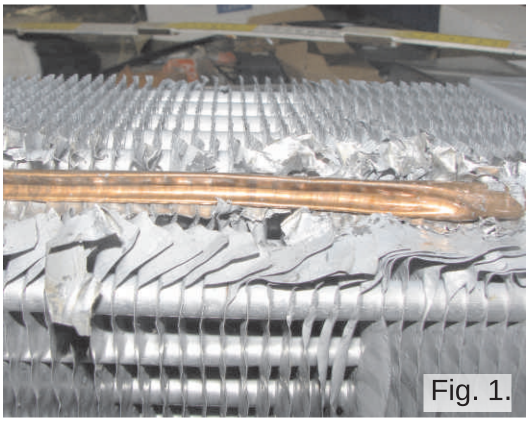
THE PUZZLE OF A CLUSTER OF COLLAPSED EVAPORATOR TUBES

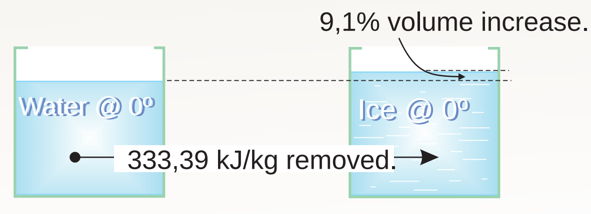
I have an Internet friend, by name of Peter Christiaen, who lives and works in Belgium. Sometimes I ask his valued advice on refrigeration problems and at other times he sends me fascinating photographs. Over Christmas some extremely interesting photos were kindly sent through by Peter. These illustrated severe damage, clearly the outcome of freezing, which Peter had picked up on the evaporator of an installation. Fig. 1 will give you an idea of the nature of the problem. So, you have guessed it! We will put our series on 'Air' onto hold for this month, and will chew over this fascinating problem from Belgium. (Almost better than that country's fine chocolates)!

Peter earns his bread from refrigeration. Not only does he do the stuff in a big way—he teaches it too, and is also a Moderator of the popular Website, "Refrigeration Engineer". So Peter gets around in the Industry. But he indicated that the damage he had photographed was indeed unusual. He knows how these things fascinate me, and he suggested I might care to mull over the situation. This is where I cannot resist becoming involved. So my chain was pulled.

In Fig. 1, parts of some fins have been snipped away to expose the situation. The damage shown here was not isolated. There were multiple repeats of this failure at sites around the bottom of the coil. To get up to speed, we will work through the 'icing' issue. Fig. 2 shows an open-topped container carrying some water at 0°. This water has next been frozen. Alongside, we see the resultant ice. Both are at 0°C. What are the essential differences between the left and right examples?



FIRST VIEW OF THE DAMAGE
AFTER TEARING BACK OF SOME FINS.



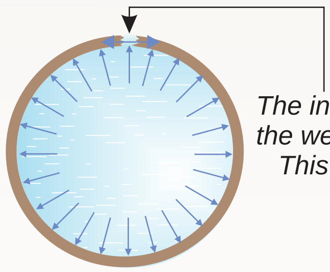
WHEN WATER FREEZES... Fig. 2.

What had to take place for water at 0° to become ice at 0° is that 333,39 kilojoules of heat for every kilogram of the sample had required to be removed to bring about this change. By way of comparison, you have to remove on average just 4,19 kilojoules of heat from one kilogram of water to change its temperature by one degree. (The volume of one kilogram of water, incidentally, is very close to being one litre. Indeed, when at 0°, it is *exactly* one litre). This large amount of heat that must be removed to bring about freezing in itself produces not a hint of temperature change. It sets up a *state* change—that of water solidifying into ice. When involved in this way the heat is hidden. For this reason the heat involved in bringing about such a process is termed *latent* (hidden) *heat*.

HEAT IS HEAT

Please don't become confused—heat is heat. The difference lies in what is achieved by the "heat in" or "heat out" change having been brought about. In our case, the process occurred because heat was being removed when the water was already critically poised on the threshold of being due to freeze. If we were to compare the latent heat just discussed with a change in heat content which brings about a temperature shift, we would note that a move of latter form can be *sensed* (as by a thermometer). It therefore is termed *sensible heat*.

Now back to Fig. 2. One change is very noticeable. Water does an extremely unusual thing when it freezes. It *expands*, and by a substantial amount too. If it weren't for this, icebergs would sink to the bottom of the ocean. In cold places, ponds and rivers would freeze solid from the bottom up. There would be no aquatic life in many parts. The climate would be radically different. Indeed, it is my understanding that life as we know it on the planet would be totally impossible. What an extremely fortunate accident of nature for water to possess these quirks! Except that some people, such as me, don't believe it to have been any sort of an accident at all. As for it being an unusual characteristic, it is the less-than-common metal, antimony, that in isolation shares with water this unique property of expanding somewhere down the track as it cools.



- Volume increases by 9,1% as water freezes.
- If there is no-where for the developing ice to go, irresistible forces are generated.
- In this example, the wall of the tube containing the water being frozen must unavoidably split.

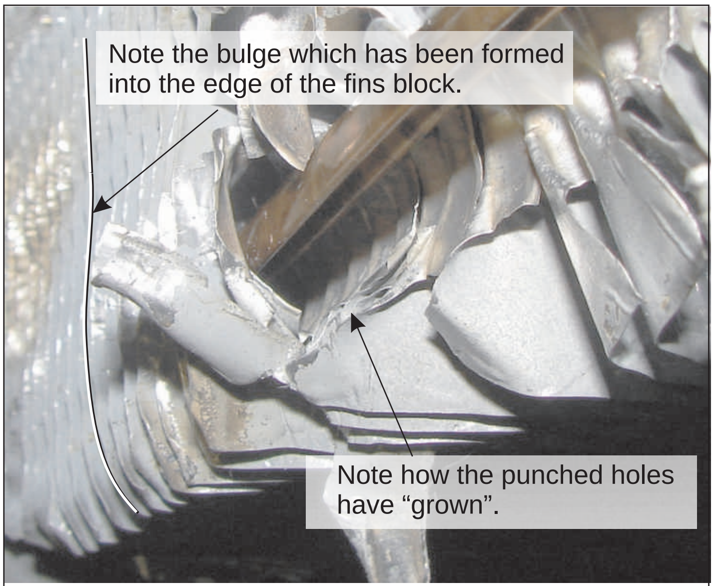
Fig. 3.

THE MECHANICS OF FREEZING INSIDE A TUBE.

In Fig. 2, there was no top seal present to attempt to restrict the upward expansion of the ice. Indeed, with many types of refrigerator ice tray, you notice a pronounced mound on the top of each ice cube, illustrating this effect. But what happens if there are restrictions which attempt to limit this expansion? The fact is that, for practical consideration, ice is an *incompressible* solid. If it is not permitted to expand freely as it develops, momentous forces are exerted. Something has to give! It is as simple as that. In Fig. 3 a pipe, filled with water, has been exposed to freezing conditions. Maybe there were a couple of colder spots at different points along the way. The water froze solid at these points, 'locking in' the water at our section in Fig. 3. As this now proceeded to freeze, there remained nowhere left for the expanding slurry to go. This caused irresistible forces to be imposed on the pipe. Its wall stretched as far as the metal would allow. The tube then split, as has finally happened in Fig. 3.

While we may be sharply aware that water expands as it freezes, are we equally mindful of the fact that *contraction* takes place as ice converts into water? In this article I will develop the idea that this occurrence was instrumental in bringing about the eventual damage.

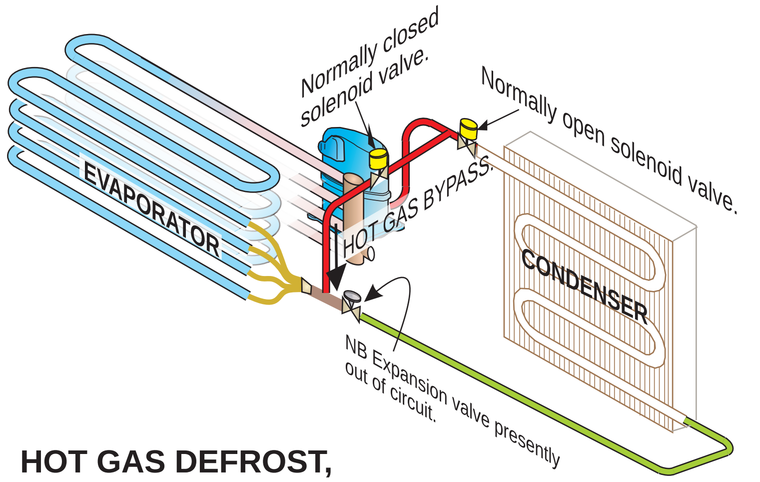
A BACKGROUND TO EVENTS



EVIDENCE OF DISTORTING FORCES. Fig. 4.

Peter tells me that they were asked to look into a failure of an installation which had been executed by someone else. Initially the fellow who attended had found the job to be short of refrigerant, although he could find no leak. He topped up the charge. The refrigerated chamber had been designed to operate at —20°C. Refrigerant was R404a. The guys were astonished to find that suction pressure was working down at —40°C. Initially they shook their heads and put this down to the blower coil having been sized too tightly for the application.

After a period the job died again. This time round they found a leaky solenoid valve, which they replaced. But the problem repeated yet another time. On this occasion they determined that there was a leak from behind the fins. This being irreparable, they duly replaced the evaporator. It was only after the original had been extricated from its deeply concealed dwelling spot in the blower unit that they discovered the true nature of the damage.



HOT GAS DEFROST,
BY MEANS OF VAPOUR DIVERSION. Fig. 5.

Peter tells me that the hot gas defrost arrangement as installed incorporated two solenoid valves—one to block flow in the hot gas line and a second to admit flow to a bypass loop which injects hot gas into a point between the TX valve and the distributor. Fig. 5 shows how the original installer went about achieving this. Peter says that this is an approach shunned by his company, who do what they feel more comfortable with, which is to apply a 4-way valve hot gas defrosting arrangement. I am sure this must have been highly significant in the sequence of events, and we will work our way through the apparent situation shortly.

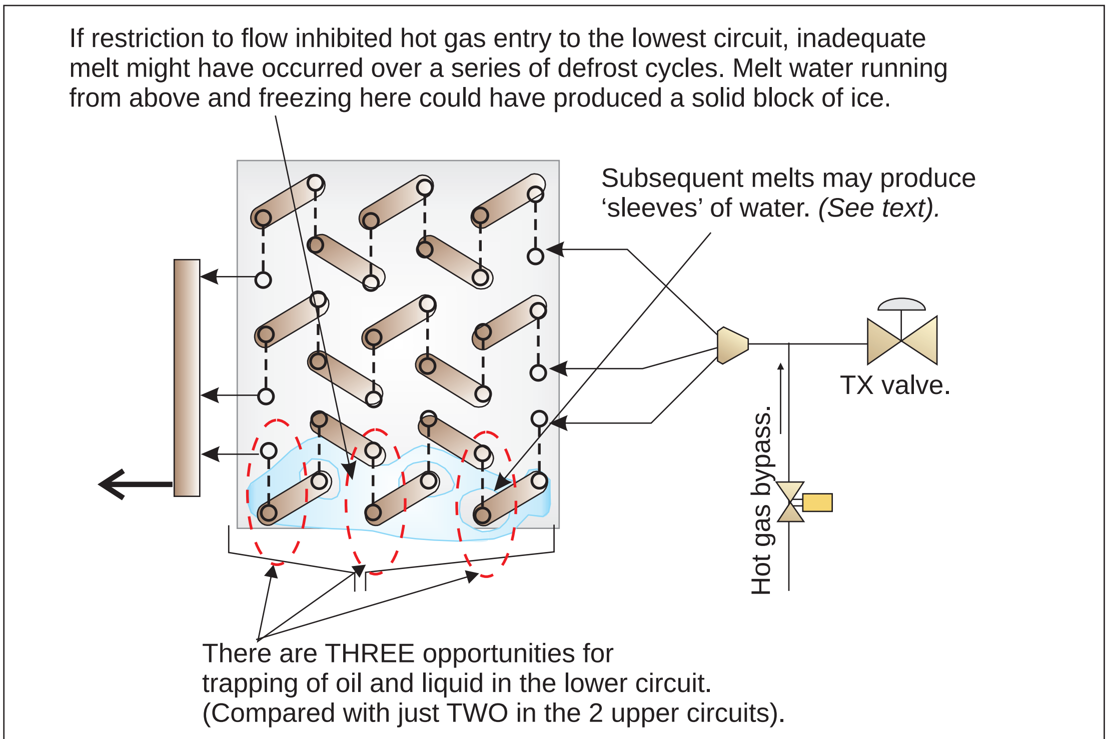
Another issue was that the thermostat tasked with the function of determining when defrosting had been completed had its sensor located in the upper part of the evaporator—above the scene of the failures.

EVIDENCE OF THE IMPOSED FORCES

The coil fins naturally would have been square-cut. But take a look at what is visible in Fig. 4. I have inserted a shaped line, to highlight the present bulging shape of what originally was a clutch of straight guillotine cuts. The fins have been markedly stretched outward in manner indicated by this line. Where the tubes penetrate the fins, the punchings originally would have been such as to provide a sliding fit. After assembly of the fins onto the tube bundle, and before the return bends were brazed on, the tubes would have been mechanically expanded so as to be a very tight fit into the fins. This is essential in order to achieve effective heat transfer from the fins and into the walls of the tubes. But just look at the huge clearance which has developed between the fins and the visible tube of Fig. 4!

It is plain that ice has formed to the extent that it thoroughly bridged between the fins, with the ice formation adhering very tightly to the fins. Then further expansion of developing ice has then taken place. Therefore the block of ice has 'grown', due to the enormous amount of force associated with the development of new ice under constrained conditions. As it has 'grown', it has stretched the fins outward as a part of the effort. It is important to note that, once ice has formed at 0°, there follows a slight *contraction* which accompanies any further cooling. Indeed, the ice now follows the 'usual' law of contracting with further temperature reduction. Therefore the problem must be associated with the repeated *development* of ice, as sharply opposed to any effect related to deeper cooling of preexistent ice.

Therefore the expansion of which we see evidence in Fig. 4 can only have been produced by consecutive freezing events taking place in the affected area with each build of new ice being fully encased within preexisting ice. I started out with some puzzlement to attempt explaining the increase in hole size of the fins where the tubes had previously fitted tightly into the punchings, but now am sure this goes some way in that direction.



POTENTIAL FOR THE LOWER CIRCUIT TO BLOCK HOT GAS. Fig. 6.

MY THEORY

By way of introduction to my theory, I have seen direct expansion air conditioning coils on a malfunctioning system iced across their bottom half to the extent that the lower half of the coil bank has been entirely encapsulated in ice. Indeed, the fins at the bottom part of the coil were completely buried under at least 20 mm of ice. This was in a sweet factory, where suction pressure and air quantity both had to be low in a rather futile attempt to meet simultaneous low temperature and low rh targets in our swampy climate, in a building about as vapour-tight as a sieve. For this reason the summer-time production of boiled sweets insisted on coming out cloudy.

In working through the evidence, I have come to the conclusion that, across a significant number of defrost cycles, ice had not been completely melted. The evidence of Fig. 4 is that this unmelted ice was hanging up at the bottom of the coil. Can we come up with reasons for this unmelted ice situated near the foot of the coil? Was something limiting or restricting hot gas flow to the lower coil circuit, thereby sabotaging the defrost objective? As an approach, let's look for a reason for oil hang-up affecting that lower circuit.

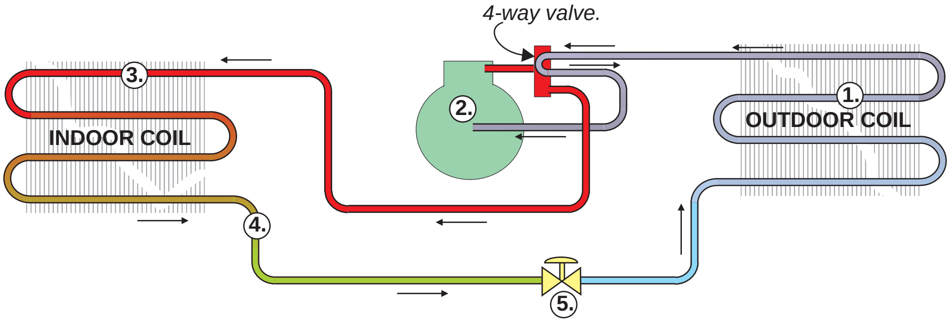
Manometers ('U'-tubes) coupled in series function rather as resistors wired in series, where $R_1 + R_2 + R_n = R$. If you look at the coil circuitry as illustrated in Fig. 6 you will note that the two upper circuits each incorporate *two* lifts after refrigerant first enters the coil. If there is oil or liquid refrigerant available to be trapped, it would be trapped by these lifts. But the bottom circuit has been configured so as to result in *three* such lifts. Therefore, if an equal amount of oil has been backed at each such lift, the overall back pressure on the lower circuit will be 3/2 of what it is in each of the upper circuits.

Over and above this, if the bottom circuit has become encased in an unmoving block of ice, it will be denied airflow. That makes it is reasonable to anticipate liquid accumulation here. Therefore, if there is just a limited pressure differential availability of hot gas being blown through the coil the upper circuits, these would blow clear any retained oil and/or liquid *before* the bottom circuit was able to clear itself. This could conceivably have caused reduced melt in the region of that circuit, making possible an undisturbed accumulation of ice in the lower reaches of the evaporator. Thereafter, in subsequent partial defrost cycles, just a 'sleeve' of a few mm of ice surrounding individual tubes of the lowest circuit would melt.

As this melt water would occupy *less* volume than the ice which melted to produce it, (the point which is so easy to overlook) and assuming there is no way in for air, a partial vacuum would result, with the potential to draw in additional melt water in from elsewhere. The available volume of the 'sleeve' left by the small ice melt would now be 100% water-filled. Over the next refrigerated cycle, no blower air would be admitted to the affected areas. The full effect of the —40° evaporating condition would be imposed on this contained water, rapidly freezing it solid. This event of course would demand 9% more volume. If the block of ice was capable of being stretched, the block itself would be pushed outward. In my mind, Fig. 4 makes it plain that this has happened, at least for some of the time.

If we assume that early in the piece the onset of hot gas injection, with its accompanying tube linear expansion, resulted in some distortion of the copper tubes as it was introduced (bear in mind the fins would have been solidly locked in ice) an initial clearance could have developed between the fin spacing collars at the punchings and the tube wall. Any initial collapse of the tube wall would squash down tube diameter, heightening this circumstance. Now, upon resumption of refrigeration, outward expansion by ice building on the low temperature tube will act from *behind* the collars, stretching the holes. I believe the oversized holes in the fins, so plainly visible in Fig. 4, indicates exactly this as having happened over a number of cycles, further expanding the holes each time.

1. Heat is recovered from the atmosphere.
2. The **temperature** of the heat is increased by compression.
3. The hot gas, so produced, is transferred to the indoor coil. Ice accumulations are melted.
4. This condenses the high pressure vapour, producing liquid refrigerant.
5. The liquid is passed through an expansion device, and returns to the outdoor coil, to repeat the defrost cycle.



HOT GAS DEFROST, BY MEANS OF A 4-WAY VALVE Fig. 7.

A 4-WAY VALVE DEFROST ARRANGEMENT

Let's put that theme onto hold for a moment, and to now instead consider a 4-way valve defrost arrangement. The regular 'heat pump' arrangement is illustrated in Fig. 7. To avoid confusion I have referred to 'indoor' and 'outdoor' coils. (Try referring to “the condenser which is currently functioning as the evaporator”, and you have the makings of a horror movie on your hands)! On the defrost cycle, liquid is fed to the outdoor coil. Even in winter, cooling of the already-cold air will enable evaporation, yielding a worthy supply of cold vapour. This is drawn into the compressor for compression into a hot gas.

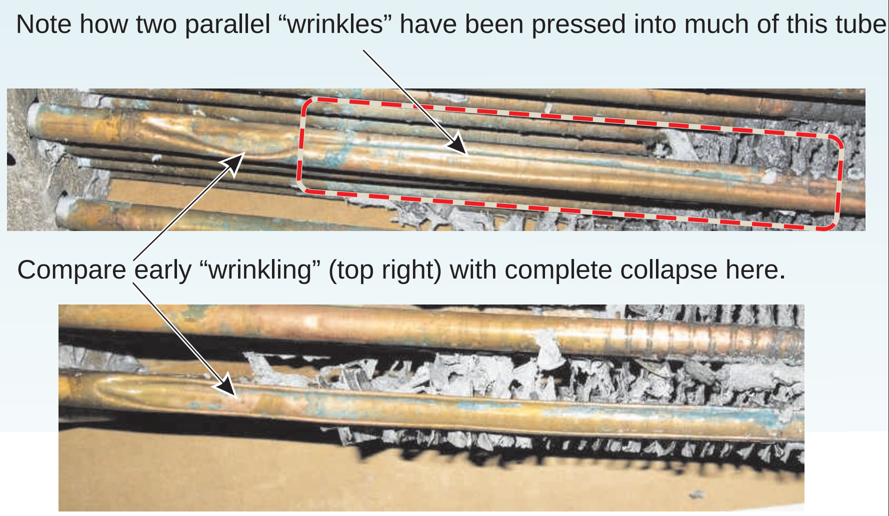
As an expansion device remains in the circuit, a good pressure lift will be assured, so a tidy amount of work will be required of the compressor motor. This adds to the heat in the vapour, and the whole shooting match is now directed to the indoor coil. A strong flow of hot gas, carrying an appreciable amount of heat, enters the coil and bites quick and deep into the ice. With the strong injection of heat, defrosting is rapidly achieved. Cooling is thereafter resumed, and immediately the 'loose' condensate, not yet drained away, has frozen into a thin layer on the fins, preventing condensate from splashing about, the blower fans are restarted.

This is good and proven technology. What of the 'simple solenoid valve solution' of the coil which failed so dismally? Flip back to Fig. 5. At the start of the defrost cycle, the open hot gas solenoid in the hot gas line will close, and the normally closed solenoid valve, controlling flow in the bypass, will open. Initially there might be traces of liquid to be brought back from the evaporator. This could come back as a spray, not immediately threatening the compressor, but swallowing up such heat as is being produced by operation of the motor. I have actually seen hot gas lines which sweat! Dumb things can and do happen.

Still looking at Fig. 5, you will see that there is a simple run-around taking place. The expansion device has been bypassed. Nothing is present to cause the discharge pressure to be much elevated. The compressor motor will tick away like a sewing machine at quarter throttle. It will add next to nothing in the way of heat. Compare this with the 4-way valve situation of Fig. 7. In that case there was substantial lift, due to the expansion device remaining in circuit. The compressor motor *has* to provide muscle, as it is doing real work, and the heat that comes with that is added to the heat scavenged by way of the outdoor coil.

The 4-way valve solution provides all that is necessary for a workable hot gas defrost arrangement. On the other hand, the solenoid valve alternative delivers just the scrappy amount of heat extracted from an under-worked motor to perform the defrost task, diluted by any splash-over of liquid which might have been present in the coil at the start of the defrost cycle.

In the early days of the installation I believe oil and liquid hold-up in the ill-fated lower circuit could have discouraged the flow of 'hot gas' (perhaps an overly optimistic term) to the lowest circuit of the evaporator, and as an outcome ice remained not melted in those lower regions of the coil. Once mechanical damage to the lower tubes had occurred, this downside effect would become runaway.



The green oxides arise from deliberate acid pickling. (See text).

STAGES OF TUBE COLLAPSE. Fig. 8.

PROGRESSIVE TUBE COLLAPSE

I believe development of this situation could have taken many months, perhaps even longer. After cutting away certain of the fins to allow a peek into a couple of the damage sites, Peter decided to pickle the coil in an acid bath to etch away the aluminium finstock, to enable more detailed examination. I found the photograph utilized in the upper part of

Fig. 8, and taken after this was done, most interesting. You will see two parallel 'wrinkles' which have been formed into the tube wall. Remember, at each refreezing of the melt water, there can be only a finite amount of expansion available to do damage. Some of the expansion, as we have already considered, could well have been directed into producing the warping in the affected fins and bringing about the substantial increase in diameter of the punchings which accommodate the tubes. Of course, immediately the point was reached when the fins no longer tightly 'bit' into the tubes, they would have become ineffectual in conducting heat into the ice accumulations. The affected tubes would effectively become prime surface and the melting effect would be delivered from the tube surfaces alone.

Towards the left of the tube in the upper part of Fig. 8 you will notice a short section where the tube has undergone total collapse, ending up with front pressing against back. Without a doubt, had operation been able to continue for a few additional weeks, this complete collapse would have progressively crept along the entire tube length, taking over the parts already weakened by the 'wrinkling', as has already happened in the lower example of tubing in Fig. 8.

SUMMARY
I see the sequence of events as having followed this pattern:

- The installed bypass-type hot gas defrost arrangement was severely short on 'muscle' as when compared with a 4-way valve hot gas defrost system.

- Because of coil configuration, with three lifts plays two, there was a greater likelihood of oil trapping (maybe liquid too) in the lowest circuit of the evaporator.

- Partly because some liquid could have been entering the compressor on the defrost cycle, and also due to the weak-kneed solenoid valve hot gas bypass concept adopted, hot gas flow during defrost could have been somewhat 'tired'.

- The upshot of the two above issues could have been the upper two evaporator circuits between themselves could have comfortably carried the full hot gas flow, such as it was, with insufficient residual pressure differential to drive trapped oil / liquid from the bottom circuit. Therefore there may have been several consecutive defrost cycles where the lower circuit received no flow at all of the mild 'hot gas'.

- During these times, additional ice, formed out of melt water trickling down from above, could have built into a solid block in the lower part of the coil.

- If now, on subsequent defrost cycles, some hot gas did make it through the lower circuit, defrost could have been limited to producing 5 or 10 mm thick 'sleeves' of water. Now it is important to be aware that the water volume so formed will be smaller than volume of the ice so melted. (We seldom think in this direction)! Being deep inside a block of ice, this could have produced 'vacuum' conditions.

- This vacuum could have pulled in melt water from higher in the coil, to completely fill this part of the void with water. This constrained water, on the next freeze, would have expanded, producing irresistible forces. Tubes would be crushed.

- This event could have repeated on numerous occasions, progressively crushing more and more the affected parts of the evaporator, until finally a tube leak developed. Right or wrong—I don't know. But I feel this is a perfectly logical scenario, which could fully explain this most unusual destructive event.

SEE YOU NEXT TIME!
What do you think of these conclusions? I found this a fascinating exercise into the 'whodunit' realms of refrigeration, and hope you enjoyed it equally. We will never know just how accurate this appraisal is, but I am sure it cannot be too far from the mark drawn by the actual line of events. Unless Peter sends some more of his fascinating photographs, next time we will pick up where we left off in our 'Air' series. Until then, stay well!