Energy Conversion
Dr. Richard Stainsby, NNL, UK

Berta Oates
Good morning. Welcome everyone to the next GEN IV International Forum webinar presentation. Today's presentation is on 'Energy Conversion.'

Before we get started I want to take care of a couple of housekeeping kind of things. You can type questions for today's presenter in the Q&A pod and we will take those at the end of the presentation as time allows.

In the files pod on your screen are the PDF version of the slide deck for today's presentation. And if you click that that will download directly to your computer.

And last but not least, in the notes pod is a link to an online survey where you can provide feedback on today's presentation. We take your feedback very seriously for opportunities for improvement and thank you in advance for providing us with that information.

Patricia Paviet is the Director of the Office of Materials and Chemical Technologies at DOE in the Office of Nuclear Energy. She's also the GIF Education and Training Task Force Chair.

Without further ado, I'll turn this time over to Patricia.

Patricia Paviet
Thank you so much, Berta.

Good morning everyone. It's a pleasure to have you today and to have Dr. Richard Stainsby from NLL with us, who is going to give again a very interesting webinar presentation.

Richard is a mechanical engineer with a Ph.D. in computational fluid dynamics and heat transfer. He is Chief Technologist for Advanced Reactors and Fuel Cycles at the UK National Nuclear Laboratory, having worked both in research facilities and industry before joining NNL.

Richard has spent the last 32 years working on light water high temperature gas reactors and on liquid metal and gas fast reactors. He has worked on contracts for PBMR in South Africa on core design and whole plant simulation, for the National Nuclear Regulator, also in South Africa, and for the USNRC on the development of licensing tools for HTGRs.

Richard is a past Chair of the GIF GFR System Steering Committee and a current Euratom member of the GIF SFR System Steering Committee. He has led two European projects on gas-cooled fast reactors and was a leader of the innovative architecture and balance of plant sub-project within the Euratom CP-ESFR project between 2009 and 2013.

Richard, thank you so much again for volunteering to give this webinar and I give you the floor. Thank you again, Richard.

Richard Stainsby
Thank you, Patricia, thank you Berta. Thank you for the introduction.

I'd just like to say it's an honor to have been invited to give this presentation. I've looked through some of the previous ones that were given and that kind of sets the bar very high. I sincerely hope that today in some way measures up to the standards of some of predecessors.

So without further ado, I'll get into the next slide, which is just generally you are looking at power conversion cycles for a nuclear power station and how this differs in some ways from power cycles that we would want to couple to a fossil-fueled plant.

For a nuclear reactor and its power conversion system, the linkage has to be much more intimate than it is really with a fossil-fueled plant. The reactor must supply heat that is controllable and of sufficient quality. So, it has to be steady, it has to be the right temperature, rather being at the right rate to match the requirements of the power conversion system. But equally well, power conversion system or more briefly the engine, the engine must supply a stable flow of coolant to the reactor that respects the material temperature limits for things like inlet flows to the reactor and the neutronic feedback requirements which are very essential to the stable operation of a reactor.

Also, a reactor is a temperature-dependent heat source and this actually a big difference between reactors and fossil-fueled systems where in a fossil-fueled we control the heat output by changing the fuel flow whereas in a reactor generally we change the power of the reactor by changing the inlet temperature. That's the way most PWRs are actually operated. The control what’s there are really just for trimming and not really for power adjustment.

That's talking about power conversion for nuclear reactors in general. This talk clearly – because it's within the Generation IV International Forum, it's specifically in the Generation IV reactors. And I want to concentrate on why Generation IV reactors in general are different to the mainstay of the reactors in the world today, which are generally light-water reactors, with some heavy water reactors and gas reactors as well.

But generally, the Generation IV reactors allow us to do much more with power conversion than we can do with Generation I, II and III reactors that we've had so far.

At least three concepts in GEN IV actually operate at high temperature, and we need heat engines that can exploit high temperature heat sources efficiently. We don't have to use the high temperature, we could actually downrate the heat output if you like to a lower temperature, and then use a steam cycle. But it seems a waste of us using a high-quality heat source if we actually do that.

Some of the high temperature systems, particularly the HPGRs and GFR use the colder fluid that returns from power conversion system to actually cool the reactor pressure vessel. We might also use it to cool parts of the pressure boundary as well. So this ultimately places a limit on the amount of heat, the waste heat recovery that we can actually achieve within the cycle. Some cycles are deliberately downrated such that we can have a lower gas temperature coming back to the core and that actually bleeds efficiency but it allows us to manage the temperature of the main pressure boundary structure.

Two of the concepts in GEN IV are gas cooled. So we're looking at GFR and VHTR [ph] in particular. And all gas-cooled reactors use a low-density coolant, which is very expensive to circulate, consumes a lot of power. In GEN IV, these two particular reactors use helium, which is a very low-density gas. In the UK here we cool gas-cooled reactors with CO2, which is quite a bit denser. But even with CO2, it does take a lot of energy to circulate the coolant through the reactor core.

So with gas reactors, we sometimes trade-off the difference between core inlet and core outlet temperature – we try to make those wide as we can to minimize the flowrate of gas through the core. And it's important to minimize the core pressure drop because the power consumed in actually pumping the gas through the core is proportional to the volumetric flowrate of coolant to the third power.

So if we drop the coolant flow rate a little by expanding temperature range out, then we do get a significant drop in core pressure lost and therefore a significant loss in pumping power.

Generation IV reactors have the means of actually doing more things with the heat than we can do with a steam cycle. So that's kind of where I am starting from. The basic structure of a thermal power station is largely the same regardless of whether it's fossil-fueled or whether it's a nuclear power station. At the left-hand side we have a heat source which generates thermal power – either combusting fuel or reacting neutrons together with fissile materials to produce heat. That thermal power then drives a heat engine. That heat engine must reject some waste heat into the environment and I'll say a lot more about that later.

The main purpose of the heat engine is to generate mechanical power and that mechanical power drives a generator, which then is used to generate electricity. There are other ways of converting heat into electricity, things like thermoelectric conversion for example or we could convert the heat into say hydrogen and then we could use the hydrogen in fuel cells.

But in this talk I am sticking completely with heat engines. The idea is we turn a shaft, the shaft turns a generator, and that generates electricity. And that's kind of the most well-established and highest technological readiness level of technology that we actually have.

If we look at the particular case of fossil-fueled power station, the heat source is actually the furnace and the boilers. So we put coal or pulverized coal or oil or gas into the furnace. We combust that with air. The combustion products, heat water in tubes and ultimately the fluid gases have to be vented up a stack, which actually carries a certain amount of energy away with it.

So with a fossil-fueled power station, we always lose energy up a stack. We can reduce the temperature a reasonable amount, but if we go too far then we start to get acid corrosion in the fluid structures and things. So we always have to waste some energy up the stack with a combustion plant.

The main prime mover or the main engine in a fossil-fueled plant is the steam turbine. The steam turbine rejects its waste heat to or its exhaust goes to a condenser. The condenser tends to be cooled by cooling water which is either drawn from a river or the sea or the ocean or in the image shown there, it's actually cooled in cooling towers. So these are natural draft cooling towers. The big clouds of vapor above those cooling towers actually carry the heat away.

And then finally, we've got an electromagnetic alternator at the end, which converts the mechanical power into electricity.

That's the case for a fossil-fueled power station. If you looked at nuclear station, a typical GEN I, II or III nuclear power station, it's pretty much the same other than instead of having the furnace in the boilers, you've got the reactor in the boilers with the most notable omission now actually being there is no stack. So for the same steam temperature, in a nuclear plant we actually do get more efficiency than we do from a coal-fired plant because we are not wasting heat up the stack anymore.

Finally, in the series of slides if we look at the situation with Generation IV reactors and I put the schematics of the six main Generation IV reactors on the left-hand side there. Generator IV reactors generate heat. I've deliberately said they are not generating steam because not all of them have steam cycles or have boilers, so they generated heat. That then drives the heat engine. The heat engine must reject some heat through the environment. That heat engine generates mechanical power which drives the generator as before.

The question then comes about, well what actually is the heat engine? What is the most suitable heat engine? And the answer is, there isn't a single-most suitable heat engine for all six different types. We can probably group them together in terms of temperature and look at different heat engines for different temperature clusters but there isn't a one-size-fits-all heat engine for all Generation IV reactors.

This leaves us with some questions, the first of which is how much mechanical power do we get for a given amount of thermal power that we actually put into cycle or put into the engine and that effectively is expressed by the cycle efficiency? Why do we have to reject heat to the environment? How do we maximize the efficiency of the whole system? And then finally, what do we put in the ‘heat engine’ box for all six Gen IV reactors? The rest of the presentation really addresses those four questions.

So the answers or where we can find them lie or at least the answers to the first three questions lie in the first and second laws of thermodynamics. And the answer to the fourth question depends on the first three, and on matching the heat engine to the specific characteristics of the reactor. And this comes back to this intimate coupling between the reactor and its power cycle. And we have to exploit the ideal temperature ranges and the metallurgical limits for each reactor in choosing the power cycle or be matched with it.

The first three questions – just repeating them again. How much mechanical power do we get for a given amount of thermal power? Why do we have to reject heat to the environment? And how do we maximize the efficiency of the whole system?

So I apologize to two groups of people. First of all, those who know a lot about thermodynamics because what I am going to say will be quite basic; and those who don't know anything about thermodynamics, you are about to learn some, which a lot of it is a statement of the obvious but it can appear to be a bit heavy at times. So I will do my best to get through to satisfy both groups.

The first law of thermodynamics is defined as ‘When any closed system is taken through a cycle, the net work delivered to the surroundings is proportional to the net heat taken from the surroundings.’ So the work, ‘W’ that's the work driving the shaft is equal to the difference between the heat we put in ‘Q-in,’ and the heat that we take out ‘Q-out.’ So it's a direct conversion between the amount of heat we consume and the amount of work that the engine produces. It's just conservation of energy.

For a steady operation of a closed-cycle, we have this diagram which is shown here. So a lot of these block diagrams. We have heat engine, we take heat from a heat source and we reject waste heat through a heat sink and we produce useful work, which will drive a generator.

The cycle efficiency is actually very simply defined as the work done divided by the heat supplied. So if we have a cycle efficiency of 100%, then all the heat that we were putting in was actually being converted into useful work, which implies that Q-out actually equals zero. So if you then go on, we find that for an ideal engine we'd actually like Q-out to be zero and there's nothing in the first law to actually prevent us having Q-out equals zero.

So we have to rely on the second law to actually see why we can't practically make the heat rejected from a heat engine, zero. So the second law of thermodynamics states ‘It is impossible to construct a system which will operate in a cycle, extract heat from a reservoir, and do an equivalent amount of work on the surroundings.’ And for reservoir, we can read heat source or heat sink.

So the second law is a statement that some heat must always be rejected from the cycle and that as a consequence the cycle efficiency will always be less than unity. And this basically comes about because we can only kind of reject heat at the temperature that the environment is. Or the minimum temperature we can reject the heat is the temperature that the environment is in which the cycle actually sits. So we can't reject heat at say 20 degrees when our heat sink temperature is actually 30 degrees.

If we look at the heat engine now sitting between two reservoirs, a hot reservoir, which could be the reactor boilers if it was a steam cycle; and the cold reservoir which would be the condenser and ultimately the sea or the atmosphere and then got the heat engine in the middle. And if we then look at what the consequences are if we take the first and second laws together.

The first law states that we can't produce more work than the amount of heat that we actually supply – you don't get anything for nothing. And in fact the work we get out must be less than the heat we supply because we've got to reject some heat to the environment because we can't reject heat at a temperature which is less than the environment in which the heat engine actually sits.

The first law basically states ‘There is no such thing as a free lunch. We don't get anything for nothing.’ And the second law is basically, ‘You don’t even get as much lunch that you think you have paid for, basically because you've got to reject heat to the environment.’

So if we go on from that, and those of you who are students of thermodynamics would have sat through all of these lectures of all proofs of the corollaries of the second law. So I am going to try and keep this very brief.

There are eight corollaries of the second law. And ‘corollary’ is a bit of an unusual word, so I've taken the time to actually define it, particularly for non-native English speakers. So a ‘corollary’ is a noun, it's a proposition that follows form, and is often appended to, one already proved. So it’s in essence about consequence of the result. There eight such corollaries of the second law. I'm not going to go through all of them in detail but I'll go through the ones which are important when we're thinking about heat engines.

Corollary 1 states, ‘It is impossible to construct a system which will operate in a cycle and transfer heat from a cooler to a hotter body without work being done on the system by the surroundings.’ So basically, heat likes to flow that have temperature gradient, it flows from hot bodies to cool bodies. If you want heat to flow from a cool body to a hot body, we must go and do some work on it in order to do that.

An everyday example of that is your refrigerator in your kitchen that cools things by doing work on a fluid, which then drives heat upwards through a temperature gradient rather than downwards, which is the way it naturally wants to flow. You can think of heat being like water. It naturally wants to flow downhill and if we want it to flow uphill, we've got to use a pump and do some work on it.

So the consequence is the system must reject heat. This heat must be rejected at a temperature not less than that of the surroundings if we wish to maximize the work for a given heat input. So practically, on Earth, a typical heat sink temperature is probably about 30 degrees sink because we've got to have a temperature drop to the atmosphere or a temperature drop to the sea to actually get the heat to actually flow out of the system.

So for all practical heat engines, the heat sink temperature must be about 30 degrees centigrade or 303 Kelvin in absolute units. Okay, you can move it to various parts of the world like into the Arctic Circle where you can go a bit lower; and equally well, if you move to the tropics you've got to go a bit higher. But generally it's about 30 degrees centigrade.

I just want to talk a bit about this term called ‘reversibility’ which is used a lot in thermodynamics. A reversible thermodynamic cycle is one where basically we can reverse the cycle and return the fluid and the surroundings back to their original state.

So if you can imagine you have an engine, you put heat in it, it generates some work and it rejects some heat to the environment. And then if we actually reversed everything and actually drove the shaft of the engine, it would suck heat from the cold reservoir, take it back a bit in temperature and push it back out into the hot reservoir, which is precisely what Oak Ridge does.

So a reversible heat engine is one that can do that ideally without any losses in the forward or reverse directions. So, a reversible heat engine is an idealization and all real processes are irreversible. We have factors such as friction. We have energy loss through noise and things like that. So in reality we can never have a fully reversible heat engine.

Therefore, an ideal heat engine is fully reversible whereas all real heat engines are irreversible.

Corollary 2 – I'll come back to reversible in this definition. Corollary 2 says, ‘It is impossible to construct a heat engine operating between two reservoirs which will have a higher efficiency than a reversible heat engine operating between the same two reservoirs.’

So it's basically saying, if we have a heat engine operating between two temperatures, it can't be more efficient than an ideal heat engine operating between those two temperatures because by definition, all real heat engines are non-ideal.

This actually gives us a very useful measure of what is the maximum efficiency we can ever achieve if we are working between two temperatures: T-in and T-out. T-in is the hot reservoir temperature and T-out is the cold reservoir temperature.

And this is actually known as the ‘Carnot efficiency,’ which is derived in an ideal cycle called the ‘Carnot cycle’ and it's just simply defined as the temperature difference between hot reservoir and a cold reservoir divided by the temperature of the hot reservoir – all in absolute units in Kelvin.

That actually puts an upper limit on what we can achieve for any reactor system regardless of which heat engine or which technology we actually use to convert the energy.

So if we look at the GEN IV reactors, we look at VHTR for example, with an inlet temperature of 1000 degrees centigrade, which is 1273 Kelvin and the maximum efficiency we could achieve if we had an ideal heat engine attached to VHTR is 76%. GFR is slightly smaller reactor core, overhead temperature of 850 degrees centigrade or 1123 Kelvin, that gives us a maximum efficiency of 73%.

And sodium cooled fast reactors, the temperature runs through about 550 degrees centigrade to give us margined boiling of the sodium. Then that gives us an efficiency of 63%. All this is based on a heat rejection temperature of 30 degrees centigrade or 303 Kelvin.

So to some extent we can't actually – no matter how good we make the engine, we will have a limit on efficiency, which we can't get around, which is driven by a core outlet temperature at the top end and then at the bottom end governed by the heat, the temperature at which we have to reject heat to the environment.

The other important corollary is Corollary 5 and its much simplified definition is ‘The efficiency of heat engine is maximized if heat is added at a constant temperature and heat is rejected at a constant but obviously lower temperature.’

So if we can put all the heat in over a very narrow temperature range and we can take all the heat out over a narrow temperature range, we will end up with a cycle which is actually more efficient than if those temperature ranges were wider. So we must minimize the temperature ranges over which we add and remove heat and the ideal is to do both of those things at constant but different temperatures.

So the impact for GEN IV reactors is different depending on which system you look at. It's very good news for liquid metal-cooled reactors, the SFR & LFR because the difference between the core inlet-temperature and core outlet-temperature in those reactors is actually quite small, which is of the order of 100 degrees centigrade to 150 degrees centigrade.

It's very bad news for the gas-cooled systems, and this takes respect of the comment I made earlier that it is very expensive to pump coal in through gas-cooled reactors. So you actually want to maximize the temperature-wise over the core rather than minimize it as would be dictated by Corollary 5.

So with the gas reactors we have a compromise where we're trading off excess of pumping power against loss of thermal efficiency. So again, this comes back to my point of there is no one-size-fits-all for power conversion systems for generation core reactors.

The other corollaries I'll just mention in passing. I think they are quite interesting, if you ever wonder why certain things are the way they are.

I mean, Corollary 3 is quite obvious, basically says, ‘The efficiency of all reversible heat engines operating between the same two reservoirs are identical.’ So basically, if you put one ideal engine next to another ideal engine, because they are both ideal, then the second one can't be better than the first one. Again the same and obvious but actually it's quite a useful definition when actually analyzing and comparing heat engines.

Corollary 4 states that there must be an absolute zero of temperature. If you ever wondered why absolute zero is -273 Kelvin, and why it even exists at all, then Corollary 4 is the explanation behind that. It's a temperature which an ideal heat engine will give you an efficiency of 1. It's clearly things as far as you can cool.

Corollary 6, which is known as the ‘Clausius Inequality,’ follows from Corollary 5 and it's on the basis of Corollary 7 – and apologize for this – which defines a new property called ‘entropy,’ which is actually useful.

Corollary 8 states that the change in entropy is zero for an adiabatic reversible process and is always greater than zero for a real adiabatic processes. So ‘entropy’ is a measure of disorderliness in a system. It's kind of an [Unclear] quantity but it's very useful and it's essential in terms of determining the performance of propeller cycles.

So entropy is used as a measure of irreversibility of real processes, things like compressors and turbines through the parameter called isentropic efficiencies. An ideal turbine without an isentropic efficiency is 1 and a real turbine without an isentropic efficiency of less than 1. I am not saying much more about entropy other than using it as an axis to plot some cycles on cycle diagrams.

The other thing we have to pay attention to is [Unclear]. And the objective of the heat engine is to produce net work. But we can actually come up with engines which don't produce any net work at all. Certain processes in the engine produce positive work, such as a turbine but some processes in the engine actually consume work, which is a compressor, for example.

And you could actually come up with a cycle which is self-sustaining but all the compressor work completely balances the turbine work and there is no net work output. So in the end we reject heat but we don't actually generate any work which leaves the system. And so let's be careful when we are designing a system to actually minimize the work which is consumed by the system itself in order to maximize the work ratio.

So typically, things in power plants which consume power, things like the feedwater pumps, the pumps which pump the water up to pressure and into the boilers, the extraction pumps which take the condensate away from the condensers before re-pressurizing it back to the boiler pressure; the condenser vacuum pumps which try and pull the condenser pressure down such that we can condense it at the lowest possible temperature we can; cooling water pumps. And for a gas turbine cycle or Brayton cycle, specifically the compressor work.

For a heat engine attached to a nuclear reactor we have to consider the work required to circulate the coolant within the primary circuit. The work ratio is actually defined as the net work which the cycle produces, the shaft work, if you like, divided by the positive work. And the net work is, as it says, the positive work minus all the internal elements of work which you consume and the positive work is the work generated by the turbine.

The cycle efficiency is maximized if the work ratio is as large as possible. So if we have no net work at all, then our cycle efficiency would be zero, for example.

Let's look at some practical cycles. The Rankine cycle is well over a 100 years now, probably about a 120 years and it is pretty much the way electricity is generated in the world today in pretty much every power station.

We have a boiler. The boiler generates steam, high-pressure steam that drives a high-pressure turbine. The exhaust from the high-pressure turbine tends to go back to the boiler and is then reheated and then passed through usually more than one turbine, an intermediate pressure turbine, an LP turbine – I've just put in this diagram with an LP turbine for simplicity.

The exhaust from the turbine comes out as low pressure, much lower temperature steam which is then condensed. It flows over tubes which are cooled by cooling water, so it's condensed back into water. And then it's fed back up this thing called a ‘feed train’ via feed pumps and feed heaters back to the boiler. These feed heaters are actually quite interesting because they actually use steam which is bled from the casings of these turbines. So it's using wet steam and steam which basically drains moisture away from the turbine casings to actually pre-heat the feed water before it actually goes back to the boiler.

If you look at the cycle background and I'll start at the boiler outlet here, which corresponds to 0.1 on the cycle diagram over here, you've got a vertical axis of temperature and you've got a horizontal axis of entropy, this imaginary quantity which I said before. Entropy measures this disorderliness and basically usually moves from left to right; the fluid becomes more disorderly.

So on the left-hand side it's all liquid, on the right-hand side it's vapor and vapor is a much is a much more disordered form of matter than liquid. And in the middle we've got a combination of liquid and vapor, which actually tends to become more vapor-like as we move to the right, and more liquid-like as we move to the left.

This domain here where we get liquid and vapor together is bounded by this bell curve here called the ‘saturation line’ and the very top of the saturation line is called the ‘critical point.’ And that's important later when I actually talk about supercritical cycles. So when I talk about the critical point, it's that point up there where in principle a supercritical fluid can go straight from being liquid to dry vapor without actually going through any wet vapor stages in the middle. But anyway, I'll come on to that in a minute.

So we start at the turbine inlet, which is 0.1 over here. Expand them through the high-pressure turbine. This steam then goes back to the boiler to be reheated and recombined with the exhaust from the high-pressure turbine to 0.4. And 0.4 is the inlet to the LP turbine here. So we're back up to full temperature that the boiler can produce and then we expand down through. Each of these lines crossing from left to right is actually a line representing a constant pressure. So as we descend down across these lines, are actually dropping in pressure until finally we reach 0.7, which is the turbine exhaust here.

Then we condense the wet vapor back across to 0.8 here by passing it over cool tubes. So that takes us to 0.8 here. And then we go up through these various pumping and heating stages. So the first feed pump takes us up to there, the feed heater takes us to there, the second feed pump to there and so on, until finally we reach the end of the feed chain where the water is almost at boiling point. It's hot water which is only a few degrees below the boiling point. So all the boiler is doing really is, it's not really raising the temperature of the water at this stage, it's actually changing its phase because it's already almost at boiling point.

And this power cycle is typical over in a gas cooled reactor in the UK. It's a bit more complicated than you find on a pressurized water reactor because we can't get up to this high temperature on a pressurized water reactor and therefore, we don't have things like reheat and we have very little of superheat. So it's a very standard cycle, pretty much unchanged from what you'd see for the last 100 years for coal-fired power stations.

This is just setting out in words what I've just talked you through in the cycle. So I think I'm not going to go through every point on this slide but it’s there for you to read offline if you wish. Apart from the last one where basically we would say, ‘High efficiency is achieved because of an excellent work ratio and the bulk of heat addition and heat rejection actually occurs as a constant processes.’

So when we are evaporating the water – and I'll just go back a slide – when we are evaporating the water across here, this heat addition actually is occurring in almost constant temperature. We are putting some heat in to get superheat, which isn't at constant temperature but that's actually a small fraction compared to the heat input to change water into steam. So we are complying with Corollary 5 and the second law. That we're adding the heat at constant temperature. The feed pumps require very little work so we've got an excellent work ratio.

And then finally I'll just go back to this slide for one last time. When we reject the heat, we are rejecting the heat between 7 and 8 in the condenser, and again that's happening along this horizontal line. So it's happening at constant temperature. Again, this complies very well with the requirements of Corollary 5 of the second law. So, there’s a reason why steam cycles have lasted so long and why they are highly regarded and highly optimized because they do give you very high efficiency over the range of temperatures that they are actually working because of the particularly thermodynamic characteristics of the fluid.

So let me come up with some of the higher temperature Generation IV reactors, we can get a bit more adventurous with power conversion and we can look at things like using gas turbines. Anybody who has been on a jet aircraft will have some familiarity with gas-turbine technology. The difference here is we actually want the turbine to drive a generator.

The thing which isn't shown in this diagram is the shaft and then a generator on the back end of it and their arrangement would be pretty much as shown there, the shaft just drives the compressor and the exhaust from the turbine produces the thrust to drive the aircraft. But in this case we're interested in mechanical work coming out of turbine to drive a generator rather than thrust.

This is a recuperated gas turbine which works in a closed cycle. We put in heat from a heat source and that could be directly from a reactor core with a gas reactor or it could be via a heat exchanger which put the coal to a liquid-metal reactor, for example. So the heat goes into the fluid – typically helium, could be nitrogen, and that sort of drives the turbine.

The gas expands then through the turbine, it loses pressure, it losses temperature but it's still quite hot.

This is a gas turbine cycle for a sodium-cooled fast reactor. So the maximum temperature is about 550 degrees centigrade. Even after it has come out of the turbine, it’s still at 432 degrees centigrade. So there's still quite a lot of useable heat in there. So we give that up in a recuperator, which is just a heat exchanger. And then the heat that we can't give out anymore, we reject to the environment through the pre-cooler. So that complies with the need of the second law to reject the heat [ph].

And then the gas coming back from the pre-cooler – and the pre-coolers are now just a condenser in a Rankine cycle. The gas leaves the pre-cooler at about 60 degrees centigrade and comes through the compressor and it is compressed back up to about 20 megapascals and it is taken to about 150 degrees centigrade before being reheated in the recuperator and then back into the reactor.

In the cycle diagram, we don't have any saturation line on this diagram because we're working completely in the vapor range of the work included. The saturation line would be right over here somewhere off the page for a gas like helium. So again, just walking around the cycle, we come into the compressor, in that we compress up, we absorb some heat from the recuperator, which is called ‘regeneration.’ We put the rest of the heat in from the reactor and then we expand them through the turbine. We use some of the waste heat in the recuperator to pass across to the heat leaving the compressor and then we reject the rest in the pre-cooler.

What you can actually see from this diagram, these two constant pressure lines. According to this cycle this is the 200 bar line and this is the 75 bar line at the bottom. And we notice that the vertical distance, the temperature difference between points 1 and 2 is actually slightly smaller than the vertical distance between points 4 and 3. So the temperature drop from ideal gases is proportional to the energy change between those two points. So we get slightly more work out of the turbine than the compressed consumes because of the difference in vertical height between the two constant pressure lines on both sides.

If that height was exactly the same as the height 1, 2, then the turbine would be generating exactly the same amount of work as the compressor was consuming and that would give us a work ratio of zero. So what we want for a good gas turbine cycle is for this difference in height between 4 and 3 to be as great as we can make it between 1 and 2, which generally means we've got to push this across to the right, which also means pushing up in temperature.

So gas turbine cycles tend to only work at high efficiency once we can get the turbine temperature up to actually quite a high temperature, such that we get a good work ratio out of the cycle.

Again, I am not going through this because I've just talked you through the cycle. But I'll concentrate on this last and just reiterate it. The constant pressure lines on the T-s diagram diverge slowly with increasing temperature such that the temperature drop, and hence enthalpy change, over the turbine is greater than the temperature rise over the compressor.

So we need to basically make T3 very large or we need to make T1 as small as possible in order to get a reasonable work ratio. The recuperator actually increases the temperature and reduces the temperature range over which heat is rejected. So again, we are trying to push as far as we can towards this ideal of a Carnot cycle where the heat is all injected at a constant temperature.

So if I just go back a slide, the closer we could move 0.5 up to 0.3, then it actually narrows the temperature range over which the reactor must insert the heat, and that generally drives us towards higher thermal efficiency. So the better the recuperator we have, the higher the thermal efficiency we can actually get out of the cycle. Ultimately, we can't push 0.5 above this 5-dash or 5-prime mark because we can't preheat the gas going into the reactor to be hotter than the gas which is actually just leave in the turbine.

So there is a cycle which actually combines some elements of both the cycles we've just talked about and that's the combined cycle. And this works well for high temperature reactors such as VHTR or GFR and it's also used quite a bit in gas-fired power stations as well and fossil-fueled stations to actually make use of a high temperature heat source that we can actually get with gas. We can put gas straight into a gas turbine. We don't need furnaces and boilers and things and we can use the turbine exhaust to raise steam by the steam cycle. So there's a lot of practical experiences in the world with combined cycles.

In the context of a Generation IV reactor, in this case, GFR – this is reference cycle for GFR 2400 in which the gas comes out of the reactor core. This is helium, so it's a reactor-friendly gas if you like. At 70 bar it gives up its heat to a heat exchanger and it is recirculated via a gas circulator back through the reactor core. The other side of the main heat exchanger which actually gives up the heat to a helium-nitrogen gas mixture, which then drives a gas turbine.

It's a non-recuperator turbine because we are using the waste heat to generate steam in a steam generator and the gas which comes out of the steam generator is re-compressed in a compressor and so on. So that's the gas turbine part. That drives its own dedicated electrical generator. And then finally, the steam drives a combination of high, intermedium, low-pressure turbines as we've seen in a normal Rankine cycle and we have another generator connected to the shaft of that. You could in fact couple both generators to the same shaft if you could arrange to put both these turbines around the same speed.

The waste heat from the turbine, as before, goes through a condenser, which is cooled by a flow of water, cooled by the environment back through a feed pump and a feed train into the boiler. This is a very simplified steam cycle just to show this diagram. It's a bit more complex in reality.

But what I've presented at the bottom of the slide is the overall efficiency for different cycle options. We could have a direct gas turbine cycle which is the top-grade, Grade-Out 1 and that would give us 47.5% efficiency with T-in, and that's the temperature going back to the reactor at 480 degrees centigrade. So the reactor pressure vessel and the inlet structures have to be able to withstand 480 degrees centigrade for the lifetime of the plant. But we do get the highest efficiency with that.

We can put a heat exchanger in so that we don't use the reactor gas to drive the turbine directly and that gives an efficiency which is about 2 percentage points lower than we get with a direct cycle. We can look at a direct cycle where we've deliberately tried to pull the reactor inlet temperature down, so we were going to do recuperating and that cost us about another percentage point.

Or we can do the indirect combined cycle, which gives us the same inlet temperature for about the same efficiency but it is actually there are some significant cost advantages in actually going down that route and I'll come on to that in a minute.

And then finally, we can use an indirect combined cycle which takes us down to about 42%. So the direct cycle is actually being explored quite enthusiastically by systems like VHTR and by GFR.

So, why use a combined gas turbine cycle or a combined cycle gas turbine?

The first and the overriding one is the cost of the turbine. Steam turbines are cheaper and they are made of simpler material and there’s a lot of them out there. Gas turbines, they have aero engineering with very elaborate materials and so they are expensive. So the idea would be to have a very big steam turbine generate most of the power, and the gas turbine just taking advantage of the small fraction of high-temperature heat.

Heat exchangers are quite expensive items but heat-recovery steam generators are well-established and quite a low-risk technology and highly effective gas to gas recuperators, the sort that we need for a closed cycle gas turbine, are actually very expensive to get and a very high effectiveness that we need from these.

And combined cycles have a good track record with many hundreds of years if thousands of years' experience now in the fossil-fueled combined cycle gas turbines industry.

So we deliberately try to bias the cycle – I'll just skip to the last bullet point – such that the bulk of the power is generated by the steam cycle to minimize the cost of the gas turbine cycle. And these cycles win out massively in terms of economics.

The fallback option that we looked at for GFR was Supercritical CO2. And this is a gas turbine cycle using a supercritical fluid. And it's also being explored actively by a number of nations, a number of Generation IV member states, as an option for sodium-cooled fast reactors because the chemical reactivity of the carbon dioxide with sodium is actually much less severe than the chemical reactivity of water and sodium.

The other advantage of supercritical CO2 is we can actually get quite a good efficiency for not a particularly high temperature. One of the problems we have with GFR is we may not be able to come up with a fuel technology which is capable of operating in a sustained manner at 850 degrees centigrade but we might be able to do something which operates at around about 680 degrees centigrade to 700 degrees centigrade with more conventional materials.

If that was the case such that we had a moderate temperature GFR rather than a high-temperature GFR, then this cycle would return an efficiency comparable to what we'd get with either a helium Brayton cycle or a combined cycle at a temperature which is in the range of 150 degrees centigrade to 200 degrees colder than the referenced design would actually require. This is actually quite a complicated cycle because supercritical fluids are difficult to work with. They got some bizarre thermodynamic properties very close to the critical point. So we've got to manage the heat exchanges in these recuperators very carefully by splitting and recombining fluid streams and using main compression and auxiliary compression and things like that. But the technology of these cycles in terms of thermodynamics are very well understood.

The engineering often is probably not quite so understood because the theoretical possibility of having a cycle like this has existed for quite a long period of time. But it's only in the past decade where people have actually started to build laboratory scale engines to actually test the practicalities of making one of these cycles. One of the biggest problems we have is we have to operate at very high pressure.

So we are looking at something like 250 bar for the maximum pressure, which then gives us very thick wall thickness for the pipes. It gives us very large temperature and pressure differentials across to recuperators, which present quite significant engineering challenges.

Supercritical fluids are great to compress because they are very dense near the critical point. If we can compress near the critical point, we don't use much work. But they are actually a lot more schizophrenic in nature. They can behave like liquids in some instances and behave like gases in others. So the mechanical design of the compressor is actually quite difficult as well.

And looking up, this on the temperature entropy diagram again, we're doing the bulk of the compression here where all these constant pressure lines bunch up as they run over the top of the critical point. If you imagine this, this is the top of the bell curve that I showed for the Rankin cycle before with the critical point right at its summit. So we are compressing very close to the critical point where all these lines bunch up as they run over the top of the critical point. So this requires a small amount of work.

We are doing some compression here away from the critical point but we're only compressing something like 40% of the total mass flow of gas, which is going around this circuit. So even though the height difference between there and there and the turbine there and there are very similar, we've got 100% flow going down there and we've only got 40% of the flow going up here. So we still win out overall in terms of work ratio. So I say it's quite a complicated cycle with all these slide points referring to the different recuperators.

The good thing about supercritical CO2 is it works very nicely on Earth. The critical points of CO2 is 73.9 bar absolute and 31.1 degrees Celsius. And 31.1 degrees Celsius complies very nicely with our minimum heat sink temperature of 30 degrees centigrade, which I've mentioned on one of the previous slides. So it works well on Earth because this point here corresponds very nicely to the temperatures we can achieve with terrestrial heat sinks.

The space applications are literally cycles for space power. They are not so good because in space, we want to reject heat at a much higher temperature because we're using radiators. But if you're using sea water, then the thermodynamic characteristics of CO2 at the critical point are dearly suited to the cooling of sea water or atmospheric cooling.

So that’s the supercritical CO2 cycle. I've talked a few times about direct or indirect cycles particularly for things like gas reactors but also for things like supercritical water reactors where in a direct cycle we actually use a reactor coolant, the primary circuit coolant to drive the engine directly. But that places a number of constraints on us. First, I'll talk about the constraints first as we get activation of the turbomachine. We're putting reactor coolant through a turbine and any corrosion products or erosion products which have been activated in the cool will actually get deposited inside the turbine.

Jumping ahead of it, turbine alloys generally require a lot of cobalt for things like Stellite hard facing or hot hardness for gas turbines. If we are going to put those non-reactor circuits, we've got to keep the cobalt out because it becomes very radioactive if it actually passes through the reactor core. Generally, we need to maintain very high fuel impurity, so things like oil-free bearings are required in the gas turbine for gas systems, otherwise we end up with carbon deposition on all the fuel. And the turbine must also use the reactor coolant as a working fluid.

So for the gas reactors in Generation IV it is the helium, but helium is not a great gas to work a turbine on. It's a very low-density gas and takes a lot of work to compress it. It's a good heat transfer gas but it's not a good working fluid for a turbine.

The advantages we get are we have no primary to secondary temperature drops across any heat exchanger. And there is no need to develop a high-temperature heat exchanger. The technology involved in having something which operates at 1000 degrees centigrade is actually quite formidable. So if we have a direct cycle, we can get away from that.

Indirect cycle – again, this is just a mirror image of the previous slide. We end up with primary-secondary temperature drops because we've got a main heat exchanger. We've also got to develop a high-temperature and high technological risk heat exchanger as well. But all [Unclear] we don't get activation of turbomachine; we can use very standard turbine technology with liquid oil bearings. We can use standard turbine alloys and we can have a turbine working with an optimum fluids such as nitrogen.

All the gas turbines or most of the gas turbines in the world are designed to work with air, which is mainly nitrogen. So we are in the realms of well-understood performance characteristics for turbines, which could work with nitrogen. But we can't use nitrogen as a reactor coolant, so that's an advantage that the indirect cycle actually give us.

This is just a little bit of work that Rolls-Royce did for us in the European GOFASTR project on GFR where we just evaluated the different options for the coupling at the power conversion cycle to GFR. And you could take a GFR and put VHTR in and you would get pretty much the same result as well.

So we're looking at on the top left a direct recuperated helium gas turbine. So the reactor coolant drives the turbine. We've got a recuperator to recover waste heat, two-stage compression, intercoolers and pre-coolers and things like that.

Through all here the permutations down to the one which we eventually adopted as a reference, which is actually the indirect combined cycle gas turbine where we use the heat from GFR, the heat exchanger.

I've got connection lost. Give me a second while I get back. Hi Berta, my connection has just dropped out.

Berta Oates
Try opening your link in another browser. Sometime maybe it just needs to refresh.

Richard Stainsby
I think it's a network connectivity this side. I'm getting no internet access on the Wi-Fi. Just give me a second, please. I'll just reconnect the Wi-Fi.

I think I'll give it one more go if it doesn't – oh, and new meeting room window.

It is asking me for a password this time. I've done that before.

Berta Oates
Actually, do you have the slide presentation in a separate file?

Richard Stainsby
I will have if you just give me a second. Okay, yeah. I'll just run through the slide numbers with you.

Berta Oates
So we're currently on Slide #34.

Richard Stainsby
Of course I can't use my pointer anymore but I think we're getting close to the end anyway.

Slide #34

Yeah, the right-hand side we've got the combined cycle gas turbine for GFR where we drive a gas turbine indirectly from GFR via a heat exchanger and then the gas turbine exhaust is used to raise steam to drive the steam turbine. And so that's now the reference solution for GFR and the AREVA ANTARES HTR program are looking in the same cycle as well.

So if I move ahead to Slide #35, where we get on to maximizing the efficiency of the whole system:
A pre-requisite for high cycle efficiency is to operate between max and min temperatures that give a high Carnot efficiency. So we want to push the maximum temperature as high as possible and we want to push the minimum temperature as low as possible driven by the environment in which we have to reject waste heat.

The next, steps to minimize the temperature ranges over which heat is injected and rejected from the cycle. So in something like a Rankine cycle we use feed heating. So we use bled steam from the later stages of a turbine's pre-heat feed water. So what we really want to do in a Rankine cycle is use the heat input to change the phase of water into steam, which we can do at constant temperature rather than to actually heat the steam up from sort of the ambient temperature up to its boiling point.

In a Brayton cycle, we use a recuperator pretty much to do the same thing. We use the waste heat from the gas turbine exhaust to pre-heat the gas before the heat addition from the heat source which in our case would be a reactor.

And then finally, we must maximize the work ratio. So we must minimize the work associated with pumping or compression of the working fluid to maximize the turbine work. For a nuclear plant, it's also important to minimize the pumping power in the coolant – the primary coolant in the reactor as well because certainly for gas reactors that can be a significant fraction of the power output from the actual power station itself.

So moving to Slide #36. This is starting to answer what goes in the heat engine box for the Generation IV reactors. So if we look at them in turn, for SFR, all the sodium-cooled fast reactors in the world so far have actually been paired with Rankine cycle and it worked with reasonably good efficiency. And certainly the steam power plant in the UK was delivering round about 40% to 41% thermal efficiency using quite a highly optimized steam plant but it's a steam plant nonetheless.

The biggest problem with sodium-cooled fast reactors to date has been steam generator tube leaks. Even though we've got an intermediate sodium circuit, the time taken to clean up after the consequences of a sodium-water interaction resulting from a steam generator tube leaks are considerable and expensive as well.

Future SFR projects such as the French ASTRID project are actually looking at eliminating the steam cycle altogether, to remove completely the risk of sodium-water interaction. The short-term option for ASTRID is to actually use a nitrogen Brayton cycle. But as I said before, for Brayton cycle we've really got to drive to high temperatures to get a good work ratio out of it.

So the ASTRID Brayton cycle will deliver thermal efficiency which is actually quite low for a fast reactor. It'll be delivering a thermal efficiency of round about 30% to 32%, which is comparable to what you get from a pressurized water reactor, but probably 10 percentage points below what you'd expect for a sodium-cooled fast reactor.

But it's a first step. It'll be a first time somebody's tried a couple of fast reactors to a non-steam cycle power conversion system. In the longer term, a number of nations including France are actually working on supercritical CO2 cycles for SFR, specifically the recompression cycle as I showed earlier, has a longer term high efficiency options.

Slide #37

If you look at LFR, the current LFR concepts are well matched to steam Rankin cycles and currently LFR is losing [ph] to quite a lower core outlet temperature, probably around about 5 degrees centigrade maximum because of the need to avoid corrosion within the lead coolant. So we get a slightly lower core outlet temperature than an SFR.

But because there is no violent exothermic reaction between lead and water, they don't actually need the intermediate loop in that system. So we save on some of the temperature drops that you'd normally associate with a liquid metal reactor.

So overall, we get an efficiency which is similar to that with the sodium-cooled fast reactor in a Rankin cycle when we are using LFR. So we are looking at sort of 40% to 42% thermal efficiency with LFR, even though the core outlet temperature is slightly lower than SFR.

Future high-temperature LFR concepts, if you are looking at things like using silicon carbide, fuel cladding and structural materials and things like that, high-temperature LFR, if you will, you can actually use gas Brayton cycle.

Slide #38

If we look at GFR and VHTR, they both share similar core outlet temperatures. In fact, the near-term VHTRs are probably lower than what we are writing out for VHTR.

The lowest risk and most economically favorable option for both reactors is the Brayton-Rankine combined cycle, the gas turbine cycle and then the option there to either go for direct or indirect gas turbines. The direct eliminates the need to go with a high-temperature heat exchanger but it then places all the technological risk on to the turbine instead.

The most efficient for both of these is a fully recuperated direct pure gas turbine cycle, Brayton cycle. But that's actually quite technologically-demanding in terms of the gas turbine technology. And so it's quite a big turbine as well by gas turbine standards because that single turbine has to create all of the power from the reactor rather than just the high temperature – a fraction of it.

The fallback option for low temperature variants for both GFR and VHTR is the supercritical CO2 recompression cycle. And ultimately for all these plants this thing, the Rankin cycle is the ultimate fallback option. If you look at HTR-PM in China at the moment, HTR-PM is a high-temperature gas pebble-bed reactor that's aiming to drive a gas turbine steam cycle with things like the Brayton cycle being a future option.

So molten salt reactors. The issue I have molten salt reactors is that there's a number of different concepts from different parties all operating at different temperatures. So it's difficult in advance to actually say, which is the best conversion system.

And looking at the range of options which are available for MSR and MSFR, it could be anything from steam cycle up to gas turbine Brayton cycle depending on the combinations of fuel salts and coolant salts and structural options and things like that.

I think one thing you must guard against is one of the main safety advantages of molten salt reactors is they operate at low pressure, operate at atmospheric pressure. All heat engine circuits will operate at higher pressures. So if you do get a leak in one of the main heat exchangers, you will get power conversion system fluids actually leaking into the salt circuits, which is not good.

If you get water entering into a molten salt circuit, then you've got some severe corrosion issues. If you get gas leaking in, then you've got some pressurization issues for the structure and things like that. So you might still need to have intermediate circuits in molten salt reactors in order to protect the fuel salts from being contaminated by working fluids from the power conversion system.

So supercritical water reactors. I mean this one kind of answers itself. Supercritical water reactors is generally an evolution of boiling water reactors, which are a direct cycle steam cycle reactors. So the power cycle is a supercritical steam Rankine cycle and these exist already. Particularly in Germany with highly optimized fossil-fueled plants, there is quite a lot of experience already with supercritical steam Rankine cycles.

It would be possible to use alternative power cycles for an indirect cycle such as a supercritical CO2 cycle. There may be some benefits in doing that. Again, of course you are keeping the power generation engine, if you like, separate from the reactor circuit and also the turbine machinery for a supercritical CO2 cycle is actually quite a bit smaller. So there may be some cost savings in actually doing that.

And that's my last slide. I hope I've answered the question mark about what goes into the heat engine box for the six systems adequately enough. Clearly, you can get a lot more detail when you look at different variance or different systems. So clearly, in the time that's available I can't go into too much detail on this. But I hope I've given you a flavor for what the options are for Generation IV reactors and their power conversion system options.

So I'll hand back to Berta now to make some announcements and then in the meantime, I'll try and log back into the webinar room so I can actually look at some questions.

Thank you very much.

Berta Oates
Thank you, Dr. Stainsby.

And if you have questions on today's presentation, feel free to type those into the tab pod models. Questions are coming in.

We'll just look at the upcoming webinars. In October, a presentation by Dr. Rothwell on ‘Estimating Costs of Generation IV Systems.’ November, a presentation from Dr. Guidez in France on the ‘Feedback from Phenix and Superphenix.’ Coming in December, rounding out the calendar year, a presentation on the ‘Sustainability of Gen IV Nuclear Energy Systems,’ by Dr. Poinssot, also from France.

Richard Stainsby
Okay. Just give me 30 seconds here. I just need to go back into the meeting room. I have problems because our secure email systems scrambles the link as it comes in. I've got to unscramble it before I can push it to you.

Berta Oates
We can mail it to you.

Richard Stainsby
I think it'll just get scrambled again. So I've got to take out some of the additional characters that are booked in such that we can't open the link automatically. Just bear with me a second longer. Almost there. This is typically the situation where the link worked perfectly during the rehearsal and then falls over during a live session.

Almost there. Do we have questions coming through, Berta?

Berta Oates
We do have a few yeah. Do you want me to read them to you? I don't know if you'll be able to address them while you are doing that.

Richard Stainsby
I think I really need to concentrate on this for the next 30 seconds and then I can…

Berta Oates
No worries. Take your time. No worries.

[Pause]

Richard Stainsby
Okay, this is looking good. Until we connect.

Berta Oates
Can I see you?

Richard Stainsby
I am now locked in as a presenter. Can you still hear me?

Berta Oates
I can. So in the Q&A pod there are the two tabs. One is a presenter view and one is a participant view. And if you click the presenter view, you should be able to answer a question –

Richard Stainsby
Here we go. Click to expand question.

Berta Oates
Do you see the question from Zaven? What power..

Richard Stainsby

Yeah. ‘What power conversion systems are best for MSR – molten salt?’ Yeah, I think my penultimate slide basically said I think because of the wide range of molten salt reactants, it's actually quite difficult to come up with an ideal at the moment because different vendors or proponents in the systems are actually at working to different temperature ranges.

Some ones have I guess what in Europe we'd call the ‘EVOL’ type system where it's molten salt in a vat. Other ones have developments of the technology that was originally developed at Oak Ridge before the MSRE. So they have individual fuel tubes of salt and these fuel tubes are surrounded by coolant tubes and these operate at quite widely different temperatures.

But I think, if you go back all the way back to Generation IV roadmap, I think MSR originally was intended to be a high-temperature system driving a gas turbine and I think that's probably still an option for some of the systems. I think there are a few technological challenges associated with heat exchangers that clearly whatever you do in a molten salt reactor, you've got to do it as an indirect cycle. You're not going to be driving a turbine with salts directly. So there are issues surrounding the heat exchanger technologies. And the higher temperatures you go to then the more demanding the technological requirements for that heat exchanger actually become. And we have to combine that with the high-temperature operation with the potential corrosion issues and also looking at, as I mentioned in the slide, what happens if the power conversion system fluid is actually leaking into the salt circuits. So if you are driving a steam cycle I should imagine it's pretty catastrophic if we actually get a high-pressure steam or water leaking into a low-pressure salt circuit in terms of producing a very corrosive salt solution in that salt circuit. So we might need to consider technologies like the double wall heat exchangers or have some intermediate fluid which is neither salt nor water and which is compatible with them both to actually address that.

I think, it's very analogous to the sodium-water interaction problems you see with sodium-cooled reactors but it might not be the same chemical reaction in terms of generating hydrogen and things like that. But the corrosion issues you get from generating sodium-hydroxide in sodium-cooled fast reactors would be very analogous knowledge to what you've actually seen in a molten salt reactor if you start to make salt solutions in some of the salt circuits.

How do I tell if the answer was I think what..?

Berta Oates
Well, they will follow-up in a Q&A if we missed the point or something like that.

Richard Stainsby
Okay. So I'll scroll down a bit.

I apologize if I get your names appallingly wrong. Edgaras Smigelskis, '28th slide – the temperature gradient is very high. How about thermal stressed? How is it solved and are there any challenges?'

I just need to go back. The presentation should be coming up in the main window for me, so I'll go back to my standalone copy.

I am not quite sure what you mean by temperature gradient in this case. I mean, 400 degrees centigrade core inlet to 850 degrees centigrade core outlet is pretty typical of the high-temperature gas reactors – GFR and VHTR.

So I think again, that's 450 degrees centigrade temperature rise over the core and that's to try and get the pumping power down to be something sensible and also to be able to use the incoming gas to cool the reactor pressure vessel.

In all high-temperature reactors, you keep the core outlet gas away from metallic structures. So the core outlet gas will be handled completely by ceramic-lined structures, either graphite-lined structures in the case of VHTR or some other ceramic-insulated structures within GFR. There is nowhere in GFR other in things like heat exchangers and turbines to expose metallic structures to 850 degrees centigrade.

Again, I hope I've answered the question.

I've got the next one. Edgaras asked again, 'Is the 0.6% to 0.7% efficiency for the electric output heat produced/electricity generated having in mind that conventional NPP efficiency as 0.3?'

That's actually a good point. When I was talking about Carnot efficiency earlier in the presentation, that was simply about the conversion of thermal energy into mechanical energy. There is another small efficiency drop as we go from mechanical energy into electrical energy, which is typically of the order of another percentage point, something like that.

And then we have further losses which are things like transmission losses and transformer losses and what have you outside. So the typical NPP, nuclear power plant efficiency of 0.3 is absolutely right for a pressurized water reactor plant. About 30% of the energy leaving the fuel becomes electricity, which is exported from the station. But to a first approximation, we can look at the thermal efficiency in terms of the mechanical efficiency to be very close to what we see as overall thermal fuel electrical efficiency.

Again, I hope that answers your question.

Michael Pimentel, ‘Thank you for your presentation today!’

Well that's an easy one. Thank you too for listening.

And I have another one from Edgaras, ‘24th slide - shouldn't there be a steam line from H.P. turbine to overheat steam before it enters L.P. turbine?’

You could well be right there because there because I was having trouble reconciling the cycle diagram on the right-hand side with the schematic on the left-hand side originally. I kind of picked these images out of the open literature. So there may be an omission there. I thought it was good in that it had all the major elements on. But again, I was scratching my head a bit working out how the schematic on the left actually corresponded with the cycle diagram on the right.

I actually think there should be a bleed of steam from the H.P. turbine into the L.P. turbine to actually give the TS diagram on the right-hand side, which doesn't seem to be present in the schematic on the left-hand side.

Can I get a confirmation for attending this webinar? Berta, you've already answered that, so yes. Okay. Not one for me!

Roger Macklin, ‘Thanks for a very informative presentation.’

Again, thank you for your attention.

I think that's all the questions I have.

Berta Oates
Yeah that's all the questions I see.

If there are additional questions, feel free to type them in, we'll take another minute or sort of wait.

Like there's just several accolades coming in for your presentation today.

Again, thank you Dr. Stainsby for taking the time to present the information. Amanda, as always, thank you for running the scenes behind the webinar. Your support is greatly appreciated. Patricia and the rest of the education training subtask committee, again, thank you for bringing these presentations.

Patricia Paviet
Thank you so much, Berta, thank you, Richard and thank you Amanda.

Richard Stainsby
Thank you. Thank you very much everybody and thanks to all of you who've actually logged in to attend the webinar today. It was a pleasure to actually give it.

Berta Oates
I do see one more question that has come in from Vlad regarding new materials.

Richard Stainsby
Any new materials being considered for coolant?

Yes I mean I guess the coolants are the coolants, so we've got things like sodium, we've got lead, we've got helium, we've got water, we've got a number of different options for salts for molten salt reactors. The issues are around the structural materials to contain those coolants. Some are more challenging than others. And even the easy ones which appear to be easy like helium for example, which is chemically inert, you'd have thought the material challenges weren't so great.

But the opposite side of that is in systems where you have no oxygen, such as a helium-cooled reactor or in a lead-cooled reactor where we try to limit the oxygen content to limit corrosion, we get the opposite problems of actually having tribology issues. We don't get protective oxides actually formed on metallic surfaces. So where we go balls and bearings and things like that we can actually get diffusion bonding of some of these moving parts because we don't have the oxide layers that you'd normally get in everyday engineering application.

So there's a lot of work going on looking at coatings for structural materials to improve the tried logical behavior in some of these coolants' environments. Things like sodium-cooled fast reactors I think are okay, we've had sodium-cooled fast reactors for the past 50-60 years and I think the material's behavior for those is actually very well understood. There are always improvements coming along in things like fuel cladding materials. But for things like sodium, I think the behavior of the structural materials is very well understood.

The high-temperature gas reactors, the main challenge there would be the actual heat exchangers. Pretty much everything else structurally we can insulate, but heat exchangers and fuel cladding you can't insulate because you're going to get heat through it. So that tends to be where the main material's challenges lie.

I think that was the last technical question.

Berta Oates
I think that's correct. So with that I'll again reiterate our thanks and wish everyone a good day.

Richard Stainsby
Thank you very much. Thanks a lot. Bye-bye.

Patricia Paviet
Good-bye.

END