FRACTURE AND SOCIETY

An ICF4 Interview with Sir Alan Cottrell FRS

As Cottrell pointed out in his opening address at ICF2, everyone is concerned, from a very early age, with why things break. Children's toys break, we break our bones, the engines of our motor cars and washing machines fracture - but more importantly, advanced large-scale structures can fracture - pipelines, bridges, skyscrapers, nuclear reactors, ships and aircraft - even the very earth itself fractures in earthquakes. The understanding and alleviation of all such fractures are the special concern of the scientists and engineers who gather together every four years at each International Conference on Fracture. The inspiration of these conferences has been Professor Takeo Yokobori, Founder-President of ICF. It is the principal purpose of ICF to regularly bring together, from every corner of the world, the major workers in all aspects of fracture for a re-assessment of the advances made and to provide a basis for sound and relevant scientific and engineering work in the future. This purpose will surely be achieved at ICF4. But, in Canada, in preparing for ICF4, we were especially conscious of the larger purpose of placing all this research in the full context of society as a whole. As the complexity of our technological systems increases, so do the possible catastrophic consequences of failure. By way of emphasis, one may cite the Presidential Campaign of 1976 in the United States where the consequences of fractures in nuclear reactors, and hence their safety, played a significant role. The safety of many of our energy systems including reactors, offshore structures, super-tankers, LNG ships, pipelines, is now of very wide social concern and is discussed regularly and thoroughly in the ordinary press. Accordingly, it is both an obligation and extremely prudent that we, at this conference, address ourselves to our responsibilities to the safety of the technological world at large.

Thus, the dominant themes of ICF4 are the *applied* aspects of fracture and especially the application to large-scale engineering structures. At the same time, the broad purpose of bringing together workers in every aspect of fracture has not been forgotten. But, to ensure that the social implications of our work can be fully appreciated and discussed, two Plenary Panel Discussions have been organized under the general heading *Fracture and Society*. The first of these focusses upon Educational issues whilst the second is concerned with the broad Socio-Political context itself. Very early in the organizing of ICF4 (1973), Sir Alan Cottrell was approached for his views on the most useful orientation for ICF4. It will be remembered that Sir Alan has very special qualifications for being so consulted. He is amongst the handful of major contributors to our understanding of fracture processes in solids. His background includes experience in Chairs at two major English Universities and in the nuclear industry and the full accolade of the world scientific community for his own research and his many books. But, for many years, in more recent times, he has been privy to the Corridors of Socio-Political Power through his appointment as Chief Scientific Advisor to the British Government. In this role, he became a household name in Britain and led a team to Canada to investigate the CANDU reactor system. He became well known in several parts of the world for lectures on *Science and Society* and for his broad consciousness and intellectual grasp of the issues confronting the development of technologically advanced nations. More recently still, he has begun another career as Master of Jesus College at Cambridge and as a rather youthful Elder Statesman. Thus, there could surely be no one better qualified to address ICF4 on the topic chosen for these panel discussions - *Fracture and Society* - in 1976, Sir Alan was approached accordingly. Unfortunately for ICF4 (but fortunately for his University) he had just been elected Vice-Chancellor and convocation precluded his absence from Cambridge. After various discussions about possible alternates, it was realized that the purpose would be best served through a published interview with Sir Alan - somewhat in the style of some American and British magazines. Such an interview would be structured around prepared questions (taken on notice) on the topic *Fracture and Society* and would be probing and wide-ranging so as to provide the best possible foundation for discussion in the ICF4 Panels - and elsewhere.

Through the good offices of Dr B. Ralph, a Fellow of Jesus, and Dr. J. F. Knott, I was able to arrange, at short notice in December 1976, a meeting in which the proposition could be put forward in detail. I was advised to approach the proposition rather slowly and not until, perhaps, the third course of our dinner in Hall. Somewhat untowardly, I discarded this advice and before we had finished our soup, Sir Alan had gladly accepted the proposition and asked me to forward to him the questions, so that he could look them over prior to the recording session. I also arranged to send him copies of a selection of the Plenary and Workshop papers for his scrutiny and we were able to sketch over some of the questions and the overall scope of the interview.

The details of the actual interview were as follows. Through discussions with various scientists, amongst whom figured Tetelman, Eshelby, Embury, Knott, Bilby, Smith, Averbach, Ralph, a list of questions was compiled and forwarded to Sir Alan during January 1977. The interview took place over a period of two hours on February 16, 1977 in the Master's Lodge at Jesus. Dr Brian Ralph and Dr John Knott, both former research students of Sir Alan, conducted the actual recording session on behalf of ICF4. The interview was tape-recorded and the printed transcript that follows has been subjected only to minor editorial changes.

On behalf of all the participants of ICF4, I wish to record here our gratitude and appreciation to Sir Alan for the task he undertook. I am sure it will be judged to be of very considerable substance, value and interest. It now only requires that in the Panel Discussions we apply ourselves equally to the task which we address. Fracture researchers are a relatively cohesive and harmonious group. It should be possible, thereby, to arrive at some sound and relevant conclusions in what has become, increasingly (Newsweek, May 9, 1977) not only a model and structure sensitive subject but also politically and socially sensitive.

D.M.R. Taplin
May, 1977

THE INTERVIEW

ICF4: *Concentrating initially on the science of fracture, do you think that it's fair to describe Griffith as the father of the science of fracture?*

Sir Alan: Yes, I think he is the father of the science of fracture. Griffith took the key step of treating the growth of a crack as a thermodynamic process; and his formula, because it balances the volume and the surface energies incrementally, has a universal application to all forms of true fracture.

ICF4: *If we now follow on with the second question: looking back over the development of our understanding of fracture since Griffith, what are the four or five major steps in that progress?*

Sir Alan: One can think of lots of steps. I would list a few of them as follows: One major step was the reaching of ideal fracture strengths in fibres of brittle substances and in rods of glass from which the natural Griffith cracks have been removed.

Another very important achievement was the extension of Griffith's theory to include effects of plasticity at the tips of cracks. This was done first by Orowan, who formally introduced a plastic work term into Griffith's surface energy. Later it was dealt with more comprehensively by a treatment of the crack in terms of dislocation theory, so that fracture theory could be linked up with plasticity theory.

A third important step was the realisation that in practice, more or less all fractures, even those in the most brittle substances, are preceded by some plastic deformation. I think that's very significant. A more practical step of great value was the application of crack theory in the form known as fracture mechanics to practical engineering problems (Irwin).

Another important step, was the realisation that plastic ruptures are not true fractures, but are forms of plastic necking and sliding-off. Yet another was the realisation that brittleness is not the same thing as fragility. The thing that the engineer wants to avoid is fragility and it is possible to have brittle materials which nevertheless are very tough; that, of course, is the principle which underlies the design of strong fibrous composites.

ICF4: *On that last point, do you think that such design was realised in a theoretical sense or was it something that came out of people experimenting with fibre composites? In other words, when did the realisation of the toughness, of what was supposed to be brittle material, arise as an experimental result? Was it really a theoretical prediction?*

Sir Alan: I think it arose as a theoretical result. Tracing back, you'll find that people were thinking theoretically along the lines of using weak interfaces as crack stoppers even before they had done much work on strong fibrous materials. Of course, staring you in the face all the time was wood and for some reason people never though about wood. It was too familiar.

ICF4: *This must have occurred also with wrought iron. To some extent the brittle fracture problem as such only came about when engineers stopped using wrought iron and started using steel.*

Sir Alan: Yes, but for some reason, people working in the theory of the subject didn't think about those things at all. They only began thinking seriously when they began to ask themselves what they could do with whiskers or strong fibres and it was such thoughts that led people to the principle that brittle materials can be tough.

ICF4: *How has it come about that so many good scientists have ended up working in the field of fracture, for at least some limited part in their scientific lifetime? It seems to me that a great many of the more notable scientists in the fields of Physics, Engineering and Materials Science and Technology have worked in some aspect of fracture.*

Sir Alan: Well, it's a very attractive subject. It obviously has a very practical interest because of big engineering failures and that sort of thing, but also it's a straight scientific challenge. What are the laws that determine the formation and growth of a crack? It's obviously something to do with atomic structures, so that, after the heroic phase of the 1920's when the theories of atomic structures were being built up, crack theory became one of the areas where one could apply these ideas, so that one virtually had both scientific and practical challenges in a field very rich in phenomena as well.

ICF4: *How much further do you think we ought to go in pursuing the theory of fracture?*

Sir Alan: It depends what you want to do. I think there are some areas of the subject which are not understood at all: a lot of fatigue, and fractures of that kind. We understand some aspects of fatigue fracture now but many of the others I think are still not understood at all, in terms of the the atomic processes going on. I think that's also true of some of the things to do with stress corrosion and corrosion fatigue fractures and some forms of the high temperature fractures, so there's a lot of atomic mechanisms which are still not understood, there, and if one is trying to build up a full atomic science of all these things there are some challenges. On the other hand, I think that for engineering design purposes, a lot of that may prove of limited value. It may well be that from the point of view of the design engineer we know what is useful to know about fatigue already: e.g., simply knowing that it is a plastic process and therefore you've got to make the stuff hard and particularly hard at the surface where the cracks begin.

ICF4: *Yes, that obviously is of value for initiation controlled fatigue. Clearly, a lot of structures have defects and cracks there already and one has to apply something which cannot prevent fatigue but can control its rate of growth.*

I think there's a number of small points I'd like to take up; if we just start with monotonic loading of cracks. Work that has been done has separated out the face-centred cubic ductile

materials and strongly covalently or ionically bonded brittle materials and we're still left with perhaps the most useful and interesting material of all: iron. Iron seems to come out as a borderline case in all calculations that have been done. Do you think that there is still an intellectual challenge here: to find out why iron behaves in the way that it does? Should scientific effort rather than engineering effort be put into this particular study?

Sir Alan: I think that the reason why it behaves as a borderline material is really a problem for quantum mechanics of the solid state rather than fracture theory. It's a matter of how the forces between atoms work out and some people find that a very challenging field to be in. I think it is an area where you can put in a lot of hard effort with not a great deal to show for it at the end of the day - that's a personal view! On the other hand, because iron is a borderline case, it shows an extraordinary richness of phenomena, there's no end to the variety of things that it will do! For that reason, it's a very rich substance to work on experimentally: just discovering in the laboratory all the various phenomena and getting them sorted and classified and understood.

ICF4: *But you think that, in terms of understanding of fundamental mechanisms, there's not that much further to go in monotonic loading; although fatigue is almost completely not-understood in terms of how atoms come apart?*

Sir Alan: Yes, that's a bit over-simplified but that is broadly the way I would see it.

ICF4: *Obviously where corrosive environments are involved our understanding is even more limited than in fatigue. One of the things we were talking about earlier is really what the aim of the game in fracture research is all about: whether we are trying to probe the fundamentals of the subject or whether our knowledge of fundamentals is sufficient for our purpose, and the attention of all these people working in the field should be taken towards application to engineering design.*

Sir Alan: Well, I suppose different people have different motives in the field: some would be in it as pure scientists, and I would have thought that, for them, parts of the subject are now complete. If they want to go on pursuing pure science then that should be done in the fatigue field and in some of the more complicated conditions of fracture where you've got to get down to corrosive effects as well. But for those who are interested in the practical side of the subject, I think that the great challenge is really turning what we know about the science of fracture into engineering design procedures. I still think there's a great deal to be done to work out a theory of how materials behave in service.

ICF4: *I think that, indeed, is where a gap is still in existence. You have outlined steps in the progress of our understanding of fracture and I think that those steps come over very well. But, suppose we were to rephrase the question in terms of the application of that knowledge to engineering design? Even* *if we take the fracture mechanics approach, the number of situations in which that can be precisely applied is really rather few.*

Sir Alan: That is true. The direct links between fracture theory and engineering design in operation are rather small. There is the fracture mechanics approach, which is but one link, but nevertheless it is a very good one, and fracture toughness is now used as a standard design parameter in lots of engineering designs. That is directly attributable to all the fracture research work. I think that, at present, all the rest of fracture theory does not get through to engineering design, but that does not mean to say that it is not useful, because it gets through to metallurgical design to provide better materials for the engineer to use. The whole business of getting fine-grain materials, fine microstructures, so that you can get great hardness without losing ductility, is again directly attributable to the theory because in the end that comes out of Griffith's equation. That has been another great area of application, although all the design engineer sees of that is that he's suddenly got some better materials than he had before.

ICF4: *Yes, and one can even go a bit further than just that. By a knowledge of the behaviour of things like inclusions and impurity elements, you can reduce the scatter in material quality.*

Sir Alan: Yes, that again is offering the engineer something of better quality.

ICF4: *I think that this is something of importance. I may be jumping ahead of some of the questions but there is certainly a tendency now: I think it comes out in Tetelman's paper and in the contribution that Wells made to the Rosenhain conference towards a probability approach to design, so that one ends up saying 'this has got a life expectancy', of whatever it may be and you get to the answer by multiplying a number of probabilities, like the probability of finding a crack and the probability of obtaining a given value of toughness. It seems to me that this is a useful diagnostic process because one can investigate what the effect of narrowing the standard deviation is on any of the parameters.*

Sir Alan: Of course, that principle has been used in the analysis of things such as nuclear pressure vessels. You go into the probability of detecting cracks of various sizes, the probability of the fracture toughness deviating and all that sort of thing and out of that you get an estimate of the chance of a failure during a lifetime.

ICF4: *In the long term you save materials because you're tightening up the engineering specification and you can get away with lighter sections. Although I don't want to jump into the topic of future research at the moment, I think that there is a point which ought to come through when one is looking at this. That is, where the effort should really be put? If one thinks of the parameters that are collected together in a fracture analysis: stress, toughness, defect length; then there are three fields of interest and we concentrate as metallurgists on material*

toughness and quality. However, look at the variability in that and compare it with the variability of say stress analysis in a structure where one doesn't know perhaps what residual stresses are acting, or the variability of non-destructive testing in terms of the accuracy with which you can measure crack lengths! It seems to me that we might be pouring more and more research effort into a field in which the benefits are smaller as time goes on and that one could pour the same efforts into other fields which would aid the engineer rather more.

Sir Alan: I think that, as regards more work on the fundamentals, if it's going to produce anything useful it will produce better materials. It may be that the more important work would be in applying what we already know to the production of better materials. You mentioned non-metallic inclusions; it may be that we could do more scientific work on how you get rid of the inclusions, or how you refine them. I think this will be physical/chemical research rather then fracture mechanics research. That is probably one example where there is useful work to be done. Coming back to engineering design, I would make again a point I made a little earlier, that the application of all this science to the development of a new science of materials in service is still a problem for the future. There are not many places where a respectable science in service exists and mostly it's just a compendium of empirical experiences and bits of know-how. Let me give you one example, it's not a fracture one but it's a failure one, where a proper understanding of materials behaviour has helped this significantly. This is in the theory of the plastic design of engineering structures. You mentioned a little while ago the business about internal stresses. A stress analysis of a complicated structure will not tell you what internal stresses are in it. The great thing about the theory of plastic design, however, is that it shows that in most cases it doesn't matter. You can work out the strength and stability of your structure by ignoring all the fine details and that rests on a sophisticated understanding of the stress/strain curve and the onset of plasticity. One feels that there must be other opportunities like this of applying what we now know about strengths, fracture and cracks and all that sort of thing. That's really an example of what I would call a proper science of materials in service. But I think that fracture mechanics and the use of fracture toughness is also an excellent example.

ICF4: *Yes, I think that comes in, even if not into the original design, which is on some plastic collapse basis. It certainly comes in to the assessment of the danger of defects which are subsequently found to be there.*

Sir Alan: I think that the things that will be useful to the engineer will not be sophisticated atomic theory. I don't see you handing the engineer something like a Schrödinger equation, which he will then plug in and work out as design. It's not going to be like that at all. I think the principles will be rather simple ones. I'll give you an example of a valuable principle that's come out of this; this is the principle of "leak before-break" in pressure systems. This again basically is another application of Griffith's crack principle. If the wall thickness is small compared with the critical crack length, then your system will leak long before it breaks - that's a valuable safety principle and I think structural engineers will become more and more convinced that they have to design that feature into structures where there are big consequences of a breakdown.

ICF4: *I wonder on that point if I could go back into history a little and probably quite unfairly ask for comments on the tests that were done at Risley many years ago with pressure vessels which are pressurized. They contained initially very long cracks which were then sealed, and at that stage pneumatic pressurization caused completely catastrophic failure although the material was well above its ductile transition temperature. Do you think that was a misleading set of experiments in terms of the dangers that really occur in pressure vessels and pipelines?*

Sir Alan: Well, I don't really know. It goes back a long time and I've forgotten the details.

ICF4: *The details are something like a pressure vessel of one inch wall thickness, 5 ft. diameter or something of that order, containing an artificial crack sawn in to the order of about a foot in length. This was then sealed with some aluminum foil or neoprene seal and what it enabled the material to do was start a fast running shear fracture at a fairly low hoop stress because there was a long initial defect. Even above the transition temperature, this gave rise to catastrophic failure. On a leak before break concept, presumably the initial defects would be less than wall thickness, in other words less than an inch to start with, and I think there's been a lot of recent discussion that the sort of results that were obtained with the artificially long cracks could not be obtained in normal practice with the sorts of defects that could be found in pressure vessels.*

Sir Alan: Yes, I think you're right. I think to that extent the cutting of the very long cracks and then sealing them up so they didn't leak is unfair to the material in that sense. You're suppressing the leak-before-break in an artificial way. On the other hand I think those tests do show in a valuable way that even well above the transition temperature a big crack running away is unstoppable.

ICF4: *Yes, that point is accepted, it's just that I wanted to bring it out at the moment because it is apparently something that doesn't mix with leak-before-break unless you think about it rather carefully. It was also the factor that I think was largely responsible for attention being paid to the prevention of fracture initiation rather than propagation. If we look at the list, may we take up the point concerning disappointments?*

Sir Alan: Well, again, I would say that I think the disappointments have been that we still don't understand a great deal about fatigue or some of the corrosion forms of failure even though there has been a vast amount of work done on the subjects. I think this is because these are processes at the atomic level where you've really got to see what is going on and we still haven't got instruments that will quite allow us to do that fully.

ICF4: *When you say we don't understand fatigue do you mean that we cannot simply rationalise it in terms of firstly hardening up microstructure by repeated to and fro plastic flow, and then being able to localise deformation along a specific slip plane; together with some gas adsorption or something of that nature which prevents complete rehealing?*

Sir Alan: I think there's a whole lot of things we don't understand. For example, there are problems in the work hardening stage, because we don't really understand why there is the localisation in specific active slip planes. Also, the oscillating mechanical system is geometrically reversible (I use the work "geometrically" because it's obviously not thermodynamically reversible) and ideally the atoms should all go back again. I'd say that there is some second order effect which is opening up a crack in the surface of these active slip bands and that is something else that we don't understand. Maybe we know the answer already but haven't proved it. It may be true that gaseous adsorption makes it structurally irreversible but we don't have a hard proof of that. It is just a good surmise.

ICF4: *And you think if that research is done we would stand a better chance of being able to advise the engineer on how to design against fatigue failure?*

Sir Alan: We might do. I don't hold out strong hopes on that point. But I think there are still other things that we don't understand about fatigue. The crack starts off down the active slip plane and then at a certain depth it turns away sharply, for some unexplained reason, and becomes the much more conventional plastic crack which I think we understand now. At least, we partly understand it, although there isn't yet an elastic/plastic crack growth theory that works in a rigorous mathematical way in the fully plastic range.

ICF4: *Yes, there's certainly been a number of attempts to carry over the simple models.*

Sir Alan: A sort of full post-yield fracture mechanics: you can go a little way beyond but you can't get into the full plastic range. I think there's a whole bunch of problems there. But whether the solutions of those would help in the question that was asked, I think is quite doubtful. I think we know enough of the qualitative principles to be able to see what you need to do to improve the fatigue strength of materials, but we can't get much beyond that point.

ICF4: *Yes, and certainly the local modes for the way in which a fatigue crack propagates in an elastic continuum with local plastic flow must be very similar to the way in which cracks initiate: there will be local sliding on slip planes inclined to the line of the crack front and the same sort of processes must go on there, and some experiments done in vacuum have shown that the cracks go a lot slower.*

Sir Alan: I think it's no criticism of those that have worked in the field that we still don't understand it. It's just a hideously tough problem where I think the vital events are so extremely localised and unless you get down there with some sort of super-microscope to see what's happening there's always doubt whether you've got the right picture when you form a theory.

ICF4: *But how do you direct that research effort to answer some of these questions? This raises the question of how you activate people to concentrate on those aspects where solutions are needed, or where the solutions you've already found need to be applied?*

Sir Alan: I think you have to distinguish between a pure science and its applications. If you know the science you can run large teams on the applications. I think that one could probably run a large team now and make good progress in developing what we call the science of materials in service. I think that if you're wanting to understand what's happening at the tip of the fatigue crack it's a bit like the cancer problem, in a way. If you run a big co-ordinated programme you may at the end of the day make no advance on it. I think the only way you can get at that sort of problem is to have a healthy university research environment and let people go round pretty freely to exchange ideas.

ICF4: *Yes, those obviously are the two extremes, I think if we move from the research to the politics behind the research, it's a question of the relative effort that one ought to put into letting people go their own way and in design.*

Sir Alan: This is an aspect of the much more general question of how much university research a country ought to do. There's nothing unique about fracture research in this. I think I might say that my own personal view is that too much "university" research is done these days. Not too much in money terms that is. I don't think the money expenditure is such a crucial factor. But university research is producing too many young men who have expectations of research careers that are not available to them afterwards. That's a great disappointment to them and it's why I think that we're overdoing the amount of "university" research at present. I don't worry about the money, because it is still relatively small compared with the cash flows through the other sectors of the economy.

ICF4: *It certainly seems to me, from a number of comments, that the thing that is lacking is the application of what is already known. We've touched on this already with regard to the fracture field and I'm sure it's true in a much broader sense than that.*

Sir Alan: That's right. A lot of university researchers are bred from the textbooks and the textbooks talk about atoms and Schrödinger's equation and that sort of thing. It's all so exciting; and

inevitably lots of research groups set out to do work of that same kind. There is a great lack of contact with industry here, and of course industry's not very helpful, because its so pre-occupied with its immediate problems that it can spare little for building bridges to the universities.

ICF4: *Do you think the situation between university/industry is worse in the United Kingdom that it is elsewhere in the rest of the world or do you think we're typical?*

Sir Alan: I suspect that it is much about the same in the USA. I think in Europe the situation is rather different, I think there's a different European tradition: for subjects such as this to be done in the applied institutes of technology, or technical universities where there is a much closer linkage with industry and a more practical approach to matters.

ICF4: *It's interesting that you think the situation is about the same in the States as it is here, because it is often held that the American academic has closer contacts with industry because he's forced to do consulting work and things of that nature. I have a question now which is, "how to teach a comprehensive knowledge of fracture to engineers in a modern university?"*

Sir Alan: It is a difficult problem, and I think the mistake is to teach it in the way that would be most interesting to people of one's own kind: to teach it as a pure science; to repeat all the steps of the argument by which you've reached full conviction that this is what happens: to go through all the evidence and analyse it critically; all the things whereby you become a good research man in materials science. That is not what the engineer wants at all. To the engineer a material is just a black box. He has to pay more money for it than he would like and he hopes it will accept the right inputs at one end and deliver the right outputs at the other end. That's all he asks of it: that there should be a satisfactory relation between its inputs and outputs and it shouldn't cost too much money. How you teach engineers in that case is a difficult problem, and the only way to teach it, I think, is as a form of intelligent engineering design rather than as advanced pure science. That means that they're not going to get a rigorous proof of some of the basic propositions of the subject but nevertheless I think that a lot of it does lend itself to a rather qualitative, even pictorial, approach. You can make very nice moving pictures of dislocations moving about and that sort of think, so that people can see in a qualitative way what's going on and immediately realise that it's reasonable, without having to go through all the mathematics of elasticity theory and checking to see if everything is going right. So I would say that the basic science should be done in a qualitative, illustrative way, and all the emphasis should be on teaching as an aspect of engineering design.

ICF4: *In that are you incorporating a description of the sort of polyphase, polycrystalline structure that one normally has for a material. My criticism in teaching engineers or in supervising engineers who are lectured to on the subject of fracture, is that they have a good knowledge of the basic equations: they know what K_{IC} is; but they have very little physical interpretation* *of it, so it's just a number they pull out of the hat and plug into the right equation. You calculate that you must not have cracks more than 11 mm in diameter, without actually realising that there are material variables that go in which mean that 11 mm isn't quite the safest number to have pulled out of an equation.*

Sir Alan: Yes, well this is another difficult problem. I think what bores the engineer stiff is to have a long exposition of the theory of microstructures and phase diagrams. We're talking about mechanical properties here; and polyphase material from this point of view is really a little engineering system; each grain is a linkage in the system: a nut and bolt in the system. Perhaps a useful intermediate step is an analysis of the strength and fracture behaviour of some of the composite materials because there the engineer actually puts them together: he puts the wires into the plastic and pulls it all apart. Its not so very different from working out what happens to a nut and bolt in a structure, so I think you can take that argument along and you can tell him, from that point onwards, when you have materials with natural structures in them, they're on a finer scale but you've got the same principles working.

ICF4: *But you do agree that he has to have some feeling for the microstructure even if its not from the thermodynamic/kinetic/phase diagram point of view?*

Sir Alan: That's right, and of course he needs it in his engineering: he needs it when he works out the strength of a bridge. He's got to work out the strength of the girders and the brackets and the nuts and bolts, the rivets and all that, so he's already got a "microstructure" to his bridge and metallurgical microstructure from his point of view is only doing the same thing on a finer scale.

ICF4: *One of the disappointments is that, for some reason, engineers are quite happy to do sets of calculations on fairly macroscopic structures and yet throw up their hands in horror when those things are reduced in size by a factor of about a hundred to talk about the parts of microstructure that really matter. I think it's because there is too much leading up to the microstructure in the way of phase diagrams and things of that nature which does bore them.*

Sir Alan: Yes, I think the thing to avoid is to take the engineer through the long story of how you get those microstructures, that's somebody else's job, but, given the microstructures as a *fait accompli*, then I think he needs to know something about how they work as engineering systems.

ICF4: *Yes, that's true and the importance of directionality and inclusions I think is about the limit in this area. I see that as being very safe when one is designing for the classical ductile/brittle situation, but if we took the cases you were talking about a moment ago - fatigue and creep - where there's the possible interaction with the plastic part, which can in fact disrupt that microstructure, then how do you get over the fact that you've got to teach him something about the thermodynamic stability of material: reversion and all that sort of thing?*

Sir Alan: I think in this case you've simply got to put down warnings to him and say "if you're getting into the high temperature range, or its a corrosive environment, you're getting into a dangerous game, you've got to bring other specialists in who will help you". In this sense he's a general practitioner: he's got to know, if he finds an acute case of kidney failure, that he's got to go to the renal specialist.

ICF4: *But surely that has been the problem in the past, he's gone to the specialist when an acute case has happened rather than before it happens. Very rarely have people of our type been called in at the design stage of a project. We're called in when Flixborough happens or something like that, to explain it from a materials standpoint afterwards.*

Sir Alan: That's right, you need some sort of information centre so that the designer can link up at an early stage, that he can say "I designed this to work under these conditions; it looks alright to me but I am not an expert on the metallurgy or corrosion or whatever, what do the experts say about it?"

ICF4: *How do you generate an infra-structure like that? How do you make him aware in the educational sense of how limited his knowledge is because students don't like being told 'you only know so much at this point, you've got to go and ask somebody else' and then, if you tell them that, where is this source of information that they go to?*

Sir Alan: Well, it all exists embryonically: a good liaison between the engineering professional institutions and the metallurgical ones should take care of that.

ICF4: *But I think bringing in materials people at the design stage is still a very hit and miss procedure.*

Sir Alan: It's done in the biggest projects, but in the more day-to-day matters there aren't the staff to do this.

ICF4: *There must I think be a degree of overlap between a materials man's training and an engineer's training so that, at least on their particular interface, they are speaking the same language and know what concerns the other person. It's a question of the degree to which this is done because I think in some of the older courses, we have seen metallurgy and engineering go along rather different routes, and the end products haven't been able to talk to each other at all. I don't know if you have any specific views?*

Sir Alan: I think this is right. The very old metallurgical training was really a kind of mining training rather than an engineering design training, so I don't think that there was anything for the materials man to say to the engineer then. I think a lot of the more modern courses have been training the materials scientists, and again I think he hasn't had much to say to the engineer because I think his outlook has been different. The engineer has got the practical problem; he's got to produce a design that will go into the drawing office in a couple of months time, whereas the materials scientist will say "We don't know anything about the behaviour of this material under that environment, we've got to stop and do research, and it'll be three years before I can say anything at all." This is hopeless for the engineer. The engineer has got to take his best chance with the thing and I think that this is where you need a new outlook in the materials line, an outlook that is much more sympathetic to the engineer's problem. The outlook has got to be that you find your satisfaction in helping to produce a successful design, rather than helping to understand some fact of nature.

ICF4: *Putting it very broadly, has it not really been that metallurgists and materials people have been concerned primarily with the making, production, and fabrication of their materials; the end point being the microstructures that are obtained, and then that material satisfying a number of, to them, fairly arbitrary criteria, like yield strength, U. T. S. These were fed in from outside and they could develop their material to meet those requirements, but they never asked the question why these requirements were needed. Is that fair or not?*

Sir Alan: Yes, I think that is a quite fair possibility. I think there is another quite different factor you have to bear in mind in this. The materials man has not found it really attractive to make a career in helping the engineer to design things. I think the materials man has known he would always be only an assistant in that kind of work. He would never become the chief designer and never become the head of the firm. It does not prove such an attractive avenue for materials people as some of the other careers.

ICF4: *Yes, I think that's an extremely valuable point. Nobody likes being in a position that can only end up as subservient.*

Sir Alan: So I think that a materials man who goes into the design side should really make himself, as well, a fully-fledged engineer so that he can have access to all parts of an engineer's career.

ICF4: *There are now some broad social questions and one of them is concerned with the view that society in general takes about failures and fractures: public enquiries and how much impact these have on public thinking, perhaps on the amount of research that is sponsored on fracture? There is also the question of how the senior political person, without any engineering background, responds to both real and perceived problems of fracture, and, generally, how the non-technically trained person should assess the risk of fracture and the needs of doing work or research or engineering design work to overcome it.*

Sir Alan: Well, the senior political person doesn't ever think about fracture from one years' end to another, and quite rightly so! He's got other problems on his plate and if he's going to think about things like fracture he won't be good at the job he has taken on. I think that the job of the senior political person, in this respect, is to make sure that the country has a good Health and Safety Inspectorate, or whatever the Inspectorate is called, and that it's working actively on all these things. I think also he

must give it strong moral support when it has to make unpopular decisions, because a health and safety inspectorate is under a very difficult set of working conditions. In a sense, the better he does his job the more unpopular he becomes. To be able to stop people in their tracks and say 'no you must not do that' he must have the backing of his ministers or whoever the authority is, otherwise his life becomes impossible. That is really the senior political person's responsibility - to see that there is a good safety inspection system that is active and, secondly, to be prepared to stand by them when they have to make unpopular decisions.

ICF4: *That's at the moment, but how does a political structure anticipate a problem of the Comet or Flixborough type and put the resources of the country to work? From the inspectorate point of view I can understand what you're saying: a sort of quality control along the line, and we need more of it; but how does a political structure, which, after all, in the long run, defines where the science and technology policy of the country goes, make sure that it's putting enough resources into the right sort of places so that situations like the Comet or Flixborough occur less frequently?*

Sir Alan: Well it doesn't try. It leaves all this to the professional institutions and, if a new type of aircraft crashes then ultimately it's because the designers in the professional institutions have not been fully up to the job: they've missed a few tricks.

ICF4: *Or is it because they haven't 'lobbied', for enough money to investigate that particular aspect?*

Sir Alan: On the whole, I don't think that is so. I think that it is impossible for the politicians to intervene in these things beforehand. I think that if they find that a certain part of the engineering activity of the country is causing a lot of trouble then they can intervene. With the box girder bridges for example - they set up a professional enquiry into that to see what's going on, raised questions about the standard of the profession and all that sort of thing, and at the moment I think the government is about to set up another enquiry into the education of engineers. This is the sort of thing that the politicians can do, but I don't think they themselves can get so far down into the technical "guts" of the country to anticipate these sorts of things going wrong. It's just impossible for them because fracture is only one of the million ways in which a country can go wrong.

ICF4: *And I think Flixborough and the Comet are really very different examples. Flixborough, despite what actually happened and the details of it, is basically due to a patched up repair job by a non-qualified person. The Comet, brings up another point. It was a modern aeroplane, designed properly, and being tested at R.A.E., but I think that, with any major advancement in design, there is bound to be some risk involved because you are stressing materials to a higher level than they have been stressed before. If you'd waited to do all your exhaustive testing before you brought it on to the market, you would have lost the market.*

Sir Alan: Yes, you're stepping into an unknown situation and this, in the Comet case, was the fact that each time the plane went up high it did another cycle of a fatigue test on the body. You can say, with the hindsight, that people should have thought of this and it's absolutely true, they should have done, but it's always easy to have hindsight. I don't see that politicians can do an engineer's job for him, they can only monitor a thing and make sure they've got an adequate engineering organisation and if it is inadequate this will show itself up in a run of failures and then they have to beat the big stick and improve the engineering profession, but they can only work in that sort of way.

ICF4: *We have two questions here that bear directly on this. I'll go through them both if you like - the first one is "What improvements could be made with respect to the extent to which society uses engineers and scientists to define and solve matters of great ecological, economic or sociological impact?" and then, more specifically, "What is seen as the future role of Standards Organisations and Professional Institutions in the rationalisation of the specification of materials and fracture behaviour from a design viewpoint?"*

Sir Alan: On the first question the initial thing you can say is the very general one that the engineering profession in Britain is at a rather low ebb. One can think of all sorts of reasons for it; to my mind the most important reason for it is that industry is at a low ebb, it's had such a battering from the government and unions and all this sort of thing, that it has little self-confidence now. I think this has affected the engineering profession as well and, until one has had several years of a governmental, political and social climate which is much more favourable to manufacturing industry in the country, I think you won't see the situation improve.

ICF4: *But is it just that? There is also the prestige point of view. We were talking earlier about the proportion of people doing fundamental research.*

Sir Alan: Well I think all that comes in as a consequence of it. I think that if we were going ahead with lots of great engineering ventures, as we started to do in the 1950's the situation would be different. Unfortunately the choices then were rather poor ones, but certainly in the early days of atomic energy, the early days of Concorde and some of the supersonic aircraft, they brightened up their branches of the engineering profession enormously. With more sensible choices then, we would have now a much stronger engineering profession. I think a lot of the problems raised there would have been solved in that way. So I would put that down to the general low state of morale in the engineering profession which goes back to the low state of industry.

ICF4: *Is that simply a British phenomenon? Is it different on the continent or in the States?*

Sir Alan: It is particularly pronounced in this country.

ICF4: *Have people lost pride in calling themselves engineers in this country more than they have in the States? On the continent the distinction is quite often lost and the engineer is also a*

Professor in an Institute and is highly regarded, and Engineer becomes the title you put in front of your name. Whereas Britain has the respect for science; the excitement about the 50's development in atomic energy was attributed to scientists as much as to anybody else.

Sir Alan: I think this country has partly lost the understanding of a need to work. The whole business of earning a living seems to be no longer a natural assumption in the country and I think many of the things we were just talking about really flow out of that sort of change of outlook. You had another question?

ICF4: *The second point, yes, was on the role of Standards Organisations and Institutions on the rationalisation of the specifications of materials and fracture behaviour from a design viewpoint.*

Sir Alan: I think this is important, because we're moving in a world where resources will be much tighter than they have been in the past. Populations are going up and we're beginning to exhaust some of the easier ores and energy sources. The result is that if we're going to get by we've got to skate on thinner ice, in our use of materials and facilities. That means that all these things are going to be so much more vulnerable to breakdown, therefore they've got to be quality-controlled and the monitoring and standardisation have got to be so much better in order that one can skate on thinner ice without falling through. The demands will be much higher.

ICF4: *But I think in rationalisation of the specification of materials as well, it is an odd feature perhaps in the way in which, shall we say, steels, have been developed in this country. There is a whole range of materials with very similar compositions and properties which are covered under a large number of different codes and where people may be working on almost identical materials because they're in different industries with very little contact between each other. It would seem that, if one could rationalise the structural materials that are being used, one could concentrate the research and design effort on to a much narrower range of materials.*

Sir Alan: There's certainly scope for doing this, yes. I think it's a thing we shall see before long: computer data banks for all these things.

ICF4: *Now we come back to the field of questions concerning brittle fracture and risk analysis and safety and things of that nature, related to the choice of nuclear reactors in Britain. I think that is seized upon as a single example of political thinking in this country, presumably this would be the case in Sweden as well, where a government was voted out on the issue of particular types of nuclear reactors. We would certainly welcome seeing you broaden your answer to that in the sense of relating to brittle fracture in the context of your other more recent expertise in the energy field: in terms of oil pipelines, gas pipelines and so on. You are one of the people who has preached a policy on energy, which I fully endorse, but one of the problems in many of the ways of acquiring and transmitting energy, is that one has to face brittle fracture questions. If you could perhaps broaden your answer it would be interesting to us.*

Sir Alan: I can't talk about the backgrounds of Government decisions of course, because of the usual rules about this. The Government decision itself, and I mean the most significant decision, was the one in July 1974 when the Secretary of State for Energy at that time announced the choice of the Steam Generating Heavy Water reactor. What he said, when he made that announcement, was that the Chief Inspector of Nuclear Installations advised that there should be no fundamental difficulties in giving SGHWR safety clearance. The reliability and the confidence that we can have in a system are of particular importance. So, in the way that governments move, it had considered safety very important when it made its decision. We do know that SGHWR is a pressure tube reactor and that pressure tubes have the fail safe principle in that they possess the "leak-before-break" feature in them.

ICF4: I think this had followed on, if I remember, from some correspondence in The Times and elsewhere?

Sir Alan: Well, I had expressed my views, that's right! That is different from a Government decision, of course. I had put the view that the thing I did not like about the pressure vessel light water reactors was that they did not have "leak-before-break". It seemed to me that, where the consequences of a major failure are as serious as they could be in a nuclear reactor, then one does need a natural safety feature of that kind; and that's why I argued against that system.

ICF4: Yes, I remember the articles, emphasising, if I recall, the need for the most stringent care being paid to fabrication techniques and to non-destructive testing.

Sir Alan: If you haven't got "leak-before-break" then the first thing you will know about such a failure is that the whole structure is coming apart. Nuclear technology is what someone once described as an 'unforgiving' technology: if you make a mistake, then it's a bad one! That means that, if you're going to dispense with a natural feature such as leak-before-break, then you're forced to the utmost precautions in your general standard of work. I think the specifications that the Americans have set for their water reactor pressure vessels are extremely rigorous, there's no doubt about that. If human frailty is able to achieve that degree of rigour in practice then they will be alright, but you must always have a question mark against human frailty and this is the thing that worries me. Whereas, with a pressure tube kind of reactor, again you have to be just as good as you can be against human frailty: nevertheless if you are let down by human frailty you've got a natural back-up - that's where the difference is and I still feel strongly about that point.

ICF4: Do you think, because of the emotive word 'nuclear', that most attention is given to the commentary you've just been going through on the nuclear reactor case, than is given in the equally worrying ecological case of having large pipelines running hundreds of miles across the bottom of the North Sea with large amounts of oil running through them where a split again could be equally disastrous.

Sir Alan: Well I think so, yes. My own position on that specific reactor problem doesn't reflect any sort of general position I have about nuclear power. In general, I feel that politicians and the general public are being taken for something of a ride by the environmentalist lobby which has being going very hard against nuclear energy. I feel that this is an extremely unfortunate development because the only assured new major source of energy for the world in the thirty years time or so is nuclear energy, and to turn one's back on that without very, very, good reasons could, I think, be a disastrous step for mankind. I think that the fossil fuel position, certainly in the western world, is really alarming. It's much worse than is said in the newspapers. We, in Britain, are locally in a good position for oil, since the North Sea will give us all we need, certainly for twenty years, possibly forty years; but if you go outside Britain into the rest of the Western world then the position is really alarming and we may already have left it too late. The only way out of the situation is the nuclear one. I think the environmentalists have served the Western world badly with their over-done campaign against nuclear energy.

ICF4: What I was really trying to get to, from outside, is that a double standard is applied because we're asking the nuclear world to fulfil these criteria of safety and I would thoroughly endorse those. However, it does seem to me that when we talk about laying pipelines along the bottom of the North Sea, where a major split; in terms of our fish, docks and so on; would be almost as disastrous as a nuclear reactor core going up, we're not asking for the same sort of stringent safety measures.

Sir Alan: Well this is true, and it's true of other things. A highly dangerous source of energy is hydro-electricity. You have the big dams and if a big dam bursts it could not only take out enormous acreages of ground but could drown large numbers of people. On the whole, a big dam bursts about once a year and these, as incidents, are large scale even by the standards of the worst imagined nuclear reactor incident.

ICF4: The next question is again a very general one but it brings us forward from the last point. What guide lines do you think should be established in public inquiries of major engineering failure?

Sir Alan: I don't know all the answers to that. On the whole I think that, when there is a major failure which gets into the public eye and produces a public inquiry, the inquiry is done fairly thoroughly, and objectively. The only point I would add to that is that it is important to have some experienced, technical people on the board of inquiry; not to let it get entirely into the hands of the lawyers. I think that these inquiries are conducted to a very high standard.

ICF4: Do you think the Boards, which are set up essentially, as I understand it, piecemeal, in this country are able to react quickly enough? In other words do you think there ought to be some semi-permanent national, European, or international organisation which can be called upon? If an aeroplane crashes, we have a standard routine that's gone into, with a group of people always waiting to do the job. Do you think now with large engineering structures in general, there's any need for some sort of world-wide organisation which can leap in and do the same job?

Sir Alan: I would prefer not. I think that for a particular incident, you're going to need particular men with particular expertise and they may not necessarily be in this group. It seems to me that the right way is if one of these big failures occurs and you've identified the very broad technical nature of the thing, to go to the most distinguished and independent people in the field. I think that's the best method of getting objectivity and authority into it.

ICF4: But, in aviation, there's a nucleus which exists continually and which can always have men on the ground who know how to take the right sort of pictures and record the data even if they can't interpret it.

Sir Alan: Yes, that kind of thing could be useful.

ICF4: Courses which pay attention to failures are very instructive, and it does seem that more use ought to be made of these failure reports as parts of the engineers education.

Sir Alan: Yes, they're very good indeed. They really challenge your basic knowledge and you realise what enormous gaps there are in it, and for practical teaching of the subject, examination of failures and diagnosing them is a very good exercise indeed. Perhaps it's a thing that is not practised enough in teaching departments but it is a very clear intellectual exercise: taking what clues there are in the form of a fracture: whether its one side of a pipe or another; discontinuous or marked in various ways; and deducing from that what's been going on in the failure. It's amazing how far you can go with a bit of practice in diagnostics.

ICF4: Do you think that that is the sort of intellectual challenge that we are looking for to encourage more people to come into Applied Sciences and particularly into Materials Science and Technology. In other words, is this the sort of case we ought to be showing as an example of our profession when we go and speak to schoolchildren?

Sir Alan: Well I think it would certainly fire their imagination, to show how one can analyse these things, because often the principles by which you make these deductions are pretty simple.

ICF4: And you're using sophisticated techniques, like scanning electron microscopy in order to record this sort of data. The thought processes are very similar to those in solving crossword puzzles or crime novels.

Sir Alan: And medical diagnosis. You have the symptoms and you've got to build deductions on them.

ICF4: Now let's have a look at the last questions. I think that we're confining it to the fracture field, and it asks what are the main areas that are in urgent need of development from the research point of view and from the point of view of educating senior political advisers? I think that we've touched on some of the research points.

Sir Alan: I'm not quite sure what is meant by 'educating political advisers'. I think you must mean permanent civil servants, Heads of the Civil Service Departments.

ICF4: I think probably it's assuming that these people will themselves be doing what in fact the inspectorates are doing.

Sir Alan: I would say that chief scientific and technical advisers must go straight to Ministers, concerning advice on decisions such as whether they should build an advanced passenger train, or get into the space programme, or whatever it happens to be. That advice should go straight to the decision makers and not be tampered with on the way, because if it goes to non-technical people on the way and is adjusted to their other considerations, then, because they're non-technical people, they will downgrade the technical aspects relative to the political, social and the economic aspects. They are bound to, because that's human nature, but when the advice gets through to the decision makers the technical advice will have been diminished in its importance. The only people who should rightly weigh the technical factors against all the other ones are the decision makers themselves: the Ministers.

ICF4: *How does the Minister, or the decision maker become sufficiently familiar with the technical arguments, so that he can weight them in a proper manner?*

Sir Alan: He doesn't, he has to trust his advisers; the advisers have to put it into language that he can understand. An adviser doesn't explain everything about brittle fractures etc.; he just says 'well if you build it in this way, there is a real chance of the thing breaking in the first ten years: in that way, the chance no longer exists", or something of that kind.

ICF4: *Is it possible to get this system working, or does it always get watered down by political and social considerations?*

Sir Alan: Well, I can only say in my own case that I delivered my advice straight to the Ministers. I think I would say one other thing here. As an adviser, you have to envisage all the main decisions or indeed all the main classes of decisions and you have to say particularly what the consequences of each of those will be, because the Minister will make a choice: he may ignore your advice in the end and he may not choose the technically best answer because the non-technical factors are overwhelming. At least, he must know the consequences of each kind of decision that he will make.

ICF4: *If I may just recapitulate a little on the first part of the question; the main areas that you believe are in urgent need of development? The field that you quoted before was application to the science of materials in service, that is the number one point, and that would then include the whole gamut of not only fracture and fatigue but presumably factors such as corrosion effects and fretting and all of those things as well. As an aid to assessing the relative merits, would you think that the probability type of analysis is of value?*

Sir Alan: I think so, yes, things do fail and you can't design a perfect structure. You've got to accept some possibility of failure.

ICF4: *If I may just look at one or two "supplementaries" - here is a question on "major new areas with regard to the development of high strength and toughness in materials over the next fifteen years". Do you think from the materials point of view that there is much scope for new materials.*

Sir Alan: I think the answer is more work on composites.

ICF4: *Then there are one or two questions concerning the state of fracture at the moment as you see it, questions directly on your examination of the contents page and papers of ICF4. Is the subject where you would have expected it to be tens years after leaving active research, in balance as well as content?*

Sir Alan: I think by and large it's at the stage I would expect, I think its gone forward a lot and its becoming much more of an applied science if you like, because the basic principles are increasingly understood and so one is getting down to the details of actual systems and how they work, I think there's one thing I am surprised hasn't been answered yet is why in so many cases of very brittle fractures the measured work of fracture comes out at a few times greater than the ideal value for the surface energy of the material. I would have hoped that with people working away at that for many years we would have had some enlightenment on that question. I think that is one of the few fundamental sore points remaining in the basic part of the subject.

ICF4: *Yes I think the situation has been looked at, in glass as I recall, by Marsh who tried to put up a physical model with movement of little ordered regions around the crack tip, the problem has certainly intrigued me in iron. Until one has really detailed ideas of the potentials and forces around in terms of atomic theory I think it's difficult to give a quantitative answer.*

Sir Alan: Yes, I think the obvious way you approach this question is to think that there is some sort of localised plasticity going on at the tip of the crack, even in the "completely brittle" case, and that somehow this plasticity reverses itself when the crack was gone past so that you see no traces of it at the end of the day. Certainly I struggled with that idea, some fifteen years ago, and it always seemed to me that if you confine it to that geometrically reversible stage then the amount of work you could get out of that effect was really rather small and you couldn't add more than perhaps 50% or so to the apparent surface energy of the material. If you tried to get a big plastic work out of that, say three or ten times the surface energy of the material, then this plasticity has to become far-ranging and would leave some permanent traces in the material.

ICF4: *We still don't have very accurate measurements of surface energy, do we?*

Sir Alan: That's true. If you put in the cleavage values, in general you would be putting in a value three or ten times the ideal value. But we know quite a lot about the ideal value. I think we know it to within a few percent, from pure theory, also from the high temperature experiments where you measure the stretching or contracting of wires with various weights on. These more or less agree with the theoretical value. Also you know the values of liquid metals and you know from general theory that the liquid value can be only say ten percent smaller than the solid value. So you can fix the ideal surface energy within ten percent I think. Those are the sorts of values I've always had in mind when talking about the ideal value.

ICF4: *If one could move a dislocation a couple of Burgers vectors on either side of the crack tip, this would produce an amount of work which if you took as being the incremental work for the fracture of each bond as the crack advanced, would give you a few times the surface energy. There is an energy hump which is reached after a couple of Burger vectors and what it seems you're doing work against is an image force. Once the crack tip has gone past and the surface unloads, the image force can pull them back out again.*

Sir Alan: The dislocation, in getting back, has somehow got to slip past the next dislocation which is coming forward out of the crack; and this gets into a very messy problem. I think the natural movement of the dislocations is to be repelled further away from the crack, by the other ones coming out. You're then onto full plasticity before you know where you are.

ICF4: *Yes, once you've got the second dislocation pushing the first one you reach yielding. The only virtue about this is that it can still be confined to within the core radius, as it were, at the crack tip.*

Sir Alan: It may be that you can get away with it on that basis; perhaps if one did some computer modelling of fracture to see what would happen.

ICF4: *Sir Alan, thank you very much indeed.*