).

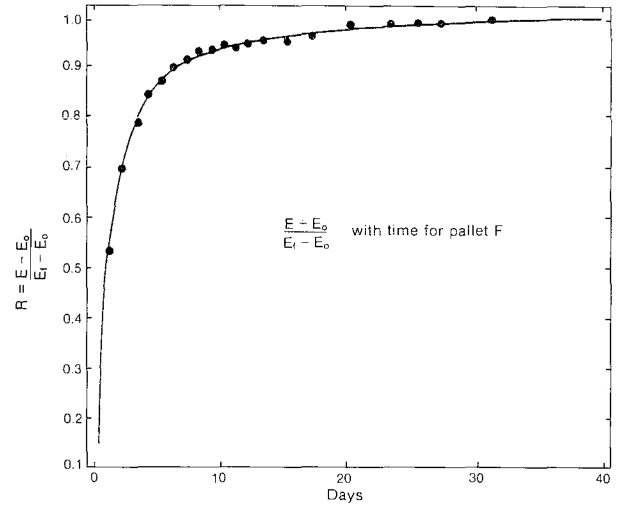


Fig. 8. A plot of the simulated values of R as a function of time for pallet F.

A computer program was written for equation (4) to carry out the required calculations as salting and curing proceeded. For this simulation the inputs to the model were the initial value of E given in equation (1), the final value of E given in equation (2) and the age distribution of the fish, as given for example in Table 13. The program contains the standard data in Table 12, which is used to generate the correct value of R for each layer of fish as time progresses.

TABLE 12. Model values of R tabulated against time (days).

Time (days)	R	Time (days)	R	Time (days)	R	Time (days)	R
0	0	10	0.94	20	0.97	30	0.99
1	0.52	11	0.94	21	0.97	31	0.99
2	0.69	12	0.95	22	0.97	32	0.99
3	0.78	13	0.95	23	0.98	33	0.99
4	0.84	14	0.96	24	0.98	34	0.99
5	0.87	15	0.96	25	0.98	35	0.99
6	0.89	16	0.96	26	0.98	36	0.99
7	0.91	17	0.97	27	0.98	37	0.99
8	0.92	18	0.97	28	0.98	38	0.99
9	0.93	19	0.97	29	0.99	39	1.0

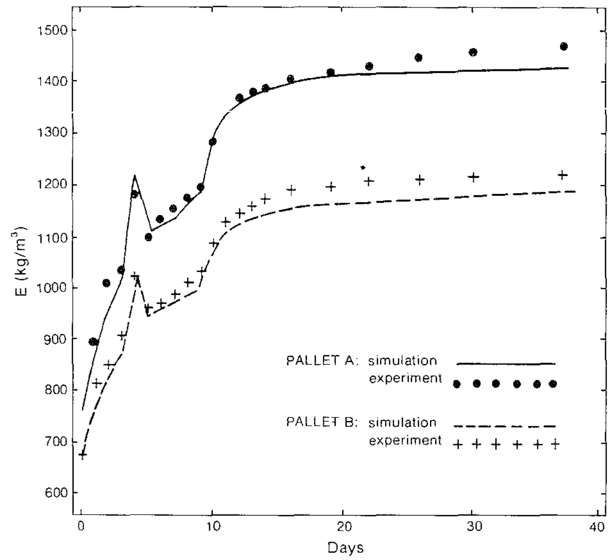


Fig. 9. Plot showing the comparison of simulation and experiment pallets A and C.

Figure 9 shows comparisons of simulated and experimental data for pallets A and C. Comparisons for the other experiments are similar, and in one case (pallet D) the agreement was better than the example given in Fig. 9. It is therefore apparent that the model predicts the behavior of E with time very well, in spite of what looked like quite irregular variations in Fig. 5. The difference between simulation and experiment as E nears equilibrium is a direct result of the fact that the theoretical E_f from equation (2) is somewhat below the experimental value, as previously discussed. It has to be kept in mind that the model neglects compression effects and will likely underestimate E_f. For the low pile (pallet D) the agreement between experimental and theoretical E_f is better, with the theoretical value actually being a little higher than experimental.

Discussion

If equations (1), (2), (4) and (5) and the information in Table 12 are assembled, the result is a model which

TABLE 13. Distribution of split fish by layers and days in salt (age) in pallets A to E. (Note that no fish was salted on day 4.)

Layer	Age (days in salt)	Pallet A kg	Pallet A F	Pallet B kg	Pallet B F	Pallet C kg	Pallet C F	Pallet D kg	Pallet D F	Pallet E kg	Pallet E F
1	0	258.0	0.105	257.6	0.103	254.5	0.101	259.5	0.243	259.0	0.140
2	1	262.2	0.107	269.7	0.108	269.0	0.107	269.7	0.253	258.4	0.139
3	2	263.5	0.107	266.5	0.106	265.8	0.106	263.1	0.246	289.2	0.156
4	3	275.8	0.112	284.9	0.114	277.1	0.110	275.8	0.258	205.9	0.111
5	5	277.1	0.113	279.2	0.111	281.7	0.112			284.2	0.153
6	6	282.6	0.115	282.9	0.113	285.5	0.114			264.9	0.143
7	7	293.0	0.119	285.5	0.114	295.1	0.117			293.0	0.158
8	8	261.3	0.106	289.6	0.115	293.0	0.117				
9	9	288.0	0.117	292.1	0.116	292.4	0.116				
Total (rounded)		2,462	1.00	2,508	1.00	2,514	1.00	1,068	1.00	1,855	1.00

has been able to predict E to within 4 or 5% for all the experiments carried out in the project. The inputs and parameters necessary to run the model are assembled in Table 14. The output is a set of values of E for each day (or other selected time interval) from the time the first fish was salted (day zero) to 40 days.

To demonstrate its versatility, it was useful to apply this model to a number of "scenarios" corresponding to imaginary fishing and salting practices at sea. In all cases the following values of parameters were used, unless otherwise specified: $r = 60\%$; $M_o = 81\%$; $M_f = 52\%$; $S = 19\%$, and other constants (e.g. densities) as in Table 14. From the present experimental data, values of $E_o = 690$ kg/m^3 and $E_f = 1{,}273$ kg/m^3.

The scenarios chosen were as follows: (a) Slow fishing: 5% of total bulk daily for 20 days; (b) Fast fishing: 20% per day for 5 days; (c) Intermittent: 20% every third day; (d) "Mostly last 3 days": 10% in each of first 2 days followed by 5 days of no fish caught, then 20, 30 and 30% in next 3 days.

The results of these calculations are shown in Fig. 10. Curves (a) and (b) show how the value of E is depressed while new fish is being salted, compared to the rapid rise towards equilibrium when salting is complete. The breaks in both curves (a) and (b) occur when salting ends. Scenarios (c) and (d) lead to highly variable patterns for E during the intermittent fishing period. The addition of new fish again forces the value of E down, and it rises quickly unless fish is being added.

It is difficult to give general rules which would apply in all situations, and it would obviously be very useful to consider practical cases based on experience. Perhaps one general rule is that by 7 days after the end of salting, no matter what the fishing pattern has been, the value of E has reached about 96% of its final value.

Photographs taken during the final stages of the experiment are presented in Appendix III.

Conclusions

The answers to the basic questions which arise from the study objectives are contained in Table 5 and Fig. 5. The salt to fish ratio controls the initial value of E as given in equation (1). In addition, the salt/fish ratio, moisture fraction and salt content also affect the final or equilibrium value of the factor. This equilibrium value can be calculated from equation (2). The variation from initial to final values is predictable, and the addition of new fish tends to reduce the factor. A set of equations has been derived and combined in a fairly simple computer program which enables the calculation of conversion factors consistent with the experiments, and also allows generalization of the results. The effect of compression in the bulk is a slight increase in the conversion factor as predicted by theory for bulk depth greater than approximately 1 m. The difference is approximately 5%.

Once the values of the parameters (Table 14) have been quantified, it is possible to calculate a definitive conversion factor within the range of 600 to 1,500 kg/m^3.

TABLE 14. Parameters for the input values and the model to predict the split fish equivalent factor.

Parameter	Description and values used
d_{sf}	Bulk density of split fish (997 kg/m^3).
d_s	Bulk density of salt (1,342 kg/m^3).
r	Salt to fish ratio.
E_o	Initial value of E. Output from equation (1), input to (4).
d_{cf}	Bulk density of cured salt bulk fish (1,176 kg/m^3).
M_o	Moisture fraction, split unsalted fish (0.80–0.82).
M_f	Moisture fraction, cured salt bulk (0.50–0.55).
S	Salt fraction, cured salt bulk (0.18–0.20).
E_f	Equilibrium value of E. Output from equation (2) input to (4).
R	See equation (3). Values of R go from 0 to 1 as fish cures and, based on experiment, describe the variation of E with time. Standard data is contained in Table 13 and the computer program.
F_n	Fraction of bulk contained in nth layer as originally salted. Input to equation 4, and program.
t	Time in days. Input to computer.
E	Split fish equivalent factor. Output from program, for any requested day up to 40.

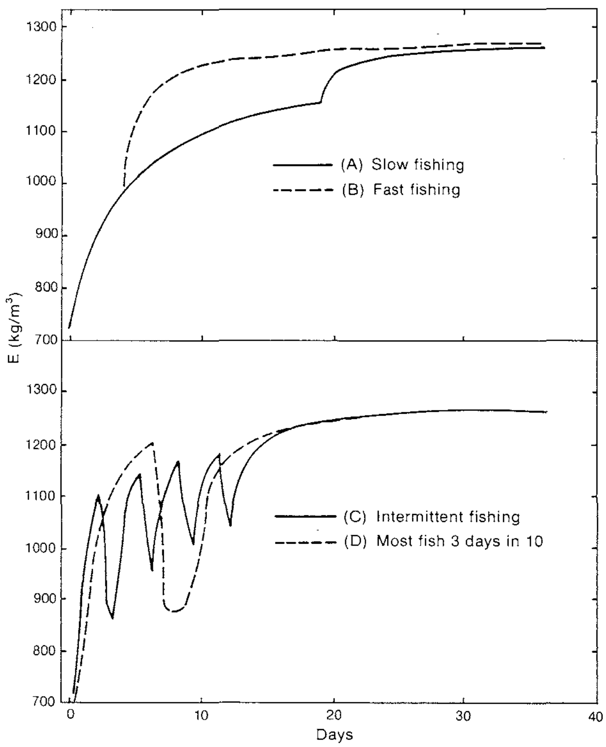


Fig. 10. Plots derived from applying various fishing scenarios and salting practices to the model.

Acknowledgements

This experiment was made possible through the combined efforts of the Department of Fisheries and Oceans and the Canadian Saltfish Corporation. Special thanks to Mr Bren Kennedy and his staff at Southside Fisheries Limited. We acknowledge the work of the Inspection Staff, Department of Fisheries and Oceans, Newfoundland Region and express our thanks to Ms Bonnie Bruce, for typing the report and to Ms Judy Gidson for editing the report. Throughout the experiment, the advice and assistance of the Fisheries Officers from the Enforcement Section (Offshore) was greatly appreciated. We also thank Mr E. B. Dunne for his support throughout the project.

This project was funded through the office of the Assistant Deputy Minister, Atlantic Fisheries, Ottawa.

Appendix I

Recoveries

One of the byproducts of this experiment was a set of data from which the "recovery" or weight of cured fish per kilogram of split could be calculated. In principle this should be a straightforward calculation, based on a mass balance, provided moisture and salt contents are known before salting and at the stage the recovery is to be calculated. There is generally some discrepancy with theory, however, since protein is always lost in the brine solution, and there is no simple theoretical way to account for this.

The mass balance before and after the salting and curing process gives the following equation:

$$\frac{W_{cf}}{W_{sf}} = \frac{1 - M_o}{1 - M_f - S} \tag{A1}$$

where W_{cf} = weight of cured fish,

W_{sf} = weight of split fish,

and other variables have been previously defined.

For fish that has been "struck" and not dried, it is also a fact that the moisture present in the flesh is completely saturated with salt. For a saturated salt solution, $\frac{S}{M_f} = 0.36$, and one of these variables can be eliminated in equation (A1). In the experiment here, however, both M_f and S were measured and the values which were found independently can be used.

The theoretical and actual values are presented in Table A1, together with other pertinent data. The actual recovery is about 5% lower than that predicted by equation (A1), and it is probably reasonable to assume that this is due to protein loss in solution during the brining process.

It is important to note that the overall recovery that can be expected depends rather heavily on initial and final moisture contents (Fig. A1). For example, a change in final moisture from 52 to 56% will increase recovery from 0.65 to 0.76.

TABLE A1. Theoretical and actual recoveries.

Pallet	Recovery Theory	Recovery Actual	M_o	M_f	S	S/M_f
A	0.618	0.603	0.811	0.511	0.183	0.358
B	0.634	0.597	0.811	0.511	0.191	0.374
C	0.630	0.591	0.811	0.509	0.188	0.369
D	0.649	0.630	0.811	0.515	0.194	0.377
E	0.645	0.608	0.811	0.514	0.193	0.375
F	0.670	0.603	0.811	0.532	0.186	0.350
Mean	0.640	0.605	0.811	0.515	0.189	0.367

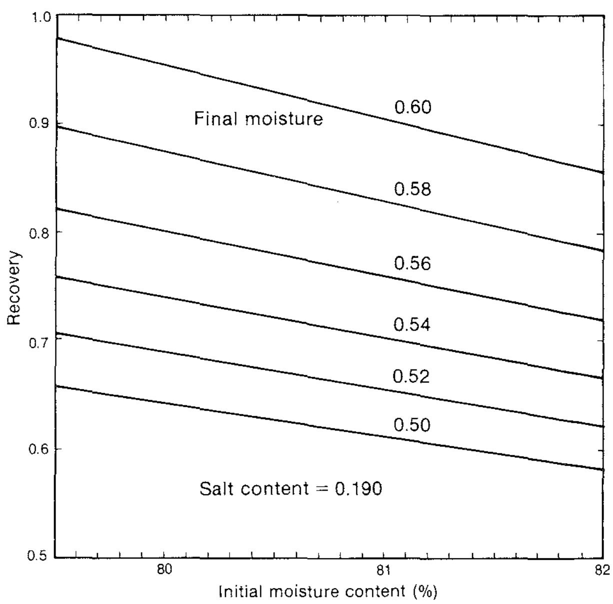


Fig. A1. Plot of theoretical recoveries.

Appendix II

Initial Value of E

$$E_o = \frac{d_{sf} d_s}{d_s + r\, d_{sf}}$$ (Equation 1 in text)

where d_{sf} = bulk density of split fish, kg/m^3

d_s = bulk density of salt, kg/m^3

r = ratio of weights of salt to fish,

E_o = initial split fish equivalent factor.

When the salt and fish are initially combined, total volume = volume of split fish + volume of salt,

i.e. $V_o = V_{sf} + V_s$ (B1)

d_{sf} = weight of split fish / $V_{sf} = W_{sf} / V_{sf}$,

d_s = weight of salt / $V_s = W_s / V_s$.

Also $E_o = W_{sf} / V_o$, and substituting into equation (B1), we get

$$\frac{W_{sf}}{E_o} = \frac{W_{sf}}{d_{sf}} + \frac{W_s}{d_s} = \frac{W_{sf} d_s + W_s d_{sf}}{d_{sf}\, d_s}$$

Rearranging,

$$E_o = \frac{d_{sf}\, d_s}{W_{sf}\, d_s + W_s\, d_{sf}} \quad W_{sf}$$

$$= \frac{d_{sf}\, d_s}{d_s + r\, d_{sf}}$$, as required

Final Value of E

$$E_f = \frac{d_{cf}\, d_s}{d_s \left(\dfrac{1-M_o}{1-M_f-S}\right) + d_{cf} \left[r - \dfrac{S(1-M_o)}{1-M_f-S} - 0.36 \left(\dfrac{M_o\,(1-S)-M_f}{1-M_f-S}\right)\right]}$$ (Equation 2 in text).

where E_f = Final split fish equivalent, kg/m^3,

d_{cf} = bulk density of cured fish, kg/m^3,

M_o = original moisture content of fish (fraction),

M_f = final moisture content of fish (fraction),

S = salt content of fish (fraction of wet weight), and

r = salt to fish ratio.

Again the final volume of the bulk of fish and excess salt is given by:

$$V_f = V_{cf} + V_{xs} \qquad (B2)$$

where V_{xs} = volume of excess salt in bulk,

V_{cf} = volume of cured fish,

V_f = total final volume, and it is noted that voids are being neglected.

$$\text{Now} \quad V_{cf} = \frac{W_{cf}}{d_{cf}}, \quad V_{xs} = \frac{W_{xs}}{d_s} \qquad (B3)$$

where W_{cf} = weight of cured fish, and

W_{xs} = weight of excess salt in bulk.

The weight of excess salt is simply the original amount of salt used less the amounts absorbed by the fish and that lost in the brine which has drained away. The amount absorbed by the fish is S W_{cf} where S is the fractional salt content (wet basis). Since the experiment showed that the brine draining away from the fish was saturated, the amount of salt lost in this way is 0.36 times the amount of water lost, which is $M_oW_{sf}-M_fW_{cf}$, where W_{sf} is the weight of split fish originally salted.

$$\text{Therefore} \quad W_{xs} = W - S\,W_{cf} - 0.36\,(M_oW_{sf} - M_fW_{cf}) \qquad (B4)$$

The weight of cured fish is simply given by the weight of original split fish less the water lost plus the weight of salt gained,

$$\text{i.e.,} \quad W_{cf} = W_{sf} - (M_oW_{sf} - M_fW_{cf}) + S\,W_{cf}$$

$$\text{which gives} \quad W_{cf} = \frac{W_{sf}\,(1 - M_o)}{1 - M_f - S} \qquad (B5)$$

Incidentally, $\dfrac{W_{cf}}{W_{sf}} = \dfrac{1 - M_o}{1 - M_f - S}$ is the "theoretical recovery" or the ratio of cured product to initial split fish weight given in Appendix I, equation (A1).

If Appendix II equation (B5), (B4) and (B3) are combined, and substituted into (B2):

$$V_f = \frac{W_{sf}\,(1-M_o)}{d_{cf}\,(1-M_f-S)} + \frac{W_s - S\,W_{cf} - 0.36\,(M_oW_{sf}-M_fW_{cf})}{d_s} \qquad (B6)$$

Dividing both sides of this equation by W_{sf}, noting that $\dfrac{W_s}{W_{sf}} = r$ (the salting ratio) and taking the reciprocal of both sides of the results gives:

$$\frac{W_{sf}}{V_f} = E_f = \frac{d_{cf}\,d_s}{d_s\left(\dfrac{1-M_o}{1-M_f-S}\right) + d_{cf}\left[r - \dfrac{S(1-M_o)}{1-M_f-S} - 0.36\left(\dfrac{M_o\,(1-S)-M_f}{1-M_f-S}\right)\right]}$$

which is the equation for E_f, as required.

Variation of E from E_o to E_f

Consider a bulk of fish and salt consisting of N layers or, more precisely, amounts of fish of various "ages", or periods in salt. In this model the various layers correspond to the daily amounts salted, but the time scale is not important to the argument in general. At any time the values of E for the layers will be E_o

$E_1, E_2, \ldots E_n \ldots E$, depending on whether it has just been salted (E_o) or has been there for a period of n days. The overall value of E for the bulk — call this $\bar{E}$ —will depend on the "age history", or the proportion of fish in the total bulk of various individual ages, and therefore in different stages of curing. Let the fraction of total bulk which is in the n^{th} layer be F_n,

i.e.: $$F_n = \frac{\text{weight of split fish in layer n}}{\text{total weight of split fish in bulk}}$$

A key point is the recognition of the simple fact that since the mass of split fish in a given layer does not change with time, the change in E results entirely from the decreasing volume of the layer, which is essentially the effect of decreasing thickness, since its area may be reasonably considered to be fixed. In other words, E_n is directly proportional to $\frac{1}{t_n}$ where t_n is the thickness of the n^{th} layer. Thus at any time,

$$E_n t_n = E_o t_o \quad \text{(B7)}$$

where t_o is the thickness of this layer at day 0.

Now the total bulk volume is the sum of all the layer volumes, and the total split fish is the sum of all the amounts in the various layers. The total amount of split fish in the n^{th} layer is $E_n t_n A$ where "A" is the area of the layer, and the total volume of the layer is $t_n A$.

Hence $$\bar{E} = \frac{\Sigma E_n t_n A}{\Sigma t_n A} = \frac{\Sigma E_n t_n}{\Sigma t_n} = \frac{\Sigma E_o t_o}{\Sigma t_n} \quad \text{(B8)}$$

A convenient way to deal with the experimental variation of E from E_o to E_f is to define the dimensionless ration R by

$$R = \frac{E - E_o}{E_f - E_o} \quad \text{(B9)}$$

Thus R varies from 0 to 1 as E varies from E_o to E_f. From Experiment 3, as described in the text, a table of R as a function of time can be derived. This is given in Table 12. For the n^{th} layer, of course, we have

that $$R_n = \frac{E_n - E_o}{E_f - E_o}$$

i.e. $$E_n = R_n (E_f - E_o) + E_o \quad \text{(B10)}$$

What is now needed is the value of R for the whole bulk — call this $\bar{R}$. Using (B9) and (B8):

$$\bar{R} = \frac{\bar{E} - E_o}{E_f - E_o} = \frac{\frac{\Sigma E_n t_n}{\Sigma t_n} - E_o}{E_f - E_o}$$

which simplifies to: $$\bar{R} = \frac{\Sigma R_n t_n}{\Sigma t_n} \quad \text{(B11)}$$

which is analogous to (B8). The variable in (B11), which is not immediately available is the value of t_n, the layer thickness. But from (B7), $t_n = \frac{E_o t_o}{E_n}$, keeping in mind here that t_o is the initial thickness of the n^{th} layer, and is not generally the same for all layers. It is possible, however, to make use of the fact that $F_n = \frac{E_o t_o A}{W_{sf}}$

which gives $$E_o t_o = \frac{F_n W_{sf}}{A}$$

Hence: $$t_n = \frac{F_n W_{sf}}{A E_n} \quad \text{(B12)}$$

Substituting this in (B11), and cancelling the constants W_{sf}/A in numerator and denominator gives:

$$\bar{R} = \frac{\sum \frac{R_n F_n}{E_n}}{\sum \frac{F_n}{E_n}} = \frac{\sum \frac{R_n F_n}{R_n (E_f - E_o) + E_o}}{\sum \frac{F_n}{R_n (E_f - E_o) + E_o}} = \frac{\sum \frac{R_n F_n}{R_n (E_f/E_o - 1) + 1}}{\sum \frac{F_n}{R_n (E_f/E_o - 1) + 1}}$$

(dividing by E_o in numerator and denominator)

which is the required equation (4) in the text. In the model program $\bar{E}$ is then calculated from:

$\bar{E} = \bar{R}\,(E_f - E_o) + E_o$.

A Simpler Equation for E

Upon further examination, it turns out that a more direct and less elaborate expression for $\bar{E}$ can be found directly from equation (B8). $E_n t_n A$ in equation (B8) is F_n times the total weight of split fish in layer n — let us call this W_{sfn}. Hence (B8) gives:

$$\bar{E} = \frac{\Sigma F_n W_{sfn}}{\sum \frac{F_n}{E_n} W_{sfn}} = \frac{\Sigma F_n}{\sum \frac{F_n}{E_n}} \qquad \text{(B13)}$$

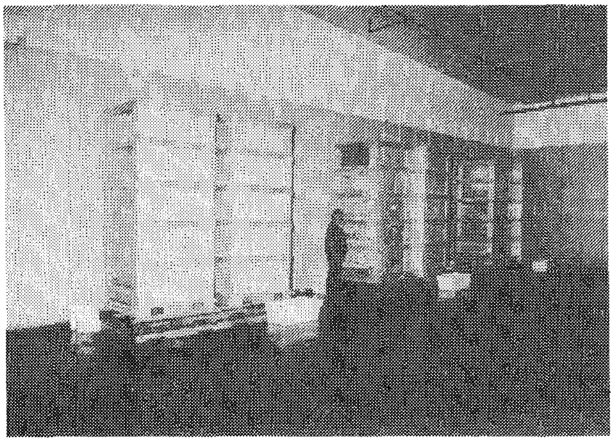
But $\Sigma F_n = 1$, and since $E_n = R_n (E_f - E_o) + E_o$, this gives:

$$\bar{E} = \frac{1}{\sum \frac{F_n}{R_n (E_f - E_o) + E_o}} \qquad \text{(B14)}$$

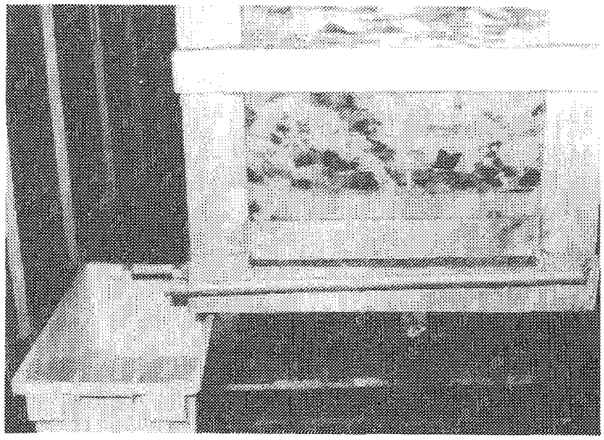
Equation (B14) is somewhat simpler than equation (4), in the text, and avoids consideration of the intermediate variable $\bar{R}$ altogether. Of course, in both cases the results are identical.

Appendix III

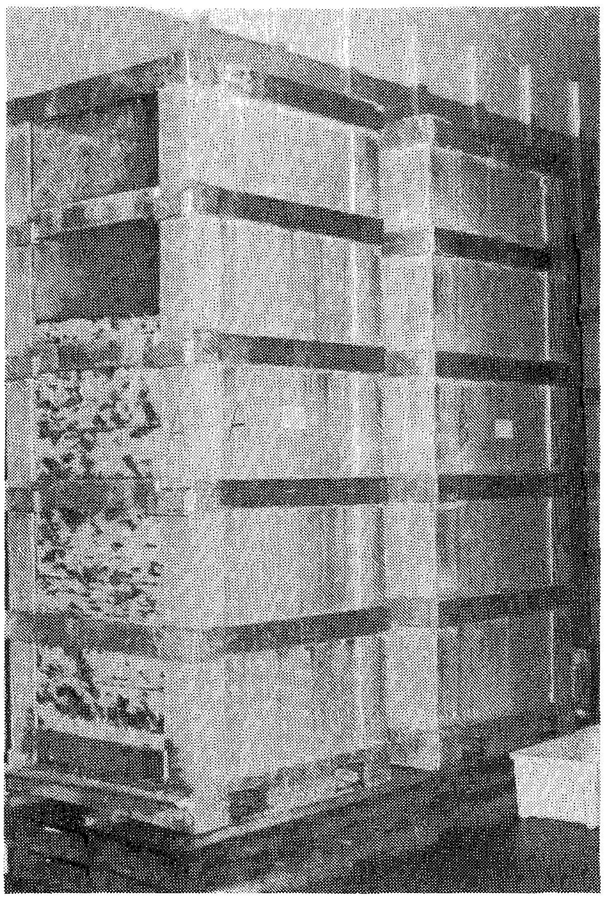
The following photographs (i to iv) were taken during the final stages of the experiment.



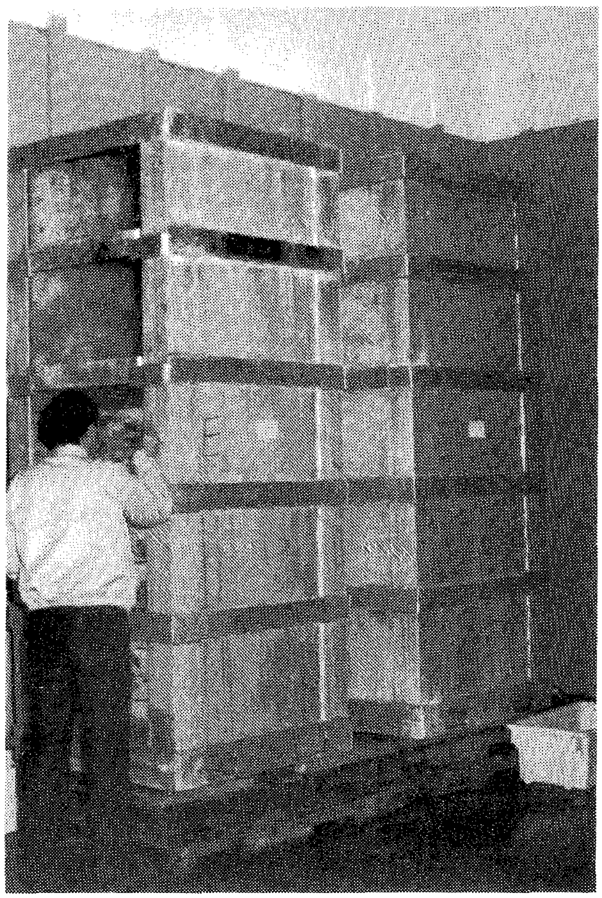
(i) Overall view of the experiment, left to right - plallets A–F.



(ii) Brine collection.



(iii) Pallet A during curing phase (note the division of daily levels).



(iv) Pallet E during curing phase, pallet dimensions 1 m x 1 m x 2.5 m.