FORUM

Conducted by Jim Rowe

Further thoughts & theories about oxygen-free copper...

Remember the discussion in the September issue about the use of "oxygen-free" copper in electronic gear? My original attempt to get hold of some further information from Japan drew a blank, but a reader in Melbourne has very kindly sent me copies of some papers by one of the leading Japanese researchers, and these throw some interesting light on the subject.

The reader concerned is Mr John Ulph, engineering manager of Alcatel STC-Cannon in Melbourne, and I'm very grateful to him for sending this material. But before we have a look at it, I'd like to quote from another letter which turned up, also with suggestions on the subject of OFC and its possible benefits in audio applications.

This letter came from Melbourne as well, from Mr Robert Vickers of Mount Waverley. And Mr Vickers believes that in the September discussion I could have overlooked a key point:

I suspect you may have just missed the rationale behind OFHC (as per Colin Campbell) in applications using multistrand signal wiring – either in links, preamps etc., or speaker cable.

As I understand the situation, AC is conducted along the surface of a conductor, rather than through the core. According to Colin Campbell, OFHC can be drawn into finer wires which have tightly bonded oxide layers on the surface. At typical hi-fi voltages, presumably two such layers would form an insulator. One can therefore manufacture a cable with many fine, insulated wires, giving a large conductive 'surface'.

I further suggest, without wishing to enter the audio-fanatical world of the 'golden-eared' audiophiles, that the signal entering one end of such a cable comes out unchanged – that is, ungarbled by random signal path lengths as electrons randomly swap from one wire to another.

I won't comment on structural uses but suffice to say, be it 'hype' or 'tripe', they need a gimmick to sell a new machine while the old one is still working.

Thanks for the comments, Mr Vickers. You're quite right too, in suggesting that I had overlooked the possibility of skin effect. I hadn't considered the other aspect you raise either, about the effects of electrons swapping from wire to wire and thus causing random variations in path length. They're both interesting ideas, although I'm not sure that they really help all that much in explaining the advantages of OFC (oxygen-free copper) or OFHC (oxygen-free high conductivity copper).

For example skin effect, or the tendency for AC to flow near the surface of a conductor rather than at its centre, doesn't really become significant in ordinary wires and cables until you get to frequencies well over 100kHz. That's because it's the result of differences in the effective inductance of the inside of the wire, compared with its outer layers. As inductive reactance is proportional to frequency, this makes it only become relevant at higher frequencies.

Just to refresh my memory about this I looked it up in that well-known engineering text *Electronic and Radio Engineering*, by the famous Frederick Emmons Terman of Stanford University. Here it quotes the effective skin conduction depth in copper at 20°C as given by 66.2mm divided by the square root of the frequency in hertz. If you work this out, you find that the skin depth at 20kHz is nearly half a millimetre – larger than the total diameter of the individual strands in a typical multistranded audio cable.

The depth is still more than 200um at 100kHz, falling to 93um at 500kHz and 66um at 1MHz. So its effect is really only likely to be significant at these frequencies and above – not down in the audio range.

In any case, I find it a little hard to see how skin effect would work to produce an advantage for OFC. If OFC has its remaining oxides concentrated on the outside surface, as Colin Campbell noted, that's surely the very place we *wouldn't* want the current to be trying to flow, in preference to inside the copper!

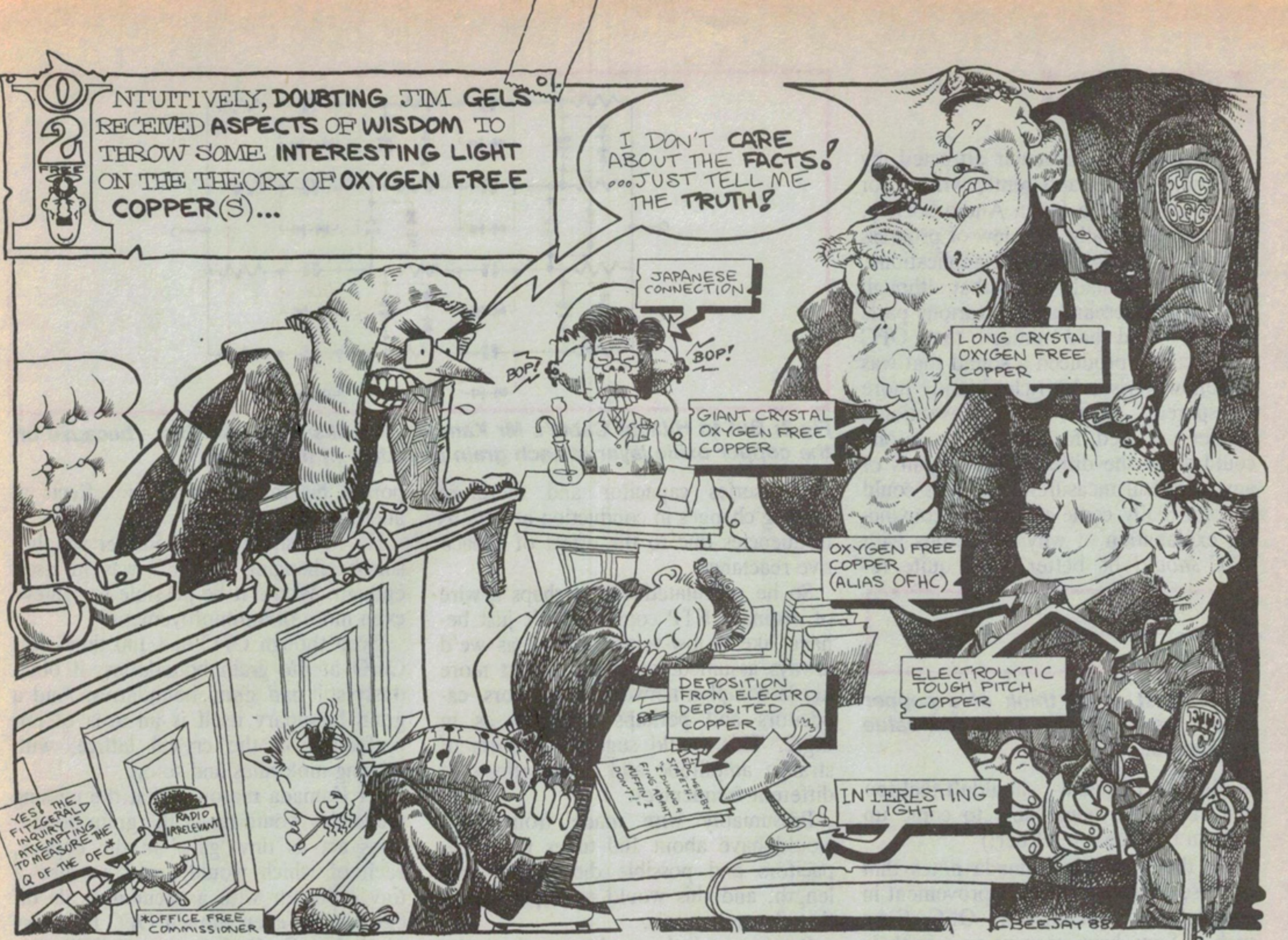
In fact if skin effect were relevant at audio frequencies, I suspect this would be more of a factor in favour of ordinary ETP (electrolytic tough pitch) copper, not OFC. At least with ETP copper the region of the wire nearest the skin wouldn't be any poorer a conductor than that further inside...

Actually Mr Vickers' other point seems in some ways a little more promising – the one about OFC's outer layer of oxide possibly acting as a kind of insulation between adjacent strands of wire in a multi-strand audio cable. On the surface this sounds as if it might be a possibility (sorry about the pun), as copper oxide is a semiconductor and in conjunction with copper metal forms a rectifying junction. After all this is how the old copper-oxide rectifiers worked.

Surprisingly, I haven't been able to find much technical information on the exact electrical properties of this kind of junction. Although copper oxide was one of the first semiconductor materials discovered, very little seems to be known about it.

I did glean from R.A. Smith's classic book *Semiconductors* that it has an energy band gap of around 1.9eV at room temperature, compared with 0.67eV for germanium and 1.12eV for silicon. This perhaps gives some support to my recollection of copper oxide/copper junctions as having a fairly high forward conduction voltage, and as being rather less efficient than either germanium or silicon.

But be that as it may, it does seem likely as Mr Vickers' suggests that two



such junctions effectively back-to-back (between adjacent strands of wire) would form an insulating layer, preventing electrons from crossing back and forth between them. Both because they're back-to-back, and because the voltages between the strands would very likely be below their forward conduction 'knee'.

This assumes, of course, that the two layers of oxide are continuous and entirely covering the surfaces of all strands. This might be a big assumption, because according to Colin Campbell the oxygen content of OFC is around .0003% – that's not much left to form oxides anywhere, let alone all over the surface.

Let's assume that it does do this, though, and that as a result a multi-stranded wire of OFC does act like many individually insulated strands. What effect would this have on the audio signals?

Mr Vickers suggests it would ensure that the overall signal path would stay 'more constant', with less 'random modulation' due to sideways motion of the electrons between strands. But frankly I can't see that the additional effective path length would be significant at audio frequencies, considering the speeds that conduction electrons would be travelling at in a metal like copper.

Don't forget that the random thermal motion of the electrons is quite great at room temperature anyway, producing what we normally call *thermal noise*. So as far as I can see, what Mr Vickers seems to be saying is that a cable with many strands of OFC would be less noisy than one of ordinary ETP copper, because the latter lacks our hypothetical layer of copper oxide insulating the strands.

If this were true, you'd expect a single large diameter wire to be much more noisy than our multi-stranded cable, even if the large diameter wire were made of OFC. In other words, Mr Vickers seems to be saying that the fatter a wire is, the more variation there will tend to be in conduction path length due to sideways detours by electrons, and hence the more noise added to the signal. And when you put it that way, it doesn't seem likely, does it?

I suppose it's possible, but you'd normally expect a single large-diameter wire to present the lowest resistance, and there's another law that links thermal noise directly with resistance. Intuitively I'd expect it to provide a connection that was *less noisy*, not more.

So you could be right, Mr Vickers, but I have my doubts. The ramifications of what you proposed don't quite seem to gel with other aspects of received wisdom.

With those comments as preamble, perhaps we can now pass on to the information sent in by John Ulph of Alcatel STC-Cannon. Mr Ulph's company is the Australian representative for Hitachi Cable Ltd., of Tokyo, and the information actually originates from that firm – which appears to be one of the major manufacturers of OFC cables for audio and video applications.

Much of the material turned out to be reprints of papers written by the chief engineer of Hitachi Cable, Mr Osao Kamada, who seems to be one of the leading researchers in the field of OFC applications in electronics. As it was therefore the first really authoritative information on this specific subject to come my way, I found it of great interest. And I think you will, too.

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One paper in particular attracted my attention. It was apparently written for the Journal of the Japan Audio Society, and was essentially a review of progress to date in the field of OFC applications.

In it, Mr Kamada writes that although quite a few researchers in various parts of the world had noticed that OFC audio cables produced a sound that was somehow 'crisper', 'richer' and 'more transparent' than when conventional copper was used, for a long time no-one could show the difference by means of any electrical measurements. Nor could anyone really come up with a convincing explanation of why the results with OFC *should* be better, until quite recently. (So I guess *we* shouldn't feel too bad about not being able to come up with an explanation, either!)

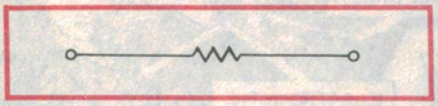

Fig.1: Most of us think of a copper wire as simply a low-value resistance...

By the way, Mr Kamada notes that because of the observed improvement in sound quality gained from OFC, firms such as Sony have been using it in their equipment for quite a while. Apparently the headphone cables on Sony's highly successful 'Walkman' have used OFC wire for about 8 years. So despite the lack of objective measurements, even a highly respected and engineering-driven firm like Sony decided that the benefits were tangible enough to proceed. An interesting point, don't you agree?

It turns out Mr Kamada was convinced that the improved sound quality provided by OFC must somehow be due to the fact that its copper crystals had very much less copper oxide concentrated at the boundaries between grains. The amount of oxygen in the copper is about 100 times less (3-5 parts per million, compared with 300-500ppm) than for ETP, so you'd expect the amount of copper oxide at the grain boundaries would be reduced by pretty well the same ratio.

Knowing that copper oxide was a semiconductor, he came to much the same conclusion as our reader Mr Vickers: that the effect of these thin regions of Cu_2O at the grain boundaries would be to upset the conduction between them. Either by introducing an element of non-linearity, due to the rectifying action, or at the very least acting like a small series capacitor and therefore causing changes in conduction at various frequencies due to the effect of capacitive reactance.

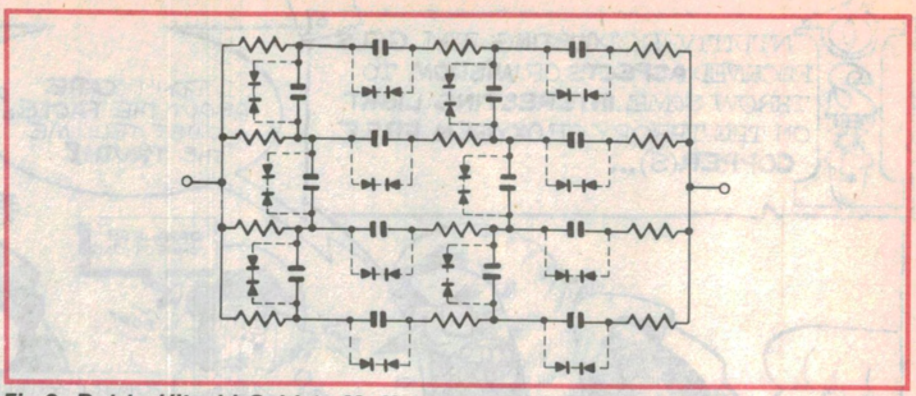

Fig.2: But to Hitachi Cable's Mr Kamada, it looks more like this – because of the copper oxide layer at each grain boundary in the copper.

So he speculated that perhaps a wire of ordinary ETP copper didn't just behave like a low-value resistor as we'd always assumed, as in Fig.1, but more like a complex network of resistors, capacitors and perhaps diodes – as in Fig.2. This would suggest all sorts of strange amplitude and phase effects at different frequencies.

Presumably wire made from OFC would have about 100 times fewer capacitors and possible diodes per unit length, and this would perhaps explain the 'clearer' signals.

Because so little was known about the precise AC behaviour of Cu/Cu_2O junctions, Mr Kamada made up some sample diodes and tested their performance. Apparently there were indeed significant amplitude and phase variations even over the audio frequency range...

Of course this was making measurements on relatively gross and 'discrete' junctions, and Mr Kamada apparently realised that you couldn't necessarily assume that these results would automatically apply at the microscopic level inside a wire. So he carried out another experiment, this time comparing the Q of physically identical microstripline resonators made from OFC, ETP and EDC (electrodeposited copper) at 10GHz.

The Q of the OFC resonator turned out to be just on 14% higher than those made from ETP and EDC, even though the 'DC' resistance of the OFC he had used was only 0.7% lower than that of the ETP and EDC.

As all other factors seemed to be the same, Mr Kamada deduced that the much greater Q produced by using OFC must be due to its lower internal 'intergrain' capacitance. And although this experiment was carried out at a microwave frequency, he decided that it supported his theory about the effects at audio frequencies.

His next step was to consider whether simply changing to OFC was in itself enough. Would it be possible to achieve even more of an improvement?

Even though OFC had 100 times less Cu_2O at the grain boundaries, it obviously still *had* grain boundaries. And a grain boundary itself is an area of imperfection in the crystal lattice, with missing molecules and so on.

Mr Kamada reasoned that the missing molecules would make the grain boundaries act as tiny 'gaps' in the copper, each of which would again act like a tiny capacitor with a vacuum as its dielectric. So even though OFC had very much less Cu_2O than normal ETP copper, it would still tend to behave electrically rather like Fig.2 (but without the diodes) – simply by virtue of having grain boundaries in the copper.

This suggested that it might be possible to achieve even better performance than had already been achieved using OFC, by increasing the size of the copper grains and hence reducing the number of grains (and grain boundaries) per unit length.

To test this theory, Mr Kamada tried another experiment – and one which should bring a smile to the face of at least some of our readers.

Remember our tongue-in-cheek story in the April issue, about the 'ultimate' speaker cable – using mercury-filled plastic hoses?

Well, believe it or not that's exactly what Mr Kamada used, to try the effect of using a cable with conductors having no grain boundaries at all. He used mercury because it's a liquid, and as a result the only metal currently available – apart from lead – in a form which lacks any grain boundaries.

(And we thought the whole idea was so way-out and impractical that it made a good April fool's joke!)

Using the mercury cables, Mr

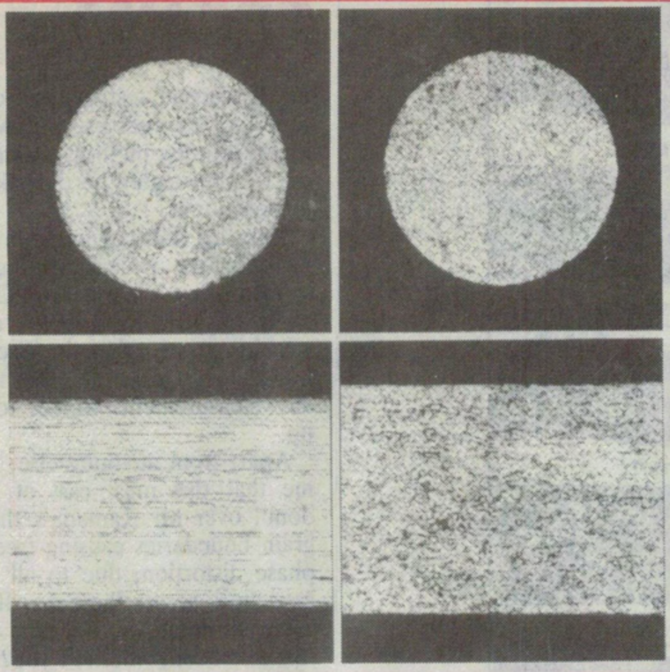

Fig.3: Microscopic photographs (x200) of Hitachi's LC-OFC (left) and ordinary OFC (right), showing the different crystal structure.

Kamada carried out A-B tests with two groups of top hi-fi critics and audio design engineers in Japan. The overwhelming consensus of opinion was that the mercury cables gave superb sound, much more 'real' and 'transparent' than cables made from even OFC or silver – let alone conventional ETP copper. And this despite the fact that mercury has a DC resistivity over 40 times that of even ETP copper, and over 50 times that of silver!

Needless to say, Mr Kamada was very encouraged by this result, which suggested that grain boundaries in copper (and presumably other crystalline metals) might indeed be a subtle cause of electrical distortion. Even though he still couldn't actually come up with any *objective measurements* which would quantify the perceived difference between the mercury and conventional cables – let alone between OFC and ETP cables...

The next step was to see if he could increase the grain size in OFC, so it would have fewer grains and boundaries per unit length.

The average grain size in OFC was already about 3 times that of ETP copper – around 20um compared with about 7um. Not a dramatic difference, but presumably worthwhile; there were only about 50,000 grains per metre length, instead of about 150,000. Presumably this was because the lower Cu_2O content allowed the crystals to grow larger.

Mr Kamada tried to make the grains grow even larger, by using a technique called 'super-annealing'. This involves holding the copper for long periods at a temperature just below its melting point, in an inert gas environment.

The results were again very encouraging. Average grain size grew to around 500um (0.5mm) – an improvement of 25 times over ordinary OFC and corresponding to only 2000 grains per metre. Measurements of this 'giant-crystal OFC' or GC-OFC, in microstripline resonators at 10GHz showed a further 3% increase in Q, and audio cables made from GC-OFC were ranked even higher than ordinary OFC cables in subjective tests.

Could the grain size be increased still further? It appeared not. But all was not lost; he realised that the really important parameter in this context was not overall grain size as such, only the *length* of the grains in the direction parallel to the wire's main axis. So he hit on the idea of drawing the wire down to a smaller size, by a ratio of 10:1. This stretched the crystals out in the direction of the wire's axis, increasing their length by about 100 times – to an impressive 50mm long.

They became a lot thinner in the process, of course, but this could be overcome by using many such wires in parallel to achieve the desired cross-sectional area. And the average number of grains/grain boundaries per metre with this 'Linear Crystal OFC' or LC-OFC cable had dropped to about 20 – an improvement of about 7500 times compared with ordinary ETP copper cables.

Fig.3 shows microscopic photographs comparing the structure of ordinary OFC wire 180um in diameter with that of LC-OFC wire of the same diameter. The elongated crystals are quite apparent in the latter, particularly in the lower view along the axis.

Apparently the subjective results in audio tests comparing this LC-OFC cable with those using both ETP copper and ordinary OFC are quite impressive. Those who have heard them describe the difference as 'very obvious', with claims that the LC-OFC cable gives much greater 'transparency', 'sharper transients', 'wider dynamic range' and so on.

There doesn't seem to be much doubt that Mr Kamada is onto *something*, then. Or that his improved 'LC-OFC' cables do provide at least a subjective improvement in audio quality. Perhaps he and Hitachi Cable are right in claiming that LC-OFC would provide even more of an improvement in audio and video systems, if it were used throughout the signal path – not just for the speaker cables.

But I still find it puzzling that even Mr Kamada, for all his ingenuity, hasn't been able to come up with a single objective test which *measures* the improvement provided by LC-OFC or even ordinary OFC, at audio frequencies.

Of course the reason for this might well be that as yet, we simply don't have measuring instruments and techniques which are as sensitive as the human ear in detecting subtle forms of frequency and phase distortion. This kind of limitation in measurement technology has certainly happened in the past.

Unfortunately in this kind of situation there's always the alternative possibility: in the absence of objective measurements, it's easy for we humans to fool ourselves into hearing what we want to hear, or what we think we should be hearing.

There was a very interesting and thought-provoking article on this effect in the July 1988 issue of the UK magazine *Electronics and Wireless World*, written by a chap called Douglas Self and entitled 'Science vs Subjectivism in Audio Engineering'.

It's hard to tell whether Mr Kamada's tests with various kinds of cable could have allowed this kind of error to creep in. I can't find any reference to 'double blind' testing, where neither the subjects nor the experimenter knows the exact test conditions at any instant during the actual testing, and can't therefore fool themselves. But Mr Kamada seems a pretty methodical kind of worker, so presumably he did take this kind of precaution.

If so, his A-B comparative tests would be objective at least to the extent of showing that cables of OFC and especially LC-OFC do improve audio quality, in a way that is discernable to humans. It's just a pity that there aren't any measurements as yet to back this up.

Apart from anything else, it seems to me that this must cast at least some doubt over Mr Kamada's theory about grain boundaries causing frequency and phase distortion, due to all those little capacitors across the gaps. If that were so, you'd think we'd be able to *measure* this distortion, wouldn't you?

It's all very puzzling, to be sure.

Another thing that occurs to me is that even if Mr Kamada is right with his theory about the importance of grain boundaries, this in itself mightn't be much of an argument for OFC as such. Perhaps the only real advantage of OFC is that it can be made to grow into larger grains than ETP copper – not the fact that it contains less oxygen.

It seems to me that the whole business of oxygen content and Cu_2O at the grain boundaries might yet turn out to be a complete phurphy, after all. If a way could be found to make ordinary ETP copper form large crystal grains, or even make it grow into single crystals, perhaps this would achieve just as big an improvement.

Just before we leave the subject, at least for the moment, a final thought: if Mr Kamada is right, and the grain boundary around each crystal is essentially a vacuum gap, how is it that a copper wire is able to conduct DC?

When you think about it, even his you-beaut LC-OFC copper wire with its grains 50mm long is still composed of a finite number of grains, supposedly linked only by the capacitance across each of their boundaries. And since capacitors only pass AC, this suggests that even an LC-OFC cable should be an open circuit for DC. Not just a high resistance, but a true open circuit!

Obviously this isn't so. Even wires made from ordinary ETP copper conduct DC exceptionally well.

Which again seems to throw a certain amount of doubt on Mr Kamada's theory, don't you think?

See you again next month.