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The Ship Hull Fouling Penalty

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The ship resistance penalties of slime, shell and weed are discussed in turn. Methods to measure the hard paint roughness of antifouling coatings are recapitulated. The determination of a satisfactory roughness parameter from correlations with measured roughness functions is described. This in turn, allows a relationship between ship added friction and roughness height to be found. This recapitulation allows consideration of using the same route for a surface with filamentous fouling. Consideration is given to low surface energy coatings and their roughness idiosyncrasies. The determination of economic penalties is discussed, both for a particular ship and globally.

Keywords: antifouling development; hull roughness; fouling drag; ablative coatings; non-stick antifouling

INTRODUCTION

The penalty of fouling is ship speed loss at constant power, or, power increase at constant speed, or, consequentially, an economic penalty due to increased fuel consumption and scheduling penalties and other delays. Penalties arise from an unsatisfactory underwater outer bottom condition, which includes propeller blade surfaces.

Almost all vessels have an antifouling paint coating over the underwater hull. Generally, propeller blade surfaces are of polished metal *e.g.* manganese bronze, and will have no antifouling provision. As far as the hull coating is concerned, a number of problems can arise. Firstly, a new antifouled surface may be hydrodynamically rough, usually as a result of poor paint application management *e.g.* drips, runs, sagging, overspray, and grit inclusion. Secondly, the coating may become rougher in service due to paint system partial failures and mechanical contact damage. Thirdly, the antifouling provision may be inadequate over time, resulting in slime development, and then weed and shell growth, variously distributed over the hull.

Propeller fouling will not be dealt with here, partly because it is normally a minor part of the ship fouling penalty, but also because there is a relatively inexpensive remedy *viz.* underwater blade cleaning, and even polishing, by specialist divers. It can be noted however, that coatings can survive on propeller blades and have been found to have some antifouling benefit. As far as propeller blade surface roughness penalties are concerned, these may be estimated from the nomograms published in Townsin *et al.* (1985).

Ship hull fouling consists of the three categories, demotically, slime, weed and shell. Comment will be made on the ship speed and power performance penalties arising from each in turn, followed by comments on hydrodynamic research issues of roughness and fouling. A survey of the economic penalties will complete the review.

The deleterious effects of fouling on ship performance have been feared and recorded from the earliest times. Between 1862 and 1904 there were eighteen papers on corrosion and fouling issues read to the Institution of Naval Architects (INA) in London. The two issues were often seen as one problem in those days, as iron was replacing wood as the shipbuilding material. Copper sheathing had protected wooden hulls from the depredations of the teredo worm, and, as a by-product, the copper kept fouling at bay. The efficacy of copper as an antifoulant led to attempts to clad iron ships with copper. The British Admiralty had to call upon Sir Humphrey Davy, to help with the accelerated corrosion of the iron and copper combination. An attempted solution at the time was to clad the iron ship hull with wood and fix

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the copper sheets to the wood, without contact with the iron; clearly, fouling was a serious performance problem. The effects of fouling at these times is well illustrated by a quotation from one of the INA papers referred to earlier (Lewes, 1889). He says "of some protective and anti-fouling compositions in use by the Navy, it is no exaggeration to say that, as far as speed is concerned, one half of our fleet would be useless before one year had elapsed, from the accumulation of rust, weed and shell".

As well as copper sheathing, many entrepreneurs were patenting and experimenting with various compositions with which to coat the outer bottoms of steel and iron ships. Indeed, the first record of an antifouling coating was in a British Patent of William Beale, in 1625. As Bertram (2000) quotes in his WEGEMT lecture, "Until 1865, more than 300 such 'patent paints' were registered. All of them were quite ineffective". Some exotic mixtures resulted from these attempts. One such was of fish scales pounded up with red lead. What transient antifouling benefit there was, resulted more from the red lead than the fish scales.

The last of the eighteen INA papers referred to earlier, was by Holzapfel (1904). Holzapfel reports on test patches, keel to light waterline, of about 100 different compositions, which he applied to some 80 boats sailing from Genoa, principally in the Mediterranean trade. He also tested composition-coated plates immersed in Genoa harbour. He distinguished two types of antifouling composition current at the time, which he called 'varnishes' and 'greases'. All his experiments were with 'varnishes'. Holzapfel found that the more successful of the 'varnishes' were those with substantial copper and mercury content; but, he writes, a successful composition must also be one "capable of being gradually dissolved in sea water" which he called 'primary disintegration'. The 'greases', which were much softer, and gave rise to greater surface friction and fuel consumption (currently they would be called 'rougher'), were supposed to shed the fouling by what he called 'secondary disintegration' under fluid frictional shear. Lewes used the word 'exfoliation' in his earlier support of 'greases'. The industry went down the 'hard varnishes' road for the next 70 years and exfoliating greases were not pursued much further. However, in Holzapfel's paper may be read the beginnings of ideas about what are now called 'ablative coatings'.

The 'hard varnishes' route led eventually to inter docking periods of 2–2.5 years, at best. It became evident that the leach rate of toxins was falling off with time, so that new coatings had an over-rich leach rate, whereas an older coating had an ineffective leach rate, even though biocide remained. Holzapfel's 'primary disintegration' was not being achieved.

All this changed with the British Patents of Milne and especially Milne and Hails (1971), which led to the so-called self-polishing copolymers (SPCs) loaded with tributyl tin (TBT) as the biocide. The chemistry of these new products provided an ablation rate which ensured a constant rate of leach of biocide. The effective life of these products depended on the coating thickness in relation to the ablation rate, and, in practice, could ensure a foul-free hull for up to 5 years, which coincides with the Classification Societies requirements for inter docking survey periods.

With the advent of tributyltin SPCs, fouling became yesterday's problem and interest began to centre upon the fluid friction penalties due to the roughness of outer bottom coatings. The roughness of new ship coatings had always been of interest because of contractual speed and power trials at hand-over of a new ship. The renowned Lucy Ashton trials, in the Gare Loch, in Scotland, were conducted in the late 1940s and early 1950s with this in mind (Denny, 1951). But now, with the prospect of foul-free hulls, the through-life roughness of anti-fouled hulls became of interest to ship operators. The Ship Performance Group at Newcastle University, among others, pursued this work, *e.g.* Townsin *et al.* (1981). The Group's formulation for calculating the resistance penalty for a ship with a moderate and measurable roughness was subsequently adopted by the 19th International Towing Tank Conference, Madrid, (ITTC, 1990).

Whilst the ablation of these products and the consequent biocide leach rate was their prime *raison d'etre*, it was also noted that any initial roughness due to application was smoothed out in service. The name 'self-polishing' for these products was therefore applied by the marine coatings industry to indicate smoothing properties, although, whilst the paint itself became smoother, the hull, overall, often became rougher due to surface damage. The added resistance due to paint surface damage was a problem recognised by Holzapfel.

The success of tributyl tin was not to last. Marine biologists, world-wide, were able to assemble evidence of the effects of TBT on coastal marine life. The poisoning of oyster beds and imposex among dog whelks were among the effects observed. The passage of vessels with TBT antifouling in coastal waters was seen as the cause, but the prime cause may have been the flushing of dry docks where the coatings were applied or removed and where no filters were used. As is well known, tributyl tin is now banned with various conditions and deadlines.

The marine coatings industry, at the present time, does not wish to lose the benefit of an ablative matrix containing a biocide. The chemistry is being reconstructed to accommodate different biocides, copper returns as the major present candidate, supplemented with booster biocides. Marine coatings chemists are attempting to improve these so-called tin-free, self-polishing copolymers to match the effectiveness of what is being banned. There is a little way yet to go before the confidence of ship operators returns, but another antifouling candidate is already being applied to the bottoms of ships, *viz* the low surface energy, non-stick, or foul-release coating. Perhaps this non-biocidal coating is the way ahead and the prophetic banning of copper biocides on some coastal stretches of Scandinavia may be noted. Work on these non-toxic coatings was underway as tributyltin SPC was being developed *e.g.* Callow and Milne (1985). The success of the latter partially obscured the promise of the former.

SLIME

The fluid friction drag of slime is the least well-understood of the three demotic categories of fouling referred to earlier. A slime layer forms quickly, constituting the beginning of fouling growth. It is sometimes the case that an antifouling does not inhibit a slime film, yet keeps weed and shell at bay. At present, this seems to be the case for foul-release coatings. Since slime is 'rootless', it is easily cleaned off, yet it resists removal even by the relatively high frictional shear rate of faster vessels. The important question is therefore, what drag penalty arises from the presence of a slime film?

The classic experiments on the Lucy Ashton, referred to earlier, consisted of a refurbished paddle steamer hull, with the paddles removed, propelled on the calm waters of the Gare Loch, off the river Clyde, Scotland, by jet engines mounted on the paddle sponsons. The engine thrust in air was accurately measured, as was the speed on the measured mile. All manner of surface conditions were explored for their drag, including the effects of hull roughness and slime. The hull was allowed to foul for 40 d, on a coating of bituminous aluminium. Only slime was present. Over the speed range of 5 to 15 knots, the frictional resistance increased by 5% *i.e.* 0.125% d^{-1}. (Conn *et al.*, 1953). Watanabe *et al.* (1969) reported an 8 to 14% increase in (frictional) resistance due to slime.

Lewthwaite *et al.* (1985) reported the 600-d development of fouling on the hull of a 23 m fleet tender, operating around the South Coast of England. The hull had a non-polishing antifouling. The local frictional resistance coefficient was measured by a total and static head wedge probe mounted near to amidships. After 240 d operation, divers reported a thin slime coverage, too thin to measure but detectable by touch. At this time, a 25% increase in the local frictional resistance was measured. At 600 d a thick 1 mm slime film had developed, with some shell and extensive weed above the bilge keels. The frictional resistance had increased locally by 80%.

A set of full-scale trials on a frigate that had an organotin and cuprous oxide antifouling coating was reported by Bohlander (1991). After 22 months out of dock, it had no weed but a very small amount of calcareous fouling and a mature slime film. Speed and power trials were conducted. The ship was then drydocked, the slime was cleaned off and further speed and power trials undertaken. A measured 8 to 18% decrease in total propulsive power was attributed to the removal of the slime film, with the highest percentage (surprisingly) being near the highest speed.

The above four sets of full-scale trials show that slime can have a substantial deleterious effect upon ship performance and many laboratory tests have corroborated this conclusion *e.g.* Loeb *et al.* (1984), in which a 5 to 8% increase in resistance for a flat plane at 40 knots, was extrapolated from disc tests. However, there is no way of predicting, for a particular ship, trade route and coating, how the slime will develop. Additionally, at present, there is no way of measuring and characterizing slime, which can be correlated with its drag. The ship operator, therefore, has to consider the cost and inconvenience of underwater cleaning, when no other substantial fouling than slime, is present, but without being sure of the consequential performance gain. The operator may attempt a before-and-after log of fuel consumption in service, but this is fraught with difficulty and inaccuracy in most cases.

Clearly, more studies are required about the prediction, characterisation and drag penalties of slime films. Fish do not foul but do have slime films. If fish generally do not carry epiphytic growths, is their slime film an antifoulant or does it have a cell wall shedding mechanism? More interestingly, for the naval architect, is the notion that fish slime, when diluted in water, has drag reducing properties, which some fish seem to 'call upon' when required (see for example, Rosen and Cornford, 1971).

SHELL AND WEED

The drag penalty for a shell infestation of a hull is relatively simple to calculate. The straightforward shell characteristics of diameter, height and distribution density can be readily measured. The drag of simulated shell on a flat surface can be measured in a ship model testing basin or a flow channel. A well-known example is the classic pontoon tests of Kempf (1937). He found that the maximum drag increase occurred with shell fouling covering 75% of the wetted surface. The shell height was 14 mm. But even with only 5% of the wetted area covered, the drag increase was 66% of the maximum. From his empirical data he was able to calculate the increased resistance of ships due to shell, in a number of cases. For example, a 120 m vessel, with 75% coverage with shell of 4.5 mm height would show an increase of 85% in skin friction resistance. If shell characteristics are known therefore, it is possible to estimate the added drag. The nature of ship service nowadays means that calcareous fouling is less common than it was in the 1930's and is supplanted today by weed fouling.

Estimating the added resistance of a ship covered with weed fouling, for example *Ectocarpus* or *Enteromorpha*, is a more intractable problem. The percentage of area covered can be estimated visually, but what of the weed itself? Wet weight, dry weight or ash weight are used for other purposes, but these are not promising parameters for correlation with drag. The average height of pliable filaments, attached perpendicular to a surface and then subjected to a fluid flow, could be used as a characterising parameter, along with some measure of the density of distribution of the filaments. Early work by Lewkowicz and Das (1986), following upon their studies of roughness drag in pipes, pioneered this approach to marine fouling drag. Work along these lines is being pursued, notably by Schultz and Swain (1999) and by Schultz (2000).

With the advent of laser-doppler velocimeters for use in flow channels and other fluids apparatus, it is now possible to study the effects of surface characteristics on the turbulent structure of fluid flow and hence the resulting added drag. The marine problem has common cause with those interested in the fluid boundary layer interactions between the wind and plant canopies *e.g.* a cornfield, which is of interest to meteorologists among others, *e.g.* Raupach and Thom (1981).

The work on filament drag is making good progress but there will be a difficulty in applying results to the circumstances of a particular ship. One problem would be the measurement of average filament length or height characteristic over the hull, presumably by a diver. Perhaps it will be sufficient to calculate the drag and fuel penalty for a few typical cases, in order to write the bad news of weed fouling. However, for the ship operator, it is a matter of deciding between the unscheduled dry-docking and re-coating costs on the one hand, and the continuing extra fuel cost penalty, in-service, on the other.

Another possibility is to provide a weighted, numerical fouling index from a visual inspection of a hull just after in-docking. The weighting would have to account for fouling type, intensity and distribution. The difference between the in-docking fouling and the re-coated, foul-free bottom could then be correlated with some performance measure *e.g.* the fuel consumptions immediately before and after docking, somewhat along the lines of Bohlander's study (Bohlander, 1991). The fouling index has to be designed with care, and in-service performance monitoring is prone to error.

RESEARCH DIRECTIONS

If the nature of a surface, for example, its roughness, can be numerically categorised, and if the added fluid frictional drag, due to the surface condition, can be measured, then there is a possibility of an approximate correlation between the surface condition, however measured, and the added drag. Once the correlation and its limits of applicability are established, it is then possible to measure another surface condition and hence predict its added drag. This research route has been followed in the case of hard (antifouling) paint surface roughness, and a correlation has been established (ITTC, 1990), which was referred to earlier.

In the case of ship hull roughness, one obvious candidate parameter to characterise the surface was a statistical measure devised for the Lucy Ashton trials. The parameter is Rt(50) and is the maximum peak to the lowest trough in a 50 mm sample length, along the rough surface. The roughness height distribution is random and therefore it is necessary to use an average value of this parameter over a measurement position (mean hull roughness, MHR), and then MHR is averaged over the hull (average hull roughness, AHR). There is a standard procedure for measurement of a ship hull surface (Townsin *et al.*, 1981). There is also an instrument for taking the measurements, the Hull Roughness Analyser. Although this 'ready made' parameter was available, it was necessary to test a variety of alternatives to correlate with added drag, especially because texture as well as a height measure has to be accounted for.

The correlation involves the velocity distribution u at a distance y from the surface, within the turbulent boundary layer. A simple model of this distribution is known as the Logarithmic Law of the Wall:-

$$u/u_\tau = (1/\kappa)\ln(yu_\tau/v) + B_o$$

where the friction velocity $u_\tau = \sqrt{(\tau_o/\rho)}$, and τ_o = the wall shear stress, with ρ = fluid density. κ is the von Karman constant, which appears to be a universal constant in most circumstances. B_o is also constant for smooth wall flows. This model has been explored by numerous measurements of fluid boundary layer flows over smooth surfaces.

Boundary layer velocity measurements over rough surfaces do not obey the Logarithmic Law as written above, but empirical results may be interpreted by adding a further term $(-\Delta u/u_\tau)$. This latter term is called the roughness function. Authorities agree that this function is a logarithmic expression involving some linear measure characterising the roughness. However, there are various proposals and some debate about the precise nature of the expression. In the end, it is important to find a linear measure of roughness, which correlates with the roughness function.

There are only about 30 sets of experimental data available concerning fluid flow over rough painted surfaces, where the surfaces have been subjected to detailed, statistical roughness measurement and where there are adequate flow measurements to allow the roughness function to be calculated. The correlation between all these roughness functions, and a number of linear measures, h, in the quantity $\log(hu_\tau/\nu)$, has been explored by Townsin and Dey (1990).

The best correlation was when $h = \sqrt{(\alpha m_0 m_2)}$, where m_0 and m_2 are the first two even spectral moments of the random roughness distribution and α is the band width parameter. The statistical modelling of a random roughness is similar to the spectral representation of ocean wave heights and is therefore familiar.

As a concession to simplicity, however, it was found that, providing the data were restricted to values of $Rt(50) < 230\,\mu m$, which is the moderately rough ship range, then the roughness function correlated well enough with $h = Rt(50)$, for all the paint surfaces tested. The way was now open to correlate Rt(50) directly with roughness added resistance values, as measured by a number of authorities. A simple formula for the added ship resistance in terms of AHR, was the outcome:

$$1000\Delta C_F = 44[(AHR/L)^{1/3} - 10R_n^{-1/3}] + 0.125$$

where the added resistance coefficient $\Delta C_F = \Delta R/0.5\rho SV^2$ (ΔR is added frictional resistance and ρ is the fluid density), the ship length is L, R_n is the ship Reynolds Number, at speed V and the ship wetted surface is S.

This explanation of the research direction taken to estimate the drag of a surface covered with a hard, rough, paint coating, gives background for the question, ‘can the same route be taken in the case of flexible (weed) roughness?’ A paper by Schultz (2000) points in the direction of an answer. The use of laser Doppler flowmeters, in association with flow channels, allows velocities in fluid boundary layers to be measured with some convenience. Hence, the roughness function over a filamentous surface may be determined. However, the same problem arises, as with paint roughness, *viz*. a linear measure of the fouling height (under flow), must be determined, in order that the measured roughness function, which includes the height, correlates with the linear measure itself. An added complication with a pliable surface coating, is that changes in the flow can, to some extent, change the fouling height, however it is measured. Also, the induced waviness caused by the flow over a pliable surface has to be taken into account. The mobility of the strands of weed fouling may interact with the turbulent velocity perturbations and it is possible that there could be a turbulent drag reduction mechanism. Possibly, the eruption and bursting of stream-wise turbulent vortices are delayed by filament mobility. All these features lead to the need for a close examination of the flow characteristics between the smooth and fully rough regimes. The Colebrook–White model (Colebrook and White, 1937), upon which dependence has been placed for some time, may not be adequate for flow over a weed-fouled surface.

Compared with studies of flow over hard rough surfaces, there is, as yet, a limited amount of published boundary layer measurements over weed fouling where there are also adequate numerical data describing the fouling itself. As yet, therefore, no measure of fouling is available to correlate with its drag. The current position is well summed up by the last sentence in Schultz (2000): ‘Scatter in the roughness functions of these surfaces indicates that further research is needed to better correlate the physical measures of the algae layer with their roughness function.’, and, it might be added, ‘and with their drag’.

Concerns attending the gradual abandonment of tributyl tin, range from fear of a return to endemic fouling, to the increased cost of replacement antifouling provision. However, despite these concerns, there are promising signs. Marine coatings companies are promoting their antifouling products on the basis of their smoothness and smoothing properties, once again. In that connection, interesting problems arise with the biocide-free, low surface energy coatings.

It seems that the chemistry of foul-release products is such that the applied coating cures with a smoother finish than other compositions, applied in the same way. Of itself, smoothness seems to inhibit fouling settlement, but it is the drag issue which is of particular interest. It is generally realised that two types of parameter are required to characterise hard roughness in order to correlate with added drag; one is a linear or height measure, the other is usually referred to as a texture parameter. A peak-to-valley height measure and the first two, even, spectral moments, as texture parameters, have already been referred to. There are other statistical parameters which have been proposed, *e.g.* Musker (1977). Hitherto, paint surface texture has consistently related to its roughness height, implying that a height measure alone, *e.g.* Rt(50), could characterise, at least moderate hull roughnesses. The foul-release surfaces, however, have a noticeably different texture, with more spectral energy in the longer wavelengths. This is likely to mean a lower drag for the same height (Candries *et al.*, 2003). An implication is, of course, that the whole correlation process of roughness measurement and analysis, of boundary layer studies and of drag measurement, has to be gone through again for low surface energy coatings.

If felt when dry these elastomerised surfaces drag like rubber, but underwater they feel fish-slippery. A consequence when using the standard, Hull Roughness Analyser, is that the stylus judders over a dry surface but the drive wheel slips when the surface is wet and measurements can therefore be unreliable. Additionally, it is necessary for the instrument to be modified to record the surface trace digitally so that texture and height parameters other than Rt(50), may be determined (Chuah *et al.*, 1990).

ECONOMIC CONSIDERATIONS

In the matter of hull fouling, it is the marine paint chemists and the marine biologists who pave the route ahead; naval architects count the cost, and the ship operators pay the bills. It is appropriate therefore, to conclude with some consideration of the economic penalties of fouling.

In a particular ship case, if the outer bottom surface condition can be numerically assessed, whether it be roughness or fouling, and if that measure can be used to predict the drag penalty, then, using discounted cash flow techniques, an outer bottom maintenance strategy can be developed and alternatives evaluated. In the case of roughness, this can be achieved (Townsin *et al.*, 1981). In the case of fouling, the difficulties of measuring and correlating with drag have already been referred to.

Another approach for a particular ship is to monitor the speed to power relationship in service. Increases in fuel consumption can then be a determinant in the maintenance strategy. However, monitoring performance at sea is fraught with imprecision. The effects of wind, waves and ocean currents, must be accounted for. The measurement and relationship between propulsive power and fuel consumption are difficult to assess in service. An example of the intricacies is in Townsin and Svensen (1980). Nonetheless, fuel consumption figures on passage are often the only hard evidence available in disputes between ship operators and the coatings industry when an antifouling is thought to have failed.

It is also worth reflecting upon the global savings due to efficient outer bottom surface maintenance and the use of effective antifouling. Ablative, organotin antifoulings were introduced in 1974. A survey of the effects on ships as to their roughness and fouling, over a decade, 1976 to 1986, was undertaken by Townsin *et al.*, (1986). The hull roughness of 47 ships was measured on 147 occasions during the decade (Byrne, 1980). Only a few of these ships had ablative antifoulings. A further 98 measurements were taken later in the decade, on ships, most of which had TBT, SPC coatings. A striking improvement in in-service roughness was noted.

The most striking change discovered, however, was in antifouling performance. Data from 672 ships prior to the introduction of ablative coatings, showed only 19% entering drydock with zero fouling and 20% were more than three quarters covered. Later in the decade, 183 ships which had tributyltin SPC antifouling were surveyed; 91% entered dry dock with zero fouling, despite longer inter-docking periods.

Milne (personal communication, 1989*) attempted the difficult task of putting a global figure of savings to the shipping industry, consequent upon the introduction of ablative coatings, based upon the decadal study referred to. Savings were calculated in four groups, *viz.* fuel cost savings due to the reduced ship frictional resistance, savings due to extended inter docking periods, savings due to consequential lower dry dock costs, and indirect savings, including, for example, savings due to the lower requirement to transport bunkers to refuelling ports. The annual savings in the four categories in US $ millions came to 720, 409, 800 and 1080, respectively, giving a grand total annual saving, for the world fleet, of about US $ 3,000 million.

Anyone working in the antifouling field could feel proud to have assisted in achieving these savings for the shipping economy. For many, however, a greater source of satisfaction in producing efficient antifoulings, is the reduction in smoke–stack emissions, notably the greenhouse gas and global warmer, carbon dioxide, and the acid rain and ozone depleters, nitrogen oxides and sulphur oxides. In line with other estimates, Milne (personal communication, 1989*) calculated an annual world fleet fuel consumption of 184 million tonnes, at the time of the decadal study. From that study he took a figure of 2% reduction due to smoother hulls and a further 2% reduction due to improved antifouling, yielding an annual fuel saving of 7.36 million tonnes. The carbon content of liquid fuels is quite constant at 85%–86% and every tonne of fuel used creates 3.1–3.2 tonnes of CO_2 (Nurmi, 2001). The savings in greenhouse gas due to improved antifouling during the decadal study, was, therefore, about 20 million tonnes per

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*Aquatic biocides: their benefits and environmental risks. Unplublished lecture to the Royal Society of Chemistry, Autumn meeting, 1989.

annum. Perhaps another decadal study should be undertaken in the post-TBT, SPC era.

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