Refrigerated transport of frozen tuna

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Biographical note

Ian Goulding qualified as an Environmental Health Officer in 1978, and worked for 4 years in food safety enforcement at district level. He took a Masters in Food Science in 1979, and obtained his PhD in 1983, whilst working as QC and technical manager in a processing establishment for farmed trout and salmon in Scotland. He designed and implemented QC systems for new products for sale in the company's main retail customer, Marks and Spencer. After a period of lecturing, he spent 2 years in Ecuador, assisting the Competent Authority to develop new codes of practice and inspection systems, to meet the health requirements of the USA, particularly with respect to farmed shrimp and canned tuna. He spent 4 years in Egypt, developing a fish technology training and research centre at Alexandria University and he founded food and fisheries consultants Megapesca in 1993. Since that time he has attended numerous cargo claims involving rejected fishery products, and has advised on cause and quantum of damage, both on the spot and as an expert witness. He is a Fellow of the Institute of Food Science and Technology, and holds membership of the European Food Law Association and the International Association of Fish Inspectors.

1. Introduction

Tuna is a global commodity and there are three main distribution channels from the fishery to the cannery.

- Fresh fish landings into the cannery from fishing vessels or carrier boats; eg. canneries in Maldives, PNG, Indonesia
- Frozen fish landings directly from fishing vessels eg. canneries in Ghana, Cote d'Ivoire, Seychelles
- Frozen fish transhipped from fishing vessels onto reefer vessels eg. canneries in Puerto Rico, Spain, Italy

The seasonal and migratory nature of fishery means that even if canneries are located close to fisheries (eg.in the Indian Ocean region) they may still need to import frozen fish from other producing regions at some times.

As a result raw material for canneries is frequently transported long distances by sea, from the fishing grounds to the main processing regions. Some of the main transport routes are shown in Table 1.

Table 1: Main sea trade routes for frozen tuna

Main catching regions
Indian Ocean
SW Pacific
W.Africa
Central and S.America (Pacific)

Main processing regions
Thailand
W.Africa
S and Central America
Europe

2. Quality implications of reefer transport

Reefer transport of tuna has several quality implications:

1. Given the duration of transport, there is greater opportunity for the product to be subject to mishap
2. There are three transfers compared to just the one when delivered to the cannery by the fishing vessel
3. There is a lower yield due to dehydration during cold storage and drip loss on thawing
4. There is a lower quality due to development of oxidative rancidity during cold storage

3. Claims for damaged cargo

Most operators are aware that tuna can arrive in poor condition after a long journey by sea in a reefer vessel. When a cargo is seen to be in poor condition, the immediate reaction is to blame the transport conditions ie. the reefer vessel.

Since 1990 consultants from Megapesca and our associated company MacAlister Elliott and Partners have attended 10 claims involving damaged cargoes of frozen tuna. We therefore have developed a body of experience about what can go wrong. The claims are summarised in Table 2.

All but one claim involved reports of distortion, and fish sticking together necessitating the use of crow bars for discharge, with or without some evidence of recommencement of spoilage. Many claims referred to "splits, smashed or mutilated fish", and the US Tuna Foundation Protocol (being a common industry standard for sampling and testing of batches of raw fish). "Splits smashed or mutilated fish" are defined in this protocol as having damage covering more than > 10% of the surface area of the usable portion of the fish in selected lot[1].

Only one claim involved taint, and was due to contamination with liquid fuel oil. None of the claimed cargo damage was due to excessive dehydration.

[1] A lot is defined by vessel, trip, well and species and has maximum size of 100 tonnes; sample size should be a minimum of 2 fish per box (or 1 fish if over 20lb in weight).

Table 2: Principal causes of damage in claims for damaged tuna cargo

Year	From	To	Size/Value of claim	Problem	Cause	Other factors
1999	Manta	Bangkok	N/a	Elevated temperatures during loading	High temperatures in fishing vessel;	Poor hatch seal
1998	Kiribati	Songhla	139	Distortion, spoilage	High loading temperature	Wet product from brine tanks Inefficient, old refrigeration plant
1998	Walvis Bay	American Samoa	90 tonnes		High loading temperature	
1997	Ensenada	Monteverde	352 tonnes $267k	Distortion/spoilage	High loading temperature	Poor quality pre-freezing
1995	Abidjan	Turkey	885 tonnes	Distortion/ spoilage	High temperatures in fishing vessel	Slow transhipment; faulty hatch seal
1995	Seychelles	Vigo	150 tonnes	Distortion	High loading temperature	
1994	Abidjan	Vigo	48 tonnes	Distortion, broken	Not established	
1994	Samoa	Puerto Rico/Vigo		Distortion	High loading temperature	Poor handling before freezing
1993	Ensenada	Villa Garcia	76	Distortion, spoilage	High loading temp	Slow transhipment Mixing of small and large fish
1990	Venezuela	Vigo	74	Distortion, broken	High loading temperature	Poor stowage (large and small fish) Poor transport to the vessel (open vehicles)

Detailed investigation on the spot, and study of documentation and vessel records was undertaken in each case. Refrigeration breakdowns are not a common feature, and in fact only in one case was a refrigeration defect implicated, and then in combination with other causes. Two cases involved some damage arising from faulty hatch seals. However, in almost all of the cases, the principal cause of damage was higher than ideal temperature at loading.

There are a number of unique features of the tuna fishing business which contribute to higher temperatures at loading of the reefer vessel, when compared with other fishery products. It is useful to consider these features in more detail.

4. Tuna fishing vessels

4.1 Tuna physiology

Tunas are well known for their higher proportion of lateral dark muscle, which is physiologically designed for continuous movement. Tunas are also unique in that their vascular system is designed as a counter-current heat exchanger (*rete mirabile)*, to maintain the temperature within the muscle at about 3 C above ambient temperature in the case of yellowfin tuna, or up to 7 C in the case of skipjack; this maintains muscle efficiency, increasing speed and endurance. Red muscle in tunas is located internally, to further conserve heat.

Muscle glycogen provides an energy store. Post-mortem glycolysis uses this store after the fish is caught to provide contraction of the muscle, exhibited as rigor mortis. This is also associated with heat production. Given the depth of the red muscle, its elevated temperature to start with and the loss of blood circulation as a cooling medium, the internal temperature can rise to the extent of causing a partial denaturing of the muscle protein. In tuna, more than most fish, there is therefore a need for rapid chilling after the catch is brought onboard. The use of refrigerated seawater (RSW) and brine freezing provides the rapid heat transfer needed to cool the fish quickly.

4.2 Brine freezing practices

Brine freezing is used for large fish to be frozen whole such as salmon and tuna. The technique is used extensively on board tuna fishing vessels. The fishing vessel is fitted with one or more insulated tanks containing refrigeration coils. Brine freezing practices vary depending on the type of vessel, size of tank and catch rate. The following describes a typical practice.

Before fishing starts, brine tanks are filled with seawater, which is then cooled to around -1^{o}C. As fish are caught, they are dropped or flumed into the tanks, where they are chilled and held at this reduced temperature. When a tank is full, the RSW is pumped out and refrigerated brine is pumped in, and the temperature is lowered so that the fish freeze. Alternatively, if the catch rate is high enough, the fish may be put directly into refrigerated brine.

The final temperature that can be achieved depends on the concentration of the brine - the minimum, when the brine is saturated, is about -21^{o}C. Figure 1 shows the effect of brine strength on freezing temperature of the brine. In practice, brine temperatures can be anywhere in the range - 9.5 to -17 C, depending on the fishing vessel practice.

Bear in mind that the engineer will not operate the brine at its freezing point (otherwise an ice slush forms which cannot easily be pumped) but will need a margin of a few degrees. Therefore to freeze at say -12 C, will need an 18 or 19% brine (with a freezing point at -15 C). As a result brine freezing of fish results in the final temperature at the end of freezing being much higher than the ideal.

4.3 Storage on board

Once the fish are frozen, they may be held in the refrigerated brine, or the brine may be drained from the tank and the fish held in dry condition with the refrigeration system on. This avoids the fish absorbing too much salt and drying of the wells is recommended when the storage period is longer. After drying the well, the temperature of the fish will fall slowly to achieve an equilibrium. The equilibrium depends on the vessel refrigeration system and the level of insulation of the well.

Typically the temperature will fall to an equilibrium of about -14 C over time, as shown in Figure 2.

4.4 Unloading of the fishing vessel

Re-brining (the re-introduction of brine to the dry well) is usually practiced as part of unloading procedure, to melt interstitial ice (to separate fish which become "welded" to each other) and to achieve a uniform temperature distribution. Commonly the brine will be at a temperature of -10.5 to -11.5 C, since lower temperatures require a stronger brine, and will not melt the ice as quickly. "Floating off" is a practice in which the uppermost fish separate from the mass and float to the top. As a result of re-brining, temperatures of the fish can increase slightly. In the example shown in Figure 3, re-brining results in a temperature increase from -14 up to -11 C after only one day.

4.5 What can go wrong?

Although frozen fish should ideally be kept at -18 C throughout, this is clearly not practicable in the case of brine frozen tuna. Using existing technology, the very best that transhipment temperature which can be achieved in normal practice appears to be about -14 C. As a result, temperatures between -10 C and -12 C are frequently considered to be normal in the industry.

However, there are two clear sets of circumstances in which product temperatures may be higher than this.

- When product is recently frozen (eg. just after drying off the tanks)
- When the re-brining period is too long

Figure 4 shows a set of temperatures measured at the moment of transhipment from one of the consignments which subsequently sustained damage. The temperatures were taken by the vessel crew during transhipment and noted on the Mates' Receipts. There is clear evidence that this cargo is running into problems with temperatures approaching -8 C.

5. Transhipment

Conditions of transhipment can also have a significant effect, by compounding the elevated temperature at which the fish leaves the fishing vessel.

5.1 Atmospheric conditions

Transhipment from fishing vessels into reefer vessel, often at takes place at sea and given the location of tuna resources, takes place in potentially hot climates. When considering climatic conditions, we should consider not only temperature, but also humidity and the rate of air flow.

The heat transfer rate from warm air to frozen tuna is determined by the equation:

$$Q = hA(T_f - T_s)$$

Where

Q	Rate of heat transfer
h	Heat transfer coefficient is a parameter which reflects the nature of the fluid flow pattern near the surface
A	Surface area of material
T_f	Temperature of the air
T_s	Temperature of the surface

The heat transfer coefficient h is a function of $\frac{\textit{density of gas} \times \textit{velocity}}{\textit{viscosity}}$

As a result humid, fast moving air will have a much greater warming effect on the cargo than dry still air at the same temperature. Such conditions are common in the tropics at sea.

5.2 Rate of transhipment

The rate of transhipment can also have a significant effect. Here we have found that the critical factor is the number of consecutive days on which loading of a hatch takes place before it is finally closed and subject to continuous refrigeration. Most vessels pre-chill cargo holds prior to loading (although there is no evidence that this has any significant impact). Clearly refrigeration systems cannot be run during loading; typically they are switched back on during breaks and overnight. Note that Charter Party Agreements often have a clause specifying minimum transhipment rates, but even where these are complied with, we have experienced cases of cargo damage.

Figure 5 shows the temperature history of a hatch in which cargo damage was sustained.

The graph shows 3 distinct stages:

- Pre-chilling of the hatches
- Loading
- Gradual withdrawal of heat from the cargo (where return temperature tends to delivery temperature)

Note how the period during which fish is transhipped does not permit much opportunity for cooling of the cargo if the hatch is to be opened at regular intervals. In addition some reefers have decks which are " 'tween" decks, ie two deck levels served by the same refrigeration delivery system. Slow transhipment can mean that cargo waits until the deck above is also loaded, before it final receives continuous refrigeration.

6. Causes of damage

Having shown how tuna cargo may be loaded into the reefer vessel at a temperature above its ideal, it is now appropriate to consider how deformation damage can occur given these circumstances.

6.1 Factors affecting deformation

6.1.1 Temperature

Although fish typically contain 70-80% of water - the exact percentage depends on the species - the situation is more complicated than freezing water alone. Water in the fish tissues starts to freeze at about -1^{o}C but at this point only a proportion of the water is converted to ice. At -18^{o}C, the maximum temperature usually specified for carriage of frozen fish in reefers, around 90% of the water has turned to ice. It is very hard to deform frozen fish at this temperature and below except under extremely high pressure. If the product warms at all, some of the ice melts. The fish tissue holds an increasing proportion of liquid water and a decreasing proportion of ice as its temperature rises. At -10^{o}C, approximately 84% of the water is present as ice, compared with the 90% at -18^{o}C, 76% at -7^{o}C, and 70% at -3^{o}C.

As the proportion of ice decreases, the fish tissue, though still frozen, becomes softer and can be deformed by moderate pressure. For example, it is possible to deform the surface of a product at -7^{o}C by pressing hard with the point of a pen, a temperature probe, or even a thumbnail. At -3^{o}C, 'frozen' fishery products are soft enough to deform and to sag under their own weight. If the cargo in the hold of a reefer is stacked to a height of 4 or 5 metres, as is often the case, there is sufficient pressure to distort fish to some extent at -7^{o}C, and to distort and compress fish considerably at -5^{o}C or higher. Bear in mind the pressures can be quite high at the bottom of the stack.

Individually frozen fish can be severely indented where they lie across each other, and tend to take up the shapes of the surfaces they are pressed against - ridged floor plates or edges structures in the hold. In an extreme case, a stack of fish can be compressed together into a solid mass, with almost no spaces between the fish. Blocks of products are squeezed, flattened and distorted and will extrude into gaps between cartons. They can also be indented by floor plates or pallet boards.

As far as the author is aware, there is no record of any studies undertaken to measure the effect of temperature on compressibility of frozen tuna (or of any other species of fish), and this is quite a remarkable omission given the value of product which is transported under less than ideal conditions.

Other factors may also have an impact on this process.

6.1.2 Freezing point depression

Salt in the muscle also has the effect of reducing the freezing point. Slow freezing in brine solutions results in an increase in salt content, which may rise up to 2.0-2.5% if held for too long, as shown in Figure 6.

It should also be noted that the key factor in freezing point depression is the salt concentration in the aqueous phase of the flesh, rather than salt content in the whole fish. Considering that, as a general rule of proximate composition of fish muscle, fat plus water combined provide about 78-80% of the weight, then more fat will mean less water. Tunas may have a high fat content (up to 10% is not uncommon), and in such cases then effect of salt content is also greater in terms of freezing point depression. Fish at 2% salt content and 10% fat will have a salt concentration of just under 3% in the aqueous phase, and a freezing point of just above -2.0 C. At -8 C such a product will have a much softer texture, and be more susceptible to pressure damage than fish which has not been brined at all.

6.1.3 Loss of air flow

The loss of flow of refrigerated air through cargo is also implicated in the damage which is observed. Air flow to the cargo can be restricted by mixing small and large fish, or by movement of the cargo due to a temperature excursion. The latter is a crucial factor in the occurrence of the typical damage seen in the majority of the cases reported in Table 2. Once the cargo starts to compress, the gaps between the individual fish become smaller and air flow is restricted further to the parts of the cargo which need it the most. Even if the refrigeration system is working to its full extent, the flow of chilled air to warmest parts of the cargo will be restricted, and there will be no opportunity for heat transfer.

Clear evidence of this is shown in Figure 5, in which the cargo temperature was clearly above 8 C for a sustained period, with no evidence at all demonstrated from the delivery and return temperatures of the hatch. In fact unless a pulp temperature probe is located in the damaged portion itself, the first sign of damage will be during discharge.

6.1.4 Reefer design

Vessel refrigeration systems are designed to carry frozen food, and to compensate for heat gains through the structure. They are not designed to reduce the temperature of the cargo. Although most reefers do have some spare capacity to lower the temperature of products which are put into the hold at above ideal temperature, this cannot be relied on. There is no reason why reefers should be expected to do more than they are designed or contracted to do. Material that is above the operating temperature of the hold will take a long time to cool down and will lose quality as a result.

Put all of the above factors together, and it is perhaps remarkable that losses in reefer transport of frozen tuna are not much greater. However it should be noted that we are not the only company involved in this business, and that consultants are only called in when claims are large enough to justify the cost.

Undoubtedly the problems described occur more frequently the average of once/year. There are number of short-term and long-term recommendations which could be implemented to reduce the risk of damage.

7. Recommendations

7.1 Short-term

7.1.1 Improved practices on fishing vessels

Brine freezing practices on board fishing vessels are perhaps at the root of the damage, and this is where much can be done to avert the problem, by observing that:

1. Recently brine frozen tuna should not be transhipped. Wells should be left dry at least 2-3 days after draining, to ensure that the cargo temperature reaches its minimum.
2. The vessel should only apply short periods of re-brining or "floating off, to avoid warming of the fish prior to transhipment.
3. Mixing large and small fish in the same batches should be avoided

7.1.2 Improved transhipment procedures

1. Transhipment should be rapid, and in particular operators should avoid transhipment of small batches into the same hatch over several days. Charter party agreements could be more specific on this point (eg. by specifying a maximum of three consecutive days loading of the same refrigerated area)
2. Transhipment in very hot weather, rain and particularly windy conditions should be avoided. Operators should consider transhipment at night and close hatches and refrigerate during breaks.

7.1.3 Improved pre-shipment inspection

Receivers of damaged cargoes of frozen fishery invariably allege that loss of quality occurred solely while the material was in the charge of the reefer. However since it is rare that the reefer vessel is at fault we would prefer to see a more active pre-shipment inspection, with the master of the reefer vessel refusing to accept fish which does not meet the temperature criteria. This will give a clear message to fishing vessel operators. In our view, a simple pre-shipment inspection can be done by the reefer crew, and could be a requirement of the Charter Party Agreement.

Pre-shipment inspection by the ship's officers is generally confined to visual inspection of the cargo and to measurement of physical properties such as temperature. Preshipment inspection should cover:

- Nature of cargo
- Temperature of consignment
- Condition of material
- Condition of any packaging
- Taking of photographs
- Noting any other unusual conditions (eg.adverse weather)

In the case of tuna, high temperatures on loading, which is the main cause of quality problems during reefer transport, could always be identified at loading if there was a more assiduous approach to pre-shipment inspection. There should be sufficient temperature measurements recorded against supplying vessel and if possible well number, and stowage location in the hatch.

Information on the nature of the consignment and all details of labelling should be recorded on the Mate's Receipt.

7.2 Long-term requirements

Good practice and current regulations require storage of frozen fishery products at a temperature of -18 C or less at all times. In particular EU Directive 91/493/EEC "Health conditions for the production and placing on the market of fishery products" is quite specific on this point. Chapter IV of the Annex to the Directive states that freezing of fish is required to deliver product at -18 C, with the exception that it permits freezing to temperatures of up to -9 C, in the case of brine frozen whole fish for canning. Thus brine freezing is permissible. However, Chapter VIII of Annex goes on to state that frozen fish must be stored at -18 C unless kept in brine, and intended for canning. Therefore if the fish is not kept in brine, tuna must be held at -18 C or below.

The present technology does not comply with the law, or any internationally recognised codes of practice, EU or FDA regulations. Compliance is clearly not feasible with present technological approach, since few fishing vessels appear capable of delivering fish at -18 C to the reefer vessel. This is not an acceptable situation. Industry should either comply, or if there is genuine reason why it cannot, lobby for the legislation to be changed. Clearly in the longer-term there is a requirement for changes to the technology used, to bring practice into line with these requirements, and to reduce the risk of cargo damage.

As experts we are often cross-examined on this point in court cases or arbitration. It is quite clear that present practice is unlawful, and that compliance is technically feasible. It should, in my opinion, therefore be a long term objective to modify the technology used.

The options are:

- Introduce intermediate chilling of brine frozen fish prior to transhipment
- Adopt an alternative to brine freezing

In addition, it is proposed that there is a need to modify the primitive methods used in the bulk transport of tuna cargoes to more appropriate technologies. This could include introduction of onboard packaging systems to offer greater protection to the product, and modification of reefer vessel design to address the problem of racking systems to reduce the occurrence of pressure damage. We should not rely on the frozen state to support the weight of the cargo above.

Applied research is required to develop and assess the options which are available.

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