HOUSE OF COMMONS

Science and Technology Committee

Oral evidence: Fusion, HC 230

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Watch the meeting

Members present: Greg Clark (Chair); Aaron Bell; Tracey Crouch; Dehenna Davison; Katherine Fletcher; Carol Monaghan; Graham Stringer.

Questions 1-106

Witnesses

I: Dr Nick Hawker, CEO, First Light Fusion, and Dr Tim Luce, Head of Science & Operation, ITER.

II: Professor Ian Chapman, CEO, UK Atomic Energy Authority, and Professor Steve Garwood, Professor of Structural Integrity, Imperial College London.

III: Professor Andrew Sherry, Chair in Materials and Structures, University of Manchester, and Dr Dame Sue Ion, previously Chair of the UK Nuclear Innovation Research Advisory Board.

Examination of witnesses

Witnesses: Dr Nick Hawker and Dr Tim Luce.

Chair: The Science and Technology Committee is in session this morning to look at the current issues in nuclear fusion. We are pleased to welcome our first panel of witnesses, including Dr Tim Luce, Head of Science and Operation at ITER, a major international fusion project that aims to build the world's largest fusion device. In welcoming Dr Luce, we should send our condolences to ITER, whose Director-General, Bernard Bigot, sadly passed away just in the last month. Please give our condolences to your colleagues. He was going to appear before us. We are very grateful to you for coming in his place.

Dr Luce: Thank you, Chair.

Chair: We are also pleased to welcome Dr Nick Hawker, who is Chief Executive of First Light Fusion. First Light Fusion is a University of Oxford spin-out that Dr Hawker established in 2011. We will hear more about the company. I will go straight away to my colleague Katherine Fletcher to begin the questions.

Q1 **Katherine Fletcher:** Thank you, Chair. Gentlemen, thank you so much for coming in. We appreciate that you are busy men and that your time is extremely valuable. We are grateful.

The reason we want to look at this is that it is almost "Star Trek"—let's have a sun in our pockets, or on the local industrial estate, and get unlimited levels of energy. It is a concept that we can all get excited about. The idea of it coming to fruition and generating energy that contributes to the grid has been 20 years away for many years. Are we really going to get to that point in a meaningful timescale, in our lifetimes, so that fusion can contribute to the energy solutions for this country?

Dr Hawker: Well, yes, I think it can, probably self-evidently, as I am working on it. There are a number of projects now that have very credible plans to solve and prove that the physics problem is solved in this decade. ITER and many of the start-ups are on that path. It is a difficult question to answer, however, because it is important to say that fusion is not what some people think it is, which is a silver bullet for climate change—because it is not. It will take time, and there are practical limitations to how quickly a new technology can be built out.

Q2 **Katherine Fletcher:** You mentioned the physics problem. Will you break that down for numpties who have biology degrees?

Dr Hawker: Solving the physics problem for me is showing more energy out from the fusion reaction than you put in to start it, which people call "gain" and "energy gain". At the moment, that has not been demonstrated experimentally.

The two main streams of fusion technology are magnetic fusion and inertial fusion—that is the first flag I am waving here, because I am from the inertial fusion world. The level of proof is similar for the level of gain shown in the two different approaches: they are both 0.7—so, put in 100% energy, get back 70% energy. That is obviously not what you need for power production, but for me crossing that line and showing more energy out than in is solving the physics problem.

What you need to do for power production and cost-competitive power production is to exceed that, but there is a physics change that happens, which is that you get this thing called "ignition", where the plasma self-heats and kind of bootstraps itself. You are not just putting a blowtorch on a log and, when you take it off, it fizzles out; it actually burns and keeps going, sustaining itself. That has a different character in magnetic and inertial, but it is the same thing—achieving the self-heating, this ignition.

Q3 **Katherine Fletcher:** It is definitely something we want to get into. The purpose of this session is to understand where we are with the technical challenges. To answer that headline question of whether we are 20 years away, would you say yes?

Dr Hawker: Not from the physics proof. The physics will be solved—as in we will show ignition; show burning plasma states—this decade. I think we will have a power plant in the 2030s—a pilot plant—and cost-competitive fusion power in the 2040s, but at small scale. We are not suddenly going to supply all our electricity needs from fusion in the 2040s. We still need solar; we still need wind; we still need all the sources we can get.

Q4 **Katherine Fletcher:** Brilliant. We do not have time to get into that this morning but thank you. Dr Luce, may I ask you the same question? Is it 20 years away?

Dr Luce: I think the question is what is "it"? As Nick said, there are three frontiers. The first frontier is the scientific, as he said, with break-even and energy gain. Our goal in ITER, in our baseline schedule, is to achieve that in the next decade. We will start operations in this decade. In the next decade, our ambition is to show a gain of 10, which we think is correct for a power plant scale. If you think of thermodynamic efficiency, you need about a factor of three, at least. That will get us demonstration at the power plant scale.

The next frontier that has to be broached is if you draw a circle around the plant, you have to send energy out and not in. ITER will not do that; it is not designed to do that. The next generation of plants will have to do that. When that next generation comes is exactly a decision for you folks, or for private industry when they are ready to invest in that next step.

The final frontier is that those plants have to live long enough to pay back the energy you put into them. If you remember, the original solar cells were degraded by being in the sun—we are very familiar with that—and they did not give back as much energy as it cost to make one. The same is true for any type of power plant. That is how you pay off the bills: you have to sustain the energy for enough time to pay back the energy you put in. That is the next generation.

It is a matter of the investment profile that determines how quickly we go beyond ITER or the first generation of inertial fusion that shows proof at the power plant scale.

Q5 **Katherine Fletcher:** Right. If I understand you correctly, we are roughly somewhere around 10 years off proving positive energy output. We then have a series of technical challenges to actually harness and make the energy useful for us at scale. That could be in 10 years, but those are almost unknowns at this stage.

Dr Luce: I would not say that they are unknowns; I think we know the topics that have to be addressed. What is unknown is the taste for investing a sufficient amount to achieve those in a timely fashion.

Q6 **Katherine Fletcher:** Understood. I would imagine that the investors would say, "We can't invest in something until the physics problem, or the proof of concept, has been solved."

Dr Luce: Governments and private investors are risk-averse in that sense; they want return on investment. Any technology—be it energy or something else—has to cross what is called the valley of death for technology. Between showing that it works and economic acceptance, there is always an investment path that does not guarantee instantaneous return on investment.

Q7 **Katherine Fletcher:** Let's try to help close that valley. You have a tokamak. Would you briefly describe it for the uninitiated? What is ITER's status?

Dr Luce: There are two aspects. One is what a tokamak is, and the other is our status. On what it is, first we have a vacuum chamber. That is where we place the hydrogen to make the fusion reactions. To contain the energy, we need strong magnets, and we are using super-conducting magnets. The extremes are within the plant. In our way of doing it, the fusion reactions go at hundreds of millions of degrees.

Q8 **Chair:** Dr Luce, just step back a bit further than that. For people who might be watching proceedings and who do not know about fusion, could you describe what fusion is before saying how we can accomplish it?

Dr Luce: You may remember the periodic table from your school days. There are a number of elements, and they are ordered from light to heavy. Fusion takes the lightest of the elements, hydrogen—it turns out there are three types of hydrogen, and the easiest ones to put together are the ones that are not most found in nature: deuterium and tritium. They are easier to put together, and that is why we call it fusion: we are fusing them. When they fuse, there is less mass than when you started, and the famous formula from Einstein—energy equals mass times the speed of light squared—gives you a tremendous amount of energy from a small mass change, because the speed of light squared is a huge number. The energy comes from converting mass to energy by a nuclear reaction.

That only happens, in both of our cases, in extreme conditions. We make the extreme conditions by making a rarefied gas very, very hot.

Q9 **Katherine Fletcher:** For the record—and for my niece and nephew—the sun is doing that on its own. In nature, the sun is crashing elements together—starting small and make it bigger and bigger—and you guys are trying to replicate the sun.

Dr Luce: We are trying to replicate the energy source of the sun, but the sun does it because it is enormously big. We cannot get away with that here; we have to do something else. As I said, we are making a rarefied gas very hot. Nick will tell you about how they do it, which is making something dense not quite as hot. To sustain these conditions, we need a very strong magnetic field and we need good vacuum conditions.

Q10 **Katherine Fletcher:** Is it a doughnut that you are creating?

Dr Luce: Exactly.

Katherine Fletcher: Just describe it.

Dr Luce: Okay. As scientists, we use a more elegant word—torus, which nobody really understands—but yes, it is like a standard doughnut.

You wonder how you can have 100 million degrees here and at the end of the table it can be absolute zero, and the answer is very good insulation. The magnetic field allows us to keep the energy in to keep the reactions going. As you well know, there are two things you can do with insulation: you can buy better insulation or you can buy more insulation. The strength of the magnetic field determines the quality of the insulation, and then you are left with making a bigger device, for our scheme, in terms of fusion.

We are using technology that had the highest technical readiness level when we started the design of ITER. There are other people looking at designs that have even higher magnetic fields, but that set the scale of the device. The ITER device sits in a large Thermos bottle that is about 30 metres in diameter and 30 metres high. From that, we can make 500 MW of fusion energy.

On the status of where we are—you asked about the concept and then the status—

Q11 **Katherine Fletcher:** Yes. So part of the physics problem is the amount of energy that it is taking to create the electromagnetic fields that form the outward rings of the doughnut. Is that part of the challenge—because the insulation has energy requirements as well as the actual reaction?

Dr Luce: Secondarily. We use a superconducting magnet, which doesn't expend any energy in its operation, but we have to maintain absolute zero conditions to keep that superconductivity, so there is a secondary effect of the plant. We have a very, very large refrigerator, because we have 25 tonnes of liquid helium circulating.

Q12 **Katherine Fletcher:** Oh, of course. What temperature is that? How many kelvin?

Dr Luce: It is 4 K.

Katherine Fletcher: Wow.

Dr Luce: Yes. But that means we do not expend any operating energy in the plant itself. You could do it with copper, but it would be extremely expensive from the operating cost point of view. That is what present facilities, like the JET facility in Culham, use. They use copper-based magnets, because they are pulse devices.

Q13 **Katherine Fletcher:** Right, so if you take a motor apart, there are copper wires around it that help generate a field, whereas you are using supercooled magnets, which do not actually need energy around them but they need to be very cold to work, so you have to take all of the heat of the day out.

Dr Luce: Correct.

Q14 **Katherine Fletcher:** Wonderful. So how are you getting on at ITER? What is your status?

Dr Luce: Two years ago, at the beginning of the pandemic, we launched the assembly. The Thermos bottle—we have now put the two bottom parts into the facility where the tokamak is being built. We have put two of the six coils that are necessary to shape the plasma there. We put the first vacuum vessel sector of nine, just two weeks ago, into the bit.

Q15 **Katherine Fletcher:** You are miles smarter than me. So you are building bits of the doughnut up. You can create the whole of the doughnut shape.

Dr Luce: Imagine an orange. We have put in the first slice of the orange. We have eight more to put in.

Q16 **Katherine Fletcher:** Super. Fabulously helpful. So it is quite a distance off test running at scale. ITER is bigger than the previous ones. Is that correct?

Dr Luce: Correct—yes.

Q17 **Katherine Fletcher:** By what scale?

Dr Luce: I believe it is about a factor of—let me be careful. I think it is 1.7 above JET. The magnetic field is higher. That one I forgot to prepare. I know the numbers, but I'll have to think about it. The volume is about 10 times JET—let's say it that way.

Q18 **Katherine Fletcher:** So what is the purpose of the programme? To recreate JET and expand it? But what is that for?

Dr Luce: There are two key elements. We need to demonstrate at the power-plant scale that the science works. The frontier that we haven't crossed yet is one of the things that Nick was talking about. In his field, they call it ignition. We call it a burning plasma—that the heat from the reactions sustain the reactions themselves. That has not been crossed, because we haven't made enough fusion power compared with the power that we have put in, so far.

Q19 **Katherine Fletcher:** I understand you. So, basically, you need a certain scale of stuff—all the atoms with their electrons stripped off running around—to generate sustainability. It is like when a fire burns out—you need to just have a certain scale for it to run.

Dr Luce: Yes. For the magnetic concept, it is sort of like a wet wood burner that you could run continuously but, unlike the fireplace, you get more energy out than you put in.

Q20 **Katherine Fletcher:** Okay. So that is not a small technical challenge.

Dr Luce: No.

Q21 **Katherine Fletcher:** I understand you have had a couple of challenges that have come up, with safety, and it was on hold. Could you talk to us about that?

Dr Luce: It is incorrect that it is on hold. In the formal sense, when the regulator gives you a "stop work" order, that is a very serious thing, and that has not been done. We are in the course of a normal regulatory process. When we did our preliminary licence from the French regulator, the regulator established a series of hold points, because they want to ensure that we have achieved a certain level of technical readiness before they allow us to proceed, because they do not want to be held hostage by us taking decisions that cannot be reversed if they think that they do not comply with the safety case.

Q22 **Katherine Fletcher:** Fair enough. You can understand why the public worries about mucking around with things like suns.

Dr Luce: Exactly. The French safety regime is a bit different than in other countries. It is demonstration-based, not rule-based. We are the first of a kind. This is one of the advantages and disadvantages of being at a demonstration. We can try new things there, in a sense, more easily than in a rule-based regulatory regime, because you do not have to establish the rules without knowing what the game is. On the other hand, in the demonstration case, you do not have certainty of when you have achieved the demonstration. It has to come by assent from the regulator. We are in a normal process where they have told us, "No, what you have delivered to us isn't sufficient; we need some more information." We are in that process. They have asked us to not take any irreversible steps in the assembly of the machine, which we are not and we are not scheduled to, while we settle the outstanding actions in the regulatory file.

Q23 **Katherine Fletcher:** Is it a safety issue that they are concerned about? Help me understand. We won't go into lots of detail. You have reached a natural pause—you need to demonstrate something. What do you need to demonstrate?

Dr Luce: There are two issues that the regulator is concerned about. The first is that the vacuum chamber itself is also the primary containment for radiological materials.

Katherine Fletcher: Right, so if it goes boom, the box needs to hold it.

Dr Luce: We wouldn't say it that way, because it cannot go boom. This is one of the advantages of fusion, that we only have one second's-worth of fuel in the device, so there is not a potential energy. If you look at a fission reactor, there might be a year's-worth of fuel there. It is a very different potentiality. We do not have that issue.

Q24 **Katherine Fletcher:** Yes, but anyone who has opened a crisp packet at altitude knows that changing pressures—it is a pressure vessel.

Dr Luce: Exactly right. It is a nuclear pressure vessel. The outside shell—there were manufacturing non-conformities in a small fraction of those and we have to demonstrate how we are going to accommodate that in the welding scheme. It is a natural thing when you are welding pressure vessels.

The second issue is that the building itself is the secondary containment. We always have defence and depth for the public. There was a question about whether we were going to add additional shielding for the workers, and whether that shielding could compromise the integrity of the foundation in an extreme event—for example, would a Fukushima-type earthquake compromise the secondary containment? Those are the questions that we have to answer.

Q25 **Katherine Fletcher:** So it is not actually about the reaction itself, the sustainability; it is about translation into the real world.

Dr Luce: Right, because our safety case is basically confinement of radiological materials. The reaction itself is contained by shielding, and this shielding is sufficient.

Katherine Fletcher: That is incredibly helpful, and I have taken lots of time, so thank you.

Q26 **Chair:** That was a very helpful introduction that answered a lot of questions. You contrasted the regulatory regime under which you operate with a more rules-based approach. Which jurisdictions around the world operate a more rules-based approach?

Dr Luce: I am not an expert in nuclear regulation, but I think the US and the UK, for example, have a more rules-based approach, because they are regulating third-generation devices and so have a familiarity. But this is not my area of expertise.

Q27 **Chair:** Do you have a view as to which is the better environment in which to develop your technologies?

Dr Luce: The better environment is the one that the public accept.

Chair: Very diplomatic. I think Tracey Crouch has some questions for Dr

Hawker, and then we will go to Dehenna Davison.

Q28 **Tracey Crouch:** Before I ask my questions, I think you had your hand up, Dr Hawker.

Dr Hawker: I was just going to say that, last year, as the Committee is probably aware, BEIS published a Green Paper on thoughts on future fusion regulations in this country. I understand that the recommendation is that, proportionate to the actual risk profile, it should not be regulated by the Office for Nuclear Regulation. First Light responded to that Green Paper with a contribution. I would say that in the UK at the moment it is not defined, but there is a direction, which is either to say that it is within the scope of exiting bodies, such as the Environment Agency and the Health and Safety Executive, exactly as Ian's facility is currently regulated, or possibly it is a new body, but not the existing nuclear regulator.

Q29 **Tracey Crouch:** I am a new and shiny member of the Committee, and already I wish that you guys had been my science teachers at school. I think that one of our Committee's roles is to demystify some of these issues. Dr Hawker, could you just explain how the technology that First Light Fusion is developing works and give us an overview of the progress to date, please?

Dr Hawker: Absolutely. We are working on a new method for inertial fusion. Inertial fusion is different in character from magnetic fusion. I often say that magnetic fusion is like a furnace—an analogy that has been used already. Inertial fusion is more like an internal combustion engine; it is a pulsed process where you put in some small amount of fuel, and you have something equivalent to a spark plug for triggering that fuel to burn and release a pulse of energy. For the power that you generate out, you can either go twice as fast and make twice as much power, or you can have twice as much energy per shot and have twice as much power.

We are working on a new approach to inertial fusion where we have a different spark plug, which is a high-velocity projectile. The established way of doing it is to use a high-energy laser as the spark plug. There is a complicated piece, which is that the laser shines on a target and our projectile hits a target. The design of the target is very different to make either of those two system work, so our key technology is in the target zone.

In terms of progress, I will talk about us first and then mention the largest inertial fusion project in the world. We have been working towards an experimental demonstration in the lab showing fusion from this process for the first time, and we did that late last year, confirmed it earlier this year and then announced it. This is a fundamental proof of concept that the projectile approach can work and that you can make conditions for the fusion of these targets. We have been saying for years that these work, and now we have shown that they work.

That is a very low amount of energy. For us, it is about the proof of concept and showing that our simulation tools are accurate. We are on a journey. The National Ignition Facility is the largest inertial fusion facility in the world; it is the biggest laser in the world. They had a breakthrough result last year where the number that I mentioned—the gain—jumped from 5% to 70%. They are getting very close to that threshold of getting a gain above 100%, or greater than 1, depending on how you define it. I think they are going to get there and demonstrate that this year or next year.

Q30 **Tracey Crouch:** That is really interesting. Now that you have proof of concept, what happens next, and is there a timeframe in the process of "what next"?

Dr Hawker: We are now designing our own gain demonstrator. It will be a new machine that launches a faster projectile with more energy. The aim of that gain demonstrator is to solve the physics problem and demonstrate ignition/burning plasma. We are still going through the work of detailed planning for that, but the timeline is that that machine will be operational in the second half of this decade.

In terms of the onward path from there, you asked about the engineering challenges. I think that a lot of the start-ups are benefiting from the work that has been done in the mainstream to understand the issues and questions. It is remarkable that it is such a complex technology yet there is so much flexibility and so many different solutions that could meet the requirements. There is this duality of challenge: the physics challenge and the engineering challenge. All the start-ups are in some way, shape or form wondering about changes from the baseline understanding that has gone into ITER or the National Ignition Facility—making a change and making it as small as possible so that the physics stays as close as possible to where there is most knowledge but getting maximum benefit in terms of the engineering solutions. So, a lot of the issues don't apply to the same extent with everyone's design, if that makes sense.

In focusing on regulation and, by implication, the radiological hazard posed by fusion, we believe it is possible, with our plant design, to keep the levels of tritium inventory, which is one of the main radiological hazards, less than the amount that UKAEA currently has on its site. It is a power plant, yes, but it is within the bounds of what is already accepted and regulated in a particular way. To do that, though, we have to be on a path. Less work has gone into that, so it is about looking for the opportunity and trying to solve the problem.

Q31 **Tracey Crouch:** With that in mind, do you think that the UK should focus more on developing these kinds of technologies?

Dr Hawker: I think we have a huge advantage in this country. There is a very great depth of knowledge, talent and expertise in fusion. Also, in our view, it seems like a very good place to try to build a fusion power plant, again because of the skills and expertise, and also because of the energy situation. There are countries in the world with a lower electricity price than we have. We are an established nuclear nation, with civil nuclear power and all of the supply chain and skillsets that we have for that. There is potential for a huge advantage for the UK. This could be a real area of strength.

There is already a huge area of strength in magnetic fusion. In inertial fusion, there is great academic excellence, but its level of funding and support in this country is not the same as that of magnetic fusion. That is potentially an opportunity where more could be done.

Q32 **Tracey Crouch:** Forgive my ignorance. I grew up near Dungeness. Does a fusion power plant look like a traditional nuclear power plant?

Dr Hawker: I hope not! The size is the question. A lot of the engineering challenges get harder the bigger the plant is. Most of the start-ups—ours included—are trying to work towards a smaller plant size. A smaller plant size will look a lot less imposing. We are working towards 150 MW electrical as the pilot plant size, which is a tenth of the size of Hinkley C, for example.

Q33 **Dehenna Davison:** Thank you both for being with us today. I must admit that before reading papers in preparing for today's session, the only time that I have actually heard the phrase "tritium fusion reactors" was in the "Spider-Man" movie, so forgive me any ignorance in any of the questions that I am about to ask. Dr Hawker, you mentioned the funding landscape and how inertial fusion tends to be less well funded. Why is that?

Dr Hawker: It is very well funded in the US. There is an adjacency between some of the science in inertial fusion for power production and stockpile stewardship. An acknowledged part of the field is that that presence is there. For a long while, we were the only inertial fusion start-up. There are now five or six of us with different approaches.

To offer a critique of inertial fusion in a fair way, the magnetic fusion world is ahead in articulating the challenges of building a power plant and what you would need to do—the road map—to get to that power plant, whereas in inertial fusion, although there has been a lot of work, a lot of it is very old. The plant design in literature closest to our own—the main reference for it—was published in 1995, which was the year I was born, so it is a lot older. That might be part of it: the inertial fusion community have not necessarily been as clear as they could be about the pathway to a power plant.

There are common issues, and there are issues that are unique to both. It could be that the inertial fusion way is easier; it has the potential to avoid some of the problems.

Q34 **Dehenna Davison:** I think you must have read my mind, because I was going to ask about viability. We have been talking about getting reactions to the point where they are producing more energy than they are consuming, which is clearly the first step. Obviously, there are then a lot more challenges in making that viable for mainstream energy production so that you can flick a light switch and the energy powers the light. I will stick with you for the time being, Dr Hawker. What are the key technical challenges to address between now—day zero—and mainstream energy usage? I appreciate that that is a big question.

Dr Hawker: I think the challenges are quite clear, really. I always describe three big engineering challenges. There is how you produce enough tritium. The plant has to produce its own tritium, and that can be challenging. Because of the nuclear reactions used to do that, it can be challenging to close the fuel cycle and produce more tritium, or just enough tritium, and not just consume it.

There is the heat flux challenge. You have this incredibly hot plasma—a very high-powered entity—and any material facing that sees a very, very high heat flux. Then, there is managing the neutron damage. Four fifths of the energy from the reaction comes out in the form of neutrons, so it is a very high flux of neutrons—lots of energy of neutrons—and individually the neutrons are high energy, which means that they are different from the neutrons you have in fission, so that is slightly different in the technological challenges.

Those are the three big challenges. In terms of solutions for them, as I have alluded to, there is an establishment way of doing that, and then there are people trying to think creatively about avoiding those challenges. We are very much in the camp of trying simply to avoid them. We have what is called a liquid first wall design—there are quite a few of us with that kind of design—which in one fell swoop can avoid all three of those challenges. Basically, the thing surrounding the plasma is not the vacuum vessel wall—that is not the first thing that the energy coming off it sees. We have the coolant flowing inside the vessel, so, on the heat flux challenge, if you vaporise the inner surface of that flowing liquid, it doesn't matter—it just recondenses and then, in an inertial fusion world, you reset and do it again, you fire again—

Dehenna Davison: So it can just be recycled.

Dr Hawker: Yes, it can just keep going around.

We are trying to keep our solution within existing materials and supply chains. We believe that we can do that, so we can meet the challenges while using only already known and qualified nuclear steels, and our liquid—this liquid first wall—will be pure lithium in the natural isotope balance. It is really hard to explain how profoundly important that is. There is a supply chain for that, which is enormous—it is the supply chain for batteries—whereas if you need to enrich your lithium, you are going to have to build a supply chain to supply enough. I'll stop there.

Q35 **Dehenna Davison:** Some of that was a bit above my head, but I appreciate the run-down. Dr Luce, are there similar challenges in magnetic fusion?

Dr Luce: Nick identified three of what I would say are the four challenges. The specific challenges may be different in quality, but they are the same areas, and really tritium is the first. ITER will explore some of the technologies for making tritium and closing the fuel cycle, but it won't actually be able to do it. This is a key frontier for going forward with fusion of any type—closing the fuel cycle, and making it viable at a large scale.

The one thing that Nick did not mention is remote handling. Inevitably, there will be things that have to be dealt with in the plant during its lifecycle. You wouldn't want to discard a plant simply because of one small failure; you have to be able to go in and repair. I believe that the remote handling technology—and the compatibility of the fusion technology with remote handling—is a key aspect.

That brings out the differences between inertial and magnetic. Magnetic is focused on a more stationary power plant type of condition. The structural material issues and the first wall materials are different, but they are still challenges—we have equal challenges. For high efficiency, you would like high working temperatures, and that is a challenge for any structural material with neutron damage. It may be that there is some magic and that they are self-healing and annealing—materials are very fascinating and not yet predictable in terms of how you would actually tailor-make something for a specific application. There is a very big opportunity to research materials that could provide benefit across a broad spectrum, but specifically benefit fusion, if there were a significant investment there.

Q36 **Dehenna Davison:** Neutron damage just completely breaks down the structure of a material—is that correct?

Dr Luce: There are two aspects. Yes, it can change things, but you can also get helium formation inside the material, so you get bubbles. But as you can imagine, if you could work at high temperature, the material would sort of self-regulate that effect, so there are opportunities. There are also the liquid metal approaches. Those have some challenges for a more continuous system, but people are exploring them.

Q37 **Dehenna Davison:** This is the killer question, which you might not have direct answers to: when do you think these challenges are likely to be overcome? Are we talking 12 months, 10 years, 50 years?

Dr Luce: Likely. Again, it comes back to the investment path. We have concepts that would get us to a first generation. That would have to be demonstrated as economically viable. Mostly, it is lifetime issues. It comes back to what we were talking about with the valley of death for technology. Any technology has the teething issues in getting through the first generation. Likelihood is a difficult thing to predict without knowing the driving factor, which is investment. I could say unequivocally that those two things are correlated. If we don't look, we won't solve.

Dehenna Davison: Dr Hawker?

Dr Hawker: I just want to acknowledge that I think there is a fourth challenge of remote handling. At First Light, we have accepted a remote handling challenge, which is basically how we put the projectile into the machine accurately, repeatedly hit the target in the required location and then take the spent cartridge out. We have a remote handling challenge. I think that we can de-risk that system in parallel with the gain demonstrator—they can be separated and de-risked separately, I think.

I do not think that laser inertial fusion has a remote handling challenge; it is light and there are no moving parts. It has a different challenge, which is that the laser technology at present is just too expensive. It is too expensive to get to a cost-competitive power plant without having other compromises. You can get to a cost-competitive power plant with laser fusion, but it has to be between 1 GWe and 2 GWe. Our plant will operate once every 30 seconds; they are going to have to do five times a second. It is possible with the laser costs where they are, but if laser costs were to fall then inertial fusion plant design would go up substantially.

Q38 **Dehenna Davison:** Just quickly on the remote-handling challenge, is it that you would effectively need some kind of robot to put the stuff in, but getting a robot-type thing to operate under the conditions is the challenge? Have I completely misunderstood that?

Dr Hawker: You are probably better at answering this, Dr Luce.

Dr Luce: We do need mechanical means to assemble the device, but that could be a one-off. There are certain sensors that are needed to operate the facility and if a key one was to break, you would need to go and replace it. That environment is not a place where a human should be working for the time necessary. You have to be able to take it out, move it to a facility, handle it and then put it back in. Even inside the tokamak itself, if there was some local damage or a manufacturing error, again, you do not want to throw away an entire plant because there is one small manufacturing flaw. You have to have the capability to go and repair something.

Chair: Thank you. We will have to speed up to be able to accommodate our next witnesses.

Q39 **Aaron Bell:** Thank you, I will try to be quick. Moving on to the future landscape—I think Dr Hawker alluded to this at the beginning—based on what you have both said, is it fair to say that we should not be counting on fusion to help us reach net zero by 2050 in the UK? If there is any benefit from fusion at all by 2050, it will only be marginal—is that a fair assessment?

Dr Hawker: I can take that, as I brought it up. I think that fusion is necessary, but it is not sufficient. We cannot delay on taking action now because we think that fusion is going to happen and solve the whole problem—I do not think that is realistic. However, our view of the future of energy is that there is a big problem, and it is about how fast we can build solar and wind—how fast we can build renewables. In my view, it is not a problem of cost because they are already the cheapest option. There is a debate about intermittency and how much of an issue that is. Fine—that translates as an extra cost for managing the intermittency. I think that challenge can be solved. It raises the overall system price, but not intractably.

The problem is getting to the scale we need. It is a moving goalpost. If you look at the projections, you think, “Okay, great, we are going to get to a certain level of electricity production from wind and solar.” However, it is a dual challenge: we need to build out solar and wind, but we also need to electrify other massive sectors of the economy, such as transport. The demand for electricity is massively growing as well. There is a gap, basically—we do not have the technology we need.

Q40 **Aaron Bell:** I will come to that in a minute, but by the 2050 date you do not expect fusion to be making a significant contribution to the UK being net zero?

Dr Hawker: I think there will be fusion power plants being built in the 2040s.

Q41 **Aaron Bell:** There will be fusion powerplants being built by then, but we need to do other things as well.

Dr Hawker: They will not be supplying 100% of our electricity.

Q42 **Aaron Bell:** Dr Luce, if I have understood rightly, ITER is not expected to produce electricity for the grid at any point. There is a subsequent EU DEMO programme that has first plasma in about 2055. Is that correct?

Dr Luce: I do not want to comment on the EU road map, but yes, all the members—or the groups of members—of the ITER project should, we hope, have demo plants ready to go in future. In terms of 2050, though, I think it is simple-to-do math: the UK average energy electrical usage is 30,000 MW continuous, so to make a 10% effect, you would need about 6,000 MW electric fusion plants. Are we going to build that in 2050? I think the answer is clearly no. We do not have the industrial capacity or the fuel-making capacity to do that.

The question for me about fusion is not about getting to net zero, but about sustaining it into the indefinite future. You are going to ask people to make a sacrifice if you want to meet that goal of net zero by 2050. Are you really going to ask them to continue that sacrifice indefinitely? No. I think you need to provide them with an exit strategy that gives them a sustainable, growing economy based on an energy source that is sustainable; otherwise, it is going to be very difficult for Governments to ask their citizens to make a sacrifice without some hope. What we will provide—I think we both agree on this—is the hope of a sustainable energy future by fusion.

Q43 **Aaron Bell:** Dr Hawker already alluded to this in his first answer to me. When it comes to the shape of the future energy market, it has always been assumed that fusion replaces fossil fuel as baseload and we’ve got renewables doing more and more work, but baseload requirements are going down as we get more and more different kinds of renewables closer to the home or the factory. Is there going to be as much demand for baseload in future? Dr Hawker suggested that there will be continuing demand. Is that something you need to factor into the plans for fusion?

Dr Luce: I speak from my personal, professional opinion—the ITER organisation does not have an opinion on this—but yes, I think so. The other forms of energy you are looking at are very low energy density. That means they will occupy a large physical footprint to supply what you need, and if you anticipate that the exponential growth of the energy use of human civilisation is going to continue—I do not see why we would not predict that to be true—you are going to need more and more energy. The question is whether you can satisfy that with low energy density forms of energy or high energy density ones.

Q44 **Katherine Fletcher:** I have one really short question. For the record and the tape, I am Alok Sharma's PPS, so lots of this debate about how we source new energy is part of my day-to-day world, but you guys are both talking like fusion is going to work, and I want to circle back around that. When I say "work", I do not mean that you will demonstrate it is possible; I mean that it has enough gain to actually make it commercially viable. Can I get you on the record: are we going to have positive gain plants by 2040?

Dr Hawker: I think there is going to be a working fusion pilot plant in the 2030s.

Dr Luce: In 2030? Certainly not for magnetic fusion—not net gain of the plant. Over a long timescale, over the—

Katherine Fletcher: So not quite, and only in pilot.

Chair: Thank you, Katherine. Carol Monaghan, and then finally Graham Stringer.

Q45 **Carol Monaghan:** The UK's participation in Euratom has been delayed as a result of the ongoing Brexit negotiations. What impact has that had on the JET and ITER programmes?

Dr Luce: I will not comment on JET, because the next panellist is much more qualified. It has not yet had an impact on ITER, because we have been anticipating with the assent of the Euratom member that we could continue UK staff and continue contracts in force with the UK. There has not been an interruption, but we are coming to the point where that continuity plan is ending.

Q46 **Carol Monaghan:** So in terms of staff, at the moment it has been okay. What about in terms of funding, because the funding has been affected both by the pandemic and as a result of the shortfall from the UK at the moment?

Dr Luce: I can't comment on EU internal politics, but they have complied with their obligations in the funding to ITER. There is no pass-through of any difficulty that the EU has, but I cannot comment on how the EU is doing it. From the ITER perspective, that has had zero impact.

Q47 **Carol Monaghan:** Okay. Maybe I can switch it around. What is the impact on research you do in the UK from the ongoing failure to secure—

Dr Luce: Again, I think you had best ask the next panel. They know more about that than me because I am not representing the UK; that's been established.

Q48 **Carol Monaghan:** I don't know if you have any thoughts on that, Dr Hawker.

Dr Hawker: We haven't seen a huge impact, I would say.

Q49 **Carol Monaghan:** Again, maybe it will be better to ask the next panel, but Minister George Freeman has said that Euratom and its capability would be difficult to replicate here in the UK. Do you agree with that?

Dr Luce: Again, that's not something I can comment on.

Q50 **Graham Stringer:** Following on from those questions on international collaboration, there are 30-odd nations involved in ITER, as you know. Our relationship with some of those countries is deteriorating pretty quickly. Is that having any impact on the work? I am thinking of China and Russia in particular.

Dr Luce: Just to recall, the ITER project was born out of conflict. It started with Reagan and Gorbachev discussing whether they could de-escalate a nuclear crisis. The only thing they could actually agree on was to start the ITER project. Before I was born, the UK had Khrushchev come to Harwell exactly to look at fusion, so traditionally fusion has been a bridge for diplomacy in the past. It is an acknowledgment that the need for a secure energy supply is common to any type of governance and civilisation going forward.

In answer to your specific question about if it has had an impact, we have some logistical issues, but they are not of the same order that we have had from, for example, the covid crisis, with difficulties in long-range travel and supply chain disruption.

In terms of the ITER organisation itself, we are international civil servants and professionals; we work as a team. We are not a member with a certain passport; we work together and there has been no incident, disruption, work stoppage or conflict, to my knowledge.

Q51 **Graham Stringer:** How do you deal with patents? You must have invented and discovered quite a few things. Who owns the patents?

Dr Luce: I am the intellectual property board chair of the organisation. The ITER agreement is extremely specific that all the members share equally in the intellectual property that is generated from the project, so it is open to all. We don't typically patent because the lifecycle is such that patents don't make a lot of sense in fusion at this point, because by the time they would be capitalised, the patent has reached its "best by" date.

We protect the rights of the members primarily by publication. That benefits the general public because the information is then available, and it protects the members from having to pay twice for the same technology.

Q52 **Graham Stringer:** You make the point about the costs of moving to lower energy density sources of fuel and the costs in terms of the intensity of the technology that you are developing. How much has it cost so far?

Dr Luce: The strict answer to the question is that we don't know, because the ITER project is exactly funded to have 85% of the capital delivered by in-kind contributions from the members. This was designed specifically so that the members could industrialise to prepare for their own fusion economies within their own governance and research and development funding schemes. We don't have visibility of what the various members have spent to bring the components to the ITER facility.

Q53 **Graham Stringer:** You might not know this in detail, but have you got a back-of-an-envelope estimate of the total cost—an order of magnitude?

Dr Luce: I don't know the spend to date, but in terms of the value for the capital construction, at the very beginning of the project each of the capital items was assigned value so that they could be allocated among members in an equitable way, and the value is somewhere in the order of 20 billion for the cost to complete, for construction.

Graham Stringer: Pounds?

Dr Luce: I think pounds, euros and dollars are, from this distance, the same at this point in time.

Q54 **Graham Stringer:** Dr Hawker, can you just tell us about the funding of your project, and how it works, and how easy or difficult it is?

Dr Hawker: Yes. We are private equity-funded, so we sell shares in the company to raise money. We are able to do that because there is actually a strong community in the UK for doing this; certainly in Oxford, there is a very strong community for doing it. Our initial lead investor was a company called IP Group, which specialises in technology coming out of universities. More recently, there is an Oxford fund called Oxford Science Enterprises, which has led the last two funding rounds for us. We go through their networks.

A lot of people who invest in those funds do so because they don't have the skills, capacity or time to assess high-technology stuff for themselves. They rely on these companies to do it for them and then they make co-investments alongside. They choose to invest directly in the underlying asset.

Q55 **Graham Stringer:** So there is no Government money in it at all?

Dr Hawker: We have had a few small grants, but no, basically.

Q56 **Chair:** Thank you very much indeed. I have a final question on this. You had a successful funding round this spring—quite recently—and you raised $45 million. You took in an investment from the Chinese technology company Tencent. Did that give you pause for thought?

Dr Hawker: It did give us pause for thought, yes. We considered that very carefully. That was discussed with the team managing the National Security and Investment Act, and there was a sequence of meetings and a proper process.

The level of investment didn't put us into the regime where we had to go through that process; we went through it voluntarily, because on these things we take a proactive approach.

Q57 **Chair:** Okay. Can I ask what level of investment they made?

Dr Hawker: They have less than 5%, I think. I would have to doublecheck the exact number.

Q58 **Chair:** Does that give them access to any of the intellectual property that you are developing?

Dr Hawker: No, it doesn't.

Q59 **Chair:** Or to any of the operational capability? Is it purely a portfolio investment?

Dr Hawker: No, it's a purely financial investment from their point of view.

Chair: Right. I see.

Dr Hawker: There are levels of controls. There is information that is shared from the technical team to the board and there is a very clear process spelled out, where there is a board "need to know", which is below a certain level of detail: "What is the real question? And do we actually need to talk about technical detail to answer that real question?" Then there is another level between the board and the shareholders, where the shareholders don't have a right to the information access that the board has. There are lots of levels of protection in there.

Q60 **Chair:** You mentioned the national security considerations. Were they done by your team and your advisers, or was it the public bodies that scrutinised this?

Dr Hawker: The team in BEIS do the administering under the National Security and Investment Act; they looked at it.

Q61 **Chair:** I see. So they greenlit it, in effect?

Dr Hawker: They did. On our scientific advisory board is Andrew Randewich, who is from the Atomic Weapons Establishment, so we have a close relationship with them as well. There is a way that we can ask technological questions and get clarifications, and understand these issues.

Chair: Thank you very much indeed. Thank you to both witnesses; we kept you for longer than your allotted time, but that is a reflection of the depth of interest in the subject matter. Dr Nick Hawker and Dr Tim Luce, thank you very much indeed for coming.

Examination of witnesses

Witnesses: Professor Ian Chapman and Professor Steve Garwood.

Chair: I now invite our next panel of witnesses to join us. Professor Ian Chapman is the chief executive of the UK Atomic Energy Authority and has been since 2016; he was appointed to a second four-year term in 2020. Professor Chapman leads the UK's magnetic confinement fusion research programme, which includes running the Joint European Torus.

I am also pleased to welcome Professor Steve Garwood—thank you for coming, Professor Garwood. He is professor of structural integrity at Imperial College London and was previously Director of Engineering and Technology (Submarines) for Rolls-Royce, so he has industrial experience as well. Thank you both for coming. I will go straight to my colleagues, starting with Tracey Crouch and then Aaron Bell.

Q62 **Tracey Crouch:** Thank you, Chair. You will both have heard the previous panel's answers to the following question, but we are interested in your thoughts. When do you think that the world will see the first fusion experiments achieve a net-gain output?

Professor Chapman: Before I start, I wanted to echo the Chair's comments and pay tribute to Dr Bernard Bigot, who was the director general of ITER. You will not meet somebody more committed and dedicated to their mission, and the whole community will miss him greatly.

To answer your question on when it will happen, our vision is to produce a prototype in the 2040s—we are aiming to have a prototype fusion power plant producing net electricity in the 2040s. However, that is not really contributing towards net zero, as you discussed in the first session. That is the first prototype; making a serious contribution to our energy consumption means producing thousands of power plants such as that. Clearly, it will take decades before that is a reality.

However, I will say—I want to make this point strongly—that it is very important that we do not, in the UK, just think about the UK. In the UK, we can and ought to address net zero through offshore wind and nuclear; we are a nuclear state and we have a lot of sea and wind. That does not work in most jurisdictions. The only way that you can actually have an impact on net zero is to find a solution that works globally. As the UK, we should be thought leaders; we should be providing solutions that actually work globally, and if we do not do that, it is like having a covid vaccine for just the UK—who cares? You have to have a vaccine that works globally or you do not actually have any impact.

Q63 **Tracey Crouch:** And are we leaders?

Professor Chapman: Today, we do not have a plan. We do not have a strategy that will actually solve net zero globally, and as a community, we should be acknowledging that much more and investing much more in solutions that can find carbon-free sources of electricity. That is why I think that fusion is so important, not necessarily, parochially, for UK energy policy, but for global energy policy—how are we going to get rid of the 2,500 coal power stations that we have in the world? There are 2,500—this issue is huge, and only through solutions like this do we stand a chance of solving that.

The second thing that I wanted to say about power plants is on the importance of decarbonising every part of our economy—this is not just electricity; it is all of energy production—and there are a whole load of processes that require really high-grade heat. We have discussed, through the first session, that one of fusion's challenges is that it has too much heat, so we can produce really, really high-grade heat. That is what you need for producing hydrogen, ammonia, concrete, steel or glass—it needs high-grade heat, and there are very few non-carbon sources of high-grade heat. That is another reason that fusion is really important for this transition and, as Dr Luce said, having a sustainable way of delivering net zero through the rest of the century. I think that is essential.

Q64 **Tracey Crouch:** You are very enthusiastic—

Professor Chapman: Deeply.

Tracey Crouch:—which is great, but by implication, that means that you do think that it works and that it can contribute to—

Professor Chapman: Patently, it doesn't work today, but I do think that there is a pathway to making it work.

Q65 **Tracey Crouch:** Right, okay. Professor Garwood?

Professor Garwood: I come from a slightly different aspect. I have spent all my career associated with fission, but I was on the fusion advisory board for many years, so I understand the balance between them. For the first time in my long career, there is a formulation of a nuclear strategy. I read the nuclear strategy that the Government produced, and it talks about 2100 for fusion.

As an engineer, I pick up when technology readiness levels get very mature, and as you have heard, we are not there on fusion technology. On fission, we are. We are on to the next generation of fission now. For example, pressurised water reactors are at technology readiness level 9—they are being produced—so the challenges are engineering challenges, and I will come to them in a second.

For the next generation—Gen IV—we are talking about high-temperature gas reactors, and we are in the demonstration phase for that. It is at technology readiness level 7. Everyone knows how to produce the fuel, but we can't do it in quantity yet and we haven't got a supply chain. Have we got the skills to produce it? Have we got the infrastructure—the supply chain—to produce it? Those are the challenges at technology readiness level 7.

To get that reactor built by 2030, which is what is being talked about, we have to make a decision now, because engineering-wise—I have dealt with many projects like this—it takes about 10 years to go from a fully proven activity to actually getting it built. That is at the end of the process.

In all the areas I have been in—defence and Rolls-Royce, building aero engines, for example—we have a design cycle. In defence it is called CADMID. I don’t know whether you have heard about this before. You go through concept, assessment and demonstration, and then you are into manufacture, in service and decommissioning. Fusion will have to go through that cycle. It is in concept currently, so it is at very low technology readiness levels. In my career, I have dealt with things that have got to the middle of that—what Tim called the valley of death. That is where the investment decision really comes in to say, “We have proved the concept. What are the technical challenges to go now? Can we invest the money to go now?”

To my knowledge, when you get to the demonstration of the project, that is usually funded by Governments throughout the world. Companies are not really in the position to take the risk of putting money forward. It is a huge risk. You probably know that Rolls-Royce had a technological problem in the ’70s. There was too much technology. It couldn’t cope with how much technology there was to prove, so the Government had to bail it out and recreate it. This valley of death is a real thing, and it is all financially controlled.

The short answer is that there is very little chance that fusion will be contributing anything in 2050. Perhaps it will later, but I am totally with Ian here: I see this as a contiguous strategy, which the Government have published and developed.

A couple of years ago, I was on NIRAB, the Nuclear Innovation Research Advisory Board—in fact, the next panellists were on it too, and so was Ian—and it came out with a very good report in 2020, which said, “We need everything.” The challenge is how do we afford everything financially. In that mix is technology development, skills and infrastructure. It goes through this progression. In my view, you have to go through it with fusion. You have to keep fusion alive in this technology development stage, but go with a fission reactor, keep the skills base, and then it follows naturally from one to the other, but not anywhere near 2050, unfortunately.

Q66 **Tracey Crouch:** My next question was going to be about what is needed to bring fusion energy to the grid. So actually it is less about the science and more about making sure we have the skills and technologies to support the science—would that be fair?

Professor Garwood: That’s correct, yes. I am not a physicist; I am an engineer. The physicists make it work and prove the concept, and then unfortunately your challenges start. The guys before us were talking about this blanket. That is the start. That is getting very high temperatures—much higher temperatures than a pressurised water reactor or a fission reactor. There are advantages in that, as you have heard, but from my perspective, that gives huge materials challenges. You will probably ask the next panellists about that, because they are both material scientists.

My problem—this is my expertise—is how to take that heat and generate electricity from it. First, you have something very hot damaging material that we haven't got yet. That is a technological challenge after the fusion guys—how are you going to get that thermal blanket? You have heard Tim and Nick talk about different solutions to that, but again there are low technology readiness levels.

You get through that problem, and that is still what you might call the primary circuit. You have then got to have a heat exchanger into a secondary circuit and then drive a turbine, and the turbine produces electricity.

When I was on the fusion advisory board, I kept on asking, "How would you get the electricity out?" They'd say, "Let's solve the difficult problem first." That's fair enough, but I would say if they did prove the concept, it would be 10 years before you could get to a sort of demonstrator with the thermal blanket-type work, and then it is probably another 10 years after that to get your heat exchangers to work to generate electricity. That is 20 years after you have demonstrated the proof of concept. You have to go from demonstration, which is very small—I mean, you might put it on the grid.

I might just say that we have a parallel to this, which is fast reactors. When I was at school, which was a very long time ago, we had a fast reactor in Dounreay, the DFR, which generated a very small amount of electricity. That was then followed by a prototype fast reactor and then we started designing the commercial fast reactor, which never got built. You can learn from that timescale the sort of the timescale and the steps you need to go through to get us to where we have an actual fusion generation plant.

Q67 **Tracey Crouch:** In that stepped process, where do you think the regulatory environment sits, and how can we ensure that we make it appropriate for fusion?

Professor Garwood: I have read the 100-page document that was produced—I think it went out for public comment. I think that is a very sensible approach. As has already been explained, the amount of fissile material produced by fusion is very low compared with a fission reactor, so you don't need the regulation that ONR is currently putting on licensed sites. I totally agree with that. I think that document then says we will review it every 10 years. Beyond that, as you get nearer and nearer generated power, you have to have more tritium on site—I would guess, Ian?—and so your fissile goes up. It has the advantage, as Tim said, that it is not like a fission reactor—you are not worried about explosions—but there are other things that you might be worried about, because it is still a nuclear site and it still has lots of nuclear material. It could be that at some point regulation comes in. At the present moment, where we are dealing with very small matters, that is not the case.

Tracey Crouch: Professor Chapman?

Professor Chapman: I think that bringing in the regulator right at the outset is the right way to do things. The Green Paper has now led to the statement in the Queen's Speech that the Government will bring forward legislation in this term on the fusion regulator. I think that is absolutely the right thing to do—to establish a regulatory framework really early in the genesis of this. That is already having an impact globally. The fact that the UK is aiming to instantiate a regulator that is proportionate to the radiological hazard—rather than trying to shoehorn fusion into a fission radiological regulatory framework, we are having something that is proportionate and bespoke to the hazard of fusion—is different to what other countries are doing, and already we are seeing companies move to the UK and cite as one of the reasons for coming here the approach of the Government to regulation.

Q68 **Tracey Crouch:** Can you expand on the UKAEA's current programme of work around this and where it sits in its priorities?

Professor Chapman: On regulation?

Tracey Crouch: No, on fusion.

Professor Chapman: Okay. The UKAEA is the fusion organisation for the country. We do pretty much only fusion. The other things that we do that are non-fusion are only in adjacent sectors which benefit fusion.

Q69 **Tracey Crouch:** So what is your current work programme?

Professor Chapman: We have three tracks. We operate JET, which is the largest fusion facility in the world. It is a European facility that we operate on behalf of all our fusion European collaborators. That facility, which holds the world record for fusion energy released, is due to close at the end of 2023 and is all in support of ITER, which Tim talked about—this big, large international collaboration to demonstrate that you get a thermal gain.

The second part of our portfolio is in the enabling technologies—robotics, tritium handling, materials development, manufacturing, all the challenges that you heard about in the first panel. We have a suite of facilities that are all aiming at addressing those challenges and coming up with solutions to those challenges.

The third leg of our programme is the spherical tokamak, which is a compact magnetic confinement device. You asked about the price of ITER. ITER is £20 billion. Let's say that we can overcome all the technical challenges. If every time we want to build a fusion power station, we first of all have to raise capital of the order of £20 billion or more, then the penetration into the market will be driven by economics, not by technology. In parallel, we are looking at ways to try to drive down the capital—the overnight costs, the size of the plant and the things that you really spend money on.

We are designing a compact plant, which is slightly dissimilar to fission, where power goes with size. In fusion, you can make the plant more compact but still produce the same amount of power, so that is what we are aiming to do—to still produce a high-power output, but in a much smaller device that has a lower capital cost. The big technical challenge around that is that, as you heard before, the fuel has to be hotter than the sun for fusion to happen. If you put that heat source into a smaller volume, obviously the chances of melting the walls of that device are much higher. If you do not have a solution to that specific challenge, it is a dead end, so you have to find an exhaust solution.

We built a test machine to demonstrate a new way of exhausting the heat. We were aiming to reduce the heat that got to the wall by a factor of 10, and we have done better than that, so we already have more than a 10 times reduction in the heat that gets to the wall. That really opens the opportunity that you can build compact power stations. There are still loads of technical challenges, but it opens the pathway. We are also working on a prototype design programme—a facility called STEP—which would actually aim to produce net electricity. That is the device that we would hope to have completed construction of by the 2040s, aiming to produce net electricity. That is a compact machine, and it is a UK programme, not a European or international programme.

Tracey Crouch: That leads very nicely on to the next question.

Q70 **Aaron Bell:** I wanted to ask about STEP. I note that you said a couple of times that it would be ready by the 2040s. My understanding is that the target was 2040 originally. Is that slipping?

Professor Chapman: No, it is still our target to complete construction by 2040. That is in the UK's fusion strategy, so it is the aim. As with all these things, the aim will be met as long as the funding is available to meet that aim.

Q71 **Aaron Bell:** Listening to what Professor Garwood said recently, it seems like quite a tight timetable. The concept design will take place by 2024. You want approval to build by 2032, ready to deliver some electricity to the grid in the 2040s. We have just heard that ITER will not even be fully operational until around 2035, and that is a programme that has made an awful lot of progress. Is this realistic? Obviously, you are going to say yes, but you must consider that this is incredibly tight, especially given the material challenges that Professor Garwood spoke about.

Professor Chapman: Absolutely. I genuinely believe it is realistic. I will come back to the materials challenges in a moment, but in terms of comparators, STEP is roughly the scale of JET, which was built in four and half years. There is a machine roughly of that scale, now with super-conducting magnets, that was built in Japan in seven years, so aiming to build on a decadal timescale is absolutely challenging, because we are doing more things than either of those two facilities. But it is conceivable that we can do it. It is ambitious, and we are driving as hard as we can. We also stand on the shoulders of ITER. ITER is a first of a kind—it is the first time we have ever built that much magnetic strand, and it is the first time we have built loads of these components. New companies and supply chains exist because of ITER, and we will benefit from that. It allows us to maybe go a bit faster. ITER is also a big, multi-international consortium, and that is not easy to manage. There is some inertia in the construct of the project.

Q72 **Aaron Bell:** At the moment, you are running a competition between five sites. Is that purely about location, or is it also about what technology they might be using?

Professor Chapman: There is no specific on technology, but on the siting competition, there are four selection criteria. One is the cost and the simplicity of acquisition of the land. One is around the socioeconomic background of the area—the skills base, the access to people and the access to the supply chain. One is the off-site characteristics—rail access, road access and port access—and the on-site characteristics, such as access to the grid, access to cooling water, the ground conditions and things like that. Those are the four criteria against which we are assessing. As you say, there are five sites, which were all volunteered by local communities and landowners. Actually, 15 were volunteered in three countries of the Union and all over the UK. We down-selected to five. We very recently sent a recommendation to the Minister for Science and the Secretary of State, and now it is their decision.

Q73 **Aaron Bell:** You have recommended one site, but that is private at the moment.

Professor Chapman: Correct.

Q74 **Aaron Bell:** On funding, you have had £200 million so far from the Government. I think the figure out there is £2 billion to get whichever is the winning site built. Where is that gap coming from? Is it public, private or a mixture?

Professor Chapman: We do not have a funding profile yet, we do not know the total envelope, and we do not have a detailed engineering design. Until you have that, you do not know the cost of the plant, so I certainly would not stand by £2 billion. We do not have enough fidelity to know what the costs are. As Steve said, when you are in this prototype concept phase, the risk is high. We do not expect there to be substantial private money, so we are seeking substantial public backing. However, we are trying to establish the programme in such a way that we could take private investment as well in the next tranche of the programme.

There is substantial private money going into fusion. Globally there is about £5 billion invested in fusion start-ups now. About half of that was invested in the last nine months, so the market appetite for investment in fusion is high because the imperative is so large—we must do something. There is appetite within the market, and we seek in the longer term to augment public money with private money.

Q75 **Aaron Bell:** And you also have a collaboration with a Canadian company called General Fusion, which is building a plant at Culham—a site that you own. Does that sit alongside STEP? Is it meant to inform STEP? How does that work?

Professor Chapman: We are a national lab. Our role is to make sure that fusion happens and the Government delivers on its fusion strategy. We are relatively agnostic. We want fusion to happen. If it happens through three or four different concepts, I am delighted. If one of those concepts happens faster than STEP, I am also delighted. It will happen because of STEP, and STEP is causing the Government to think about regulation and causing the establishment of a supply chain. All of that stuff is happening, which might enable other concepts, and we should try to make fusion happen as quickly as possible. That is why we are very supportive of all of the endeavours in the private sector.

General Fusion are one of many organisations with whom we partner. They are a Canadian company, and they announced that they are going to build the next demonstration facility here in the UK. That facility is probably $400 million—something of that order—and the vast majority of that will end up being spent in the UK supply chain, so this is a really great inward investment success story. Because of our fusion capability, we are seeing companies literally relocate across the world and come to the UK.

Q76 **Aaron Bell:** Which range of technologies is the national fusion programme considering? We have already heard about injection and projectile fusion. Are you considering that as well?

Professor Chapman: The UKAEA is not working specifically on them, although we will do consultancy to help them. Typically, the work that we do to enable them is in the enabling technology: how you produce tritium, the materials that might build the platform, and how you manufacture the robotics to remotely maintain the device. We typically will help in those areas rather than in the specific approach to fusion, which is usually proprietary to those companies.

Q77 **Aaron Bell:** Finally, on the technical challenges, I will ask the same question that I asked the first panel. Do you think we will get proof of concept of net gain in each of these particular technologies—the injection, the torus, the spherical tokamak? Do you think you will get proof of concept—not just production of energy, but net gain? And if so, when?

Professor Chapman: I think that is conceivable by 2050 in all of those technologies.

Q78 **Aaron Bell:** In all three by 2050. And earlier in injection, as we heard from our first panel?

Professor Chapman: Again, it depends on what you mean by gain. If you are talking about a thermal gain where you get more thermal power out than you put in, I think for sure it will happen earlier in both magnetic and inertial. If you are talking about net electricity gain, personally I think that will happen in the late ’40s.

Aaron Bell: Professor Garwood, do you have some thoughts on that?

Professor Garwood: I am not a physicist; I am an engineer. Equally, I heard the earlier presentations. I think there is a huge challenge for these guys, but they have moved forward. It is very difficult to say how many years before they prove the concept.

My role is to say: once you have proved the concept, your technical challenges are not over. You have got these materials challenges, and even when you have fixed that, you have gone from what STEP will do, which, if it works, will produce a very small amount of electricity, to the next stage, which, as I have said before, will probably take 10 years to be a real demonstrator. Then you are into commercial programmes.

As you heard from Tim, you are talking about infrastructure projects, and we all know how they can be affected by scale, skills and delays. I hope they are successful because I really believe fusion is the future, beyond fission. It should be a seamless path to that, which is why it is so important to keep the skills and the funding in the UK through that path.

However, you don’t want to rob Peter to pay Paul either. You have to do it in a staged way, as I explained before, as any engineering project is done: you assess the risk, put your resources into the next challenge and keep the challenges going all the time in a seamless way to get to the final product. I have to say, notwithstanding the difficulty that these guys have in proving the concept, there is a big technical challenge beyond that.

Q79 **Aaron Bell:** I think you have both implied this in your answers already, but, just for the record, I assume you both think that fusion will not make a major contribution to the UK’s net zero 2050 target. However, do you both agree with Dr Luce that fusion will be a huge part of the future beyond that, in terms of continuing to improve our standards of living?

Professor Garwood: Yes.

Professor Chapman: I completely agree.

Chair: Thank you very much everyone. Carol Monaghan, then Graham Stringer.

Q80 **Carol Monaghan:** I asked the last panel about international programmes, so my first question is: what benefits have programmes such as JET and ITER brought the UK?

Professor Chapman: Let me start with JET, which is the largest European science facility in the UK. It has brought us immeasurable benefit. You could contend that the UK is genuinely the world leader in fusion research; it has the largest fusion research organisation on the planet, and that is because we host JET. We have a breadth of capability that we would not have if it weren’t for our hosting JET. It is both a literal and metaphorical magnet—it brings thousands of people into the UK to do work at our campus. We have become a hub and an attractor for talent and capabilities and a whole supply chain has grown around it.

I learned recently that 3,800 companies now supply UKAEA—that is a huge supply chain and a broad base that is supporting jobs in the UK. So, JET has been a flagship of European collaboration. It is a genuinely European project, but it has enormous benefit to the host country—in this case, us.

ITER is much the same. Again, it is a huge international project that one country would not do on its own. We could not replicate ITER here on our own. We don't have the breadth of supply chain or capability, and we would not spend £20 billion on it on our own. By working together collaboratively, we are able to make that next step where we demonstrate a fusion gain that we just wouldn't be able to do alone.

Q81 **Carol Monaghan:** Professor Garwood, you were talking about skills and keeping up the skills base. Professor Chapman, you are talking about people coming here to do work at JET. Is there a bit of both going on? Are we growing our own talent as well as bringing in international partners?

Professor Chapman: Of course.

Q82 **Carol Monaghan:** Is that under threat at all because of the delays over Euratom?

Professor Chapman: Yes. Our approach and, genuinely, the Government's approach is that association to Euratom is the preferred outcome. It has fostered a great collaboration on JET. It is how we participate in the ITER programme at the moment and how we collaborate with our European partners. That is the preferred solution. Fundamentally, to meet the UK Government's fusion strategy, the biggest priority is that we have a vibrant, flourishing and successful fusion sector.

Q83 **Carol Monaghan:** What would be the alternative to Euratom?

Professor Chapman: We are working with the Government to prepare robust alternatives, which remain strongly collaborative—working with our international partners—and, perhaps, focus more on UK industry and how we can stimulate the UK supply chain and fusion industrial base. While the preferred route is an association to Euratom, we have now been in a sort of no man's land in for 16 months, with one foot in and one foot out. That situation cannot last forever, so we do need a decision.

Q84 **Carol Monaghan:** So the preferred scenario is association. If that doesn't happen—let's think worst-case scenario—what has to happen to ensure that the skills base that Professor Garwood talked about and the talent is kept?

Professor Chapman: The most important thing is to have an ambitious and wide-ranging fusion programme. If you are doing something ambitious and aiming to produce net electricity and to make a difference to the world, people will come and you will inspire young people to get involved in the field. You need a vibrant, ambitious programme. In fact, just last week, I interviewed for a chair position for a university with international applicants, who both cited the fact that the UK is doing ambitious things in this sector as the reason they wanted to come.

Q85 **Carol Monaghan:** So, ambition is one thing; money is another. How much money does it need?

Professor Chapman: The two things usually go hand in hand. I think the Government's position on this is that the money the Treasury had set aside for association to all programmes—not just Euratom but Horizon Europe and Copernicus—is not utilised for association to programmes it will still be used in nuclear science. I think that is a proportionate and appropriate way to do it. When it comes to the benefits we would lose from association, if we are making UK investment into alternative programmes we can still have an ambitious and world-leading programme.

Q86 **Carol Monaghan:** And are you confident that that funding will come good?

Professor Chapman: We hope so.

Q87 **Carol Monaghan:** Thank you. Professor Garwood, do you have anything to add?

Professor Garwood: If I could start on the skills, I appeared in front of this Committee, I think, 12 years ago or something to talk about whether we had the nuclear skills to move on to a fission future, and we agreed that we did. It is important to point out that the skills Ian is employing currently and in ITER and the First Light programme, too, tend to be more physics and early skills. The skills I am used to in the second phase of the programme—or is it the third or fourth, when you are building something and generating—are project management skills, engineering skills and general engineering skills, which are transferable between sectors. It is important that we keep those in the UK.

On the balance with Europe, it is a funding issue more than anything else, I would say. If we are successful—if these guys are successful—in producing technology demonstrators, can one country afford that huge amount of money? You have heard how much it cost to do ITER, and ITER is a demonstration. There is a proof of concept after that and a commercial demonstration before you actually produce power. That is going to take a lot of money. We are world leaders; let's keep the world leaders and keep the technology base that these guys have, but if we need to we might need to collaborate internationally. As was said very eloquently by the previous speakers, this has worldwide potential.

Q88 **Chair:** Just to follow up on one of Carol's points to Professor Chapman, surely one of the points of international collaboration is that if you do things jointly it is cheaper than if you do it on your own. So, just earmarking or reserving the funding that would have gone into Euratom and other programmes will not be sufficient if we have to replicate it. We will need more than that, and much more, presumably.

Professor Chapman: Absolutely, and when it comes to that package of alternatives, as I said, it is so important that we do that in an outward-facing and collaborative way and that we seek new and maybe deeper collaborations with other partners—maybe the US—while keeping our existing collaborations with our European partners. That has been the bedrock of our programme and we must not turn away from that. Even if we do it through a different mechanism and a different way of working, we must still remain collaborative.

Q89 **Chair:** Obviously, it is not entirely in our hands. We could have the vision to do that, but we may be refused. In a world in which we had to go it alone, as it were, what level of funding would we need and have you had conversations about securing it?

Professor Chapman: As I say, we are talking to the Government about an alternative package and how that could be administered. This is a question for the Minister, really, I think. There are ways we can do that and not damage our sector, but it needs care. It needs care to ensure that we do it in such a way as we remain collaborative and remain integrated internationally.

Q90 **Chair:** The question for the Minister is whether he can supply the funds, but you are in the position to judge what is needed. This is a Committee of Parliament that looks to find answers to such questions and to hold the Government to account. What is your advice to the Committee on what will be needed?

Professor Chapman: My approach is that we should still seek an agreement whereby we can participate in international programmes, even if it is through a different mechanism than association to Euratom. Look for ways that we can continue to co-operate and participate in ITER. There are other states that participate in ITER as non-members—Australia, for instance, recently signed a collaboration agreement with the ITER Organisation that enables it to participate in the science of ITER. There is precedent, and I think we should be seeking such arrangements, hopefully in a more ambitious way than with the precedents that have preceded us. I would still say that we must look to seek those collaborations.

The one thing I will say about the fusion community—Dr Luce said it earlier—is that it was born from conflict and has been tremendously collaborative. The whole way through the past four years, there are pockets of science where European collaborators have turned away from their UK partners just because it is difficult, they can't sort out the funding arrangements and it might prejudice their own success.

That has not happened in fusion at all. Throughout, our European partners have, at a working level, remained utterly collegiate—always trying to find a way to embed the UK and keep us involved in the programme, including at strategy decisions and decision-making committees. We have had a completely collegiate approach from our partners.

Q91 **Chair:** I don't doubt that at a working level that is the case. One hears that the case with Horizon is that the blockage seems to be at a higher political level, where the veto might be deployed. Obviously, the preferred solution—even the second-best solution—is to continue to collaborate internationally, albeit through different fora. Should that not be possible with current European partners, how much would it require to go it alone, as it were?

Professor Chapman: ITER is the big issue here. At the moment, we get various things through our membership of Euratom, but the one we really could not replace is ITER. As you heard, ITER is on a scale that could not easily replicate, and it is also at a stage where it is 80% built. We cannot just turn on something that is 80% built. It is not possible. There is just no other way of accessing a programme of that scale. Ensuring that we can continue to participate in that programme in some way is, I think, an imperative result from our approach to alternatives.

Q92 **Graham Stringer:** Professor Garwood, at the start of this session you went through the pathway, from theory to practical application, and you gave a timetable for that. There are two major examples from the last century of that timetable. My guess is that you know I am going to mention the Manhattan Project, which was done very, very quickly, and the man on the moon project—also done very quickly. They were done very quickly because they had the imperative of war in one case and presidential backing in the other. Money was no object, effectively. If money was no object in this area, how quickly do you think it could be done? How much could that schedule be collapsed?

Professor Garwood: It is certainly true that if you solved a lot of the technological issues, you could do things much quicker.

There are parallels to a small modular reactor. Because it is based on existing technology, they say the timescale would be compressed so that it could be something to generate power before 2030, so it is possible.

If money and resource are no object and if you have the skills, of course you can squeeze these timescales down. You still have the technological challenges. Some of these technological challenges, I would say, are equal to the Manhattan Project and the putting a man on the moon. That is the difficult thing. I don't think you will get a straight answer from anybody to say how much you could squeeze it down just by putting resource and money into it. It could be squeezed down, and I think these guys will achieve it. It would be faster if they had more funding. That is obviously the case, but even so, I am a pragmatic engineer. I think it would be very difficult for it to affect net zero by 2050.

Q93 **Graham Stringer:** I will ask the reverse of that question. You mentioned small nuclear reactors. Given the amount of money we have got at the moment in a project that, according to everybody, is going to take quite a long time before it makes any useful contribution, would it be better to spend that money on other low-carbon technologies? Are we investing in the right area?

Professor Garwood: I will take that first. You had a partial answer from our first panel, in that the renewables and other technologies are not as dense as nuclear—both fission and fusion. They also produce continuous power too, unlike renewables. There are solutions to try to store energy, but I cannot see a place for having this baseload. If you accept that you will need that baseload, you must continue the search and the progress to achieve that baseload.

Professor Chapman: I will comment on a few things. As I said, I do not see this as a parochial issue for the UK but as an export potential issue. If we can find a solution that works in all jurisdictions, it could be a huge part of our economy and could drive our economy. If we have an energy product that we can sell globally, that is absolutely transformative, in the same way that we have seen with vaccines—AstraZeneca has a product that it can sell globally, and now it has the best part of half the global market share. Having a solution that can really work in all jurisdictions is just an enormous opportunity. I want to get across that we must not think just about the UK.

The second thing is all the adjacent, spill-over technologies. The technology that we developed for fusion has applications in all sorts of other sectors. I give you one example: we talked about robotic maintenance. We developed a robotic maintenance system to remove some of the tiles on the inside of JET. On the back of that, a company came out of UKAEA. That company recently won a massive contract—hundreds of millions of pounds—from Fukushima to do inspection robots at Fukushima. That technology all came out of fusion. There are adjacent benefits on the pathway to this huge economic prize at the end.

The third thing you asked about was the acceleration. I do not think it is just money that matters there; just as important is the attitude towards risk and the appetite for risk. In the Apollo project, at peak, they were spending 4% of GDP, which is a huge monetary investment, but they were also prepared to take risk. There were parallel programmes; they built things that did not work; rockets that blew up. They were prepared to take risk. Our risk appetite in energy infrastructure at the moment is relatively low compared with the challenge we face.

Q94 **Chair:** Finally, following up on what you said earlier about the process for selecting sites, I think you said that UKAEA has completed that assessment and, presumably, communicated that to the Government. Is there any reason why we should not have an announcement of that preferred site imminently?

Professor Chapman: We expect there to be an announcement this year. It is a ministerial choice; they will have to take their time to understand the recommendation made, but there is also a process around the acquisition of the land. That would have to go through an approvals process in Government to make an acquisition case.

Q95 **Chair:** But you acquire the land once you have decided.

Professor Chapman: Of course. I assume the decision can be made relatively quickly, but I do not think the announcement will come until we have gone through that business case approval process. That is my expectation.

Q96 **Chair:** Given what Graham and Carol asked about speeding up timelines, would it not be to everyone's advantage to compress that, since you have commendably done your job?

Professor Chapman: According to the original timeline to deliver by 2040, we said we need to acquire the land by the end of 2022. We are still on course to do that. If you want to expedite—

Chair: Yes, but it is a question of taking the opportunity to go faster, which would be better, surely.

I am very grateful to Professor Garwood and Professor Chapman for your evidence. I will now invite our final panel of witnesses, who are joining virtually, so we will see if we can get them up on the screen.

Examination of witnesses

Witnesses: Professor Andrew Sherry and Dr Dame Sue Ion.

Chair: I am very pleased to welcome Dame Sue Ion, who has been an eminent figure for some time in the UK nuclear industry. She is a visiting professor at Imperial College London in the department of materials. She has represented the UK on several international committees for the nuclear sector, including the Euratom Science and Technology Committee and the US Department of Energy's Nuclear Energy Advisory Committee. She was previously chair of the UK Research Council's fusion advisory board. Welcome, Dame Sue, it is very kind of you to join us.

I am also pleased to welcome Professor Andrew Sherry. Professor Sherry is chair in materials and structures at the Henry Royce Institute at the University of Manchester. From 2015 to 2020, he was the chief scientist at the National Nuclear Laboratory. Welcome to you both.

Q97 **Tracey Crouch:** Good morning and thank you for joining us. We asked the previous witnesses the same question, so forgive me. When do you think the world will see the first fusion experiment that achieves a net energy output?

Dr Dame Sue Ion: Having heard the previous witnesses, it is really a two-part question. When will the physics be demonstrated so that you get net gain at what I would call an experimental level? Conceivably, that will be later this decade or the beginning of the next decade. When will you get a prototype plant that demonstrates that commercial fusion may be even remotely possible? You are talking about post-2040. If you are talking about the availability of grid-available fusion power, it is well into the second half of the century if all the engineering and technical challenges that are yet to come are solved.

Professor Sherry: I absolutely agree with the perspectives that have already been shared. Demonstrating the net power positive output will probably happen within a decade. Actually extracting power and driving it into the grid in a demonstration will, I hope, come before 2050—that is the STEP objective. I think driving reliable, commercial fusion power into the grid—either heat or electricity—will be decades beyond that.

Q98 **Tracey Crouch:** Are you both confident that it will work?

Dr Dame Sue Ion: I think there is a difference between confidence that it will work and confidence that it will work 24 hours a day, seven days a week, 365 days a year, satisfying an economic environment in which it has to live. That is different, and my answer to that is that I honestly do not know.

Professor Sherry: Yes, I think it will work, but as you have already heard, there are challenges, particularly around the engineering, the materials of engineering, the fuel, the temperature gradients and the environment in which the components have to operate. The heat is hotter than the sun and the neutrons are high-energy neutrons for prolonged periods of time—that is an enormous engineering challenge. Extracting the heat and transferring it to steam generators and turbines that then generate the electricity into the grid also needs to be demonstrated.

I would not want to underestimate the challenges around the engineering. One message from me that connects into this question is that we have a superb science base that is looking to address those challenges. The materials have come up a number of times. Just earlier this year, the director of materials at UKAEA, working with the Henry Royce Institute on the UK capability, has come up with a materials road map targeting the right challenges in the right way.

Those challenges are significant because we do not have experience of materials operating in those environments for any length of time. We do not have the materials; we do not have the qualification of those materials that would be acceptable to a regulator. We are still working out the manufacturing routes for those materials, so even the construction is a challenge, and the operation to follow in that environment also represents a significant challenge, scientifically and engineering-wise.

Q99 **Tracey Crouch:** Do you agree with Professor Garwood that this is a stepped process and that the challenges in skills, engineering, delivery and demonstration will really begin to bite after the initial concept part of the process?

Professor Sherry: Absolutely. One of things Professor Garwood highlighted and that I wrote down was the CADMID cycle that is used widely: concept, assessment of the concept, demonstration, manufacture, in-service and dismantling. In that whole life cycle, we are in the middle of the concept. On a concept scale of one to five, the latest information I have seen for STEP is that it is at level 3. The goal is level 5 by 2024, and to move it thereafter.

Dr Dame Sue Ion: I agree wholeheartedly with what Professor Garwood and Professor Sherry have just said about the process that needs to be followed and the challenges to go. We do not know which materials will be appropriate for use, and we do not know how they will perform. That work still needs to be developed—the engineering reality of the final machines—and manufacturing those materials at scale will be a challenge yet to be addressed.

The really important thing is that we have to build the prototype in order to find out where those engineering challenges are going to come from. We can do all the science base, which has got us to where we are today, but unless we take the next step and build the prototype, we will not know how successful we are going to be. Professor Chapman indicated, this is not just a UK issue. The prize is huge, if the challenges can be solved, but we will not know unless we build the prototype.

Q100 **Tracey Crouch:** In that process of STEPs, one of the key aspects of success was about the skills base, and that is what we should be thinking about now, rather than waiting for the science to happen and then sequentially investing in skills. We should be thinking about these things now. If we are thinking about what support is needed to bring fusion energy to the grid, we should let the scientists go and do their science thing, but we should be looking at how we deliver on those next parts of the process that Professor Garwood highlighted. Is that fair?

Dr Dame Sue Ion: I think that is true. Quite a lot of things on the materials side, we can begin to take forward now—start to take forward in a STEP-wise fashion, to look at different materials and ways of manufacturing. A programme like the materials road map that Professor Sherry referred to would be good in terms of support.

On the wider skills, it is not a fusion experiment that will be built in the future; it is a power station, which has all the other things—turbines, control systems, grid access, heat extraction and so on. It is about the UK's ability to service all the other—I guess, more traditional—engineering skills, which cover the whole power station concept, rather than just the fusion part of it, if you see what I mean.

Professor Sherry: Absolutely. Just to reinforce that, my observation—I am not a fusion expert, but reading in and around where things are up to—is that it is absolutely clear, and the previous panellists highlighted this, that the UK has internationally leading scientific skills in the areas that are required to be solved to deliver fusion. But the transition that needs to happen, and is starting to happen with the focus on STEP, is the move from scientific discovery and spin-out benefits in other sectors, towards an engineering-led programme to deliver a prototype, which is absolutely required. It will highlight new challenges that we do not know yet, but unless we do that, we will not know them.

The transition from science push to engineering pull across that valley of death is absolutely what needs to happen, so that we can take STEP towards fusion power. Without that engineering pull, I think that we may be looking for the perfect solution as the enemy of the good solution—if I can put it that way, to try to quote Voltaire. The engineer will look at things in a different way from a scientist, and that is as much a cultural change as a skills challenge—and a funding challenge as well.

The way that the programme is funded now is through the research councils, with their metrics of internationally leading science, publications, impacts in all sorts of ways, and so on. In terms of funding towards a prototype, that is a much more programmatic, engineering, pragmatic approach than the current science base. We would not want to lose that science base, because the solutions will come, but there is an additional dimension that is required to deliver towards STEP.

Q101 **Tracey Crouch:** I am now completely bought into and invested in Professor Chapman's enthusiasm for the UK's ownership of this issue, so how do we make sure that we can stimulate further private investment to ensure that the UK continues to be a world leader in fusion?

Professor Sherry: A couple of thoughts from me. It is a really interesting time in terms of the funding of nuclear projects—fusion, and fission as well—because the private sector funding is now flowing in, as we have already heard. There is an opportunity around a given project for some form of public-private support that will balance the risk on the one hand, which is where the public funding comes in, and the drive towards economic, low-carbon fusion energy for the future on the other. That coupling is very powerful, enabled by scientific funding to identify solutions and provide an interesting model.

The other thing I would say about this is that we have seen this already in the space sector around some of the developments and the challenges that NASA has faced in delivering a space programme. The entrepreneurial private sector funding has stirred that programme up to deliver space travel in a way we might not have imagined even 10 years ago. We are perhaps at that tipping point within the fusion programme, but the focus will be on the engineering and managing the risk, not only the science.

Dr Dame Sue Ion: I agree with Professor Sherry about risk appetite. There is a difference between the largely venture capital business angel funding that is going into a number of the very small start-ups and the big investment that is required to take a prototype forward. What you actually want is skin in the game from some of the big engineering companies that will help you take the prototype forward, and that requires commitment at state level—whether it be the UK, the United States or wherever—in order to give the big private sector enterprises confidence that we are serious about a journey to commercial fusion. A certain amount of dialogue needs to be held with Government about how best to facilitate international partnering with big private sector engineering companies that are likely to help deliver the goods.

You asked about the UK lead; the really big thing is that the UK does have a lead in the science that underpins all of this. We have been extremely fortunate, in a way, to have had the JET experimental machine, which has been majority funded by Europe, not just the UK—although the UK has obviously had skin in the game—but also our support of MAST, the precursor of the ideas that are going into STEP. If you look at the timeline for ITER, you are not going to be producing the gain. You are talking about 500 MW for 400 seconds, so its goal is not a continuous power plant, and that is out into the 2030s. The requirement then will be to build another machine called DEMO, of similar cost, size and type, to get you to the next stage. STEP, from the timeline that is being indicated by Professor Chapman, will beat that, so the UK's idea of going to small and more compact may well win through. That would really give us something to build on export-wise for the future.

Q102 **Graham Stringer:** Could I ask similar questions to those I asked the last panel? Moving to a low-carbon economy means either moving to intermittent energy sources of much lower energy density than fossil fuels, or to very high-technology energy sources such as fission and fusion. We have heard this morning that moving towards fusion is going to take us a long time and a lot of money. Do you think the assessment work on alternatives to fusion, whether it be small nuclear reactors or something else, has been properly done?

Dr Dame Sue Ion: One of the things that I wished when I chaired NIRAB was that fission had been benefiting during the last decade from the same enthusiasm as fusion was being treated with. Fission had been short-changed for the best part of nearly three decades, because it was thought to be commercial technology and that Government didn't need to step in at all and it should fly by itself, yet in relation to the more modern nuclear systems, because of the risk appetite of the private sector and whether Governments were committed to fission or not, the investment wasn't coming forward. There is no doubt in my mind that both fission and fusion—if fusion realises its potential—will be the drivers for global stability of energy for the future. Both offer more than one mission. Both offer more than just electricity generation. Both offer the potential to manufacture hydrogen and to use the heat for industrial assisted processes.

The light-water reactor versions of the fission system are ready to go. They just require the final push and the commitment that we actually want them and are prepared to donate the sites and help kick-start the private sector investment that will flow thereafter. The next generation of reactor systems, the high-temperature reactors and the fast reactors, which have more in common with fusion in terms of materials challenges, will need a prototype before they will be pushed to commercial reality, but they will still have that heat output potential to generate hydrogen as well as baseload electricity generation.

Professor Sherry: To pick up on that point, I think it was Professor Garwood who talked about a programmatic approach and the different phases of nuclear technology that are leading towards fusion. One of the things we are perhaps not very good at is securing the benefits from one development of technology and transferring them to the next. An example is the approach that Rolls-Royce are taking with their SMR, which is proven technology but put together in a very different fashion, in a modular fashion—built in-factory and constructed on site, 24/7. That modular approach to construction—that design and manufacturing thinking—absolutely benefits fusion and the STEP programme. Similarly, as Dame Sue Ion has said, the next generation of advanced modular reactors are higher temperature. They benefit from our advanced gas-cooled programmes and technology. And taken together, those can benefit the fusion programme through the high-temperature materials and the advanced manufacturing technologies that can be proven. So I think there is an opportunity to work at the interface and to maximise the transfer of technology and engineering from one phase of nuclear development into the others, with all feeding into fusion.

Q103 **Graham Stringer:** Can I come back to Dame Sue and ask the same question in a different way? If you were making the case to Government, which seems now to be committed to small nuclear reactors and has said it is going to build 10, would it not make sense to use some of the money in the fusion project? I know we have seen this morning a lot of enthusiasts for fusion. Would it not make sense to put some of the money going towards fusion into more small modular nuclear reactors?

Dr Dame Sue Ion: I think, going back to what I said, it's the kick-start that is needed for the small modular reactors, and commitment to move ahead with the first three or four of them. The money going into fusion is still establishing the scientific integrity and base, which is required to get you to the first concept. The moneys we are talking about are small in the overall scheme of things. This is the money going into STEP to date and the money going into the commitment to the Rolls-Royce-led team for small modular reactors. It's tiny in the overall scheme of things when you look at the challenges ahead. So I would not play one off against the other. Fusion is going to be much later than fission. We can have fission on the grid, with small modular reactors, by 2030 if there is commitment now to help get the private sector away. That is the most important message from me on that one.

Q104 **Dehenna Davison:** We heard from the UK Science Minister, who said that the UK alone cannot do fusion, and that it has to be an international collaboration. Dame Sue, do you agree with that sentiment?

Dr Dame Sue Ion: I think Professor Chapman has also indicated the importance of international collaboration, going forward. We have been part of the international fusion community now for decades, and arguably lead the way on that. Going forward, it is very difficult to see how you would go it alone, because of the investment that is required to take it forward. International collaboration is good because you are learning from everybody else's progress as they take their projects forward.

Dehenna Davison: Professor Sherry, would you agree?

Professor Sherry: I would agree with that, and I would add that, given the scale of the facilities to demonstrate some of these designs, components and so on, no one nation can have all of the above. So I think collaboration is vital, in terms of the skills and the expertise, the facilities that are required—that is not just about STEP; we have heard about the MAST upgrade and other facilities: ITER and so on—and the programmes to solve the big challenges, including the blanket, the fuel and the magnets and radiation damage and so on. That requires a huge international effort.

Q105 **Dehenna Davison:** Let us talk about this international collaboration. Professor Sherry, I will start with you. Do you think that the UK is striking the right balance between our own home effort and taking part in international programmes?

Professor Sherry: I would say so, yes, at the moment. Scientifically, as we have all said, having the JET facility, which has operated since, I think, the mid-'80s, has put the UK in this leading position, where it can actually start to plan for a demonstrator plant—a prototype plant. Without that support we would not be in the position that we are in today. Having said that, access to international funding, expertise and specialist facilities to enable that STEP plant to be built by the 2040s and operated thereafter is absolutely key.

I would add that the UK's approach to regulation is actually attracting inward investment and players moving to the UK. We have a goals-based regulatory regime in the UK; it is not a rules-based approach. That requires that a duty holder operating a plant really understands it—doesn't simply follow the codes and standards but thinks for themselves what the safety, security and environmental challenges of that plant would be. The UK is in a leading position, both from the regulatory perspective—I know the review is ongoing—and from that of the expertise base, to make that work.

Q106 **Dehenna Davison:** Finally, Dame Sue, do you agree with Professor Sherry that we are just about striking the right balance between home-grown efforts and international programmes?

Dr Dame Sue Ion: Yes, I think so. If you are leading, you tend to attract international interest and inward investment—with both the regulatory regime you are operating, the facilities that you already have, which the UK is blessed with, and the skill base and talent that is here in the UK. So the attraction to work with the UK is very high, and our willingness to collaborate with overseas national labs, companies and so on, has always been good in fusion and I don't see any reason why it would not continue to be so.

Chair: Thank you to both our witnesses, Dame Sue Ion and Professor Andrew Sherry. That concludes this meeting of the Committee. I would like to thank all the witnesses that have helped brief us and bring us up to date and helped us explore some of the questions and tensions in the policy environment around nuclear fusion. We are very grateful for their evidence, and the Committee will reflect on it and make some observations to Government in due course.