Thematic Investing

Step inside a Nuclear Fusion reactor!

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BofA Nuclear Fusion Field Trip: towards energy abundance

BofA Sustainability, Thematic and Utilities research teams hosted a field trip to two pioneering nuclear fusion research centres in France: CEA which recently broke the world record fusion duration (22 mins), and ITER – the world's largest fusion research project currently under construction. Why now? Breakthroughs in AI, material science and supercomputing are enabling faster testing, and expanding potential reactor designs. Fusion could be pivotal for decarbonisation, often viewed as the holy grail of the energy transition offering a safe and sustainable pathway to clean energy. Containing and controlling plasma (a hot charged state of matter essential for creating nuclear reactions that produce energy) long enough to be commercially viable remains the key challenge.

Seeing how we recreate the conditions of the sun on earth

Nuclear Fusion is the process that powers the sun and stars. Recreating it on earth could unlock limitless clean energy, with fuel abundant in seawater (deuterium), without the risks of chain reaction or long-lived radioactive waste (the key challenges in deploying nuclear fission). To do so requires the manipulation of gas into a plasma 10x hotter than the sun, controlling it for enough time to obtain more energy than is used to create these conditions. The engineering challenges of doing so remain significant - particularly around the creation of materials capable of handling the temperature & conditions in the reactor– but progress is accelerating from both government and private sector companies towards longer duration and higher temperature fusion.

ITER – the world's largest fusion research project

ITER is the world's largest fusion research site, a $22bn multinational project with the goal of demonstrating the feasibility of fusion power at scale. In a presentation and tour we saw the ongoing construction of the machine that will be used to create the fusion, and assembly of several components including cryogenics, fuel, and power sources. Up to 620MW electricity will be required at peak, and magnets with a field so strong they could theoretically be used to levitate an aircraft carrier. Whilst not due to be fully operational until 2039, commercialising breakthrough technologies learnt throughout the project may come sooner. Robotics, material science (high strength components for aircraft and trains), precision diagnostics improving healthcare, and enhanced mapping of the human brain are innovation spin-offs from ITER already cited to date.

CEA – world record fusion plasma containment to date

We visited CEA's WEST tokamak nuclear fusion reactor which recently set the world record for holding a fusion plasma (22 minutes, at 50m degrees Celsius). The project serves as a test for the components ITER will need. The end goal is to control the plasma for longer periods, and increase temperature in the reaction >100m degrees.

Refer to important disclosures on page 17 to 18. 12835064

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On the road to the future of clean energy

BofA Nuclear Fusion Field Trip: May 2025

BofA Sustainability, Thematic and Utilities research teams hosted a field trip for investors to see two pioneering nuclear fusion research centres in France. We met the CEA – France's Alternative Energies and Atomic Energy Commission, and ITER – the International Thermonuclear Experimental Reactor, in Saint-Paul-lez Durance, France. Both use a tokamak device – a type of magnetic confinement fusion reactor – to control plasma heated to millions of degrees Celsius and attempt to contain the energy created as part of the process. CEA's device was constructed and the first plasma (often referred to as the fourth state of matter, alongside solids, liquids, and gases) achieved in 2016. ITER's machine will be 10x larger, but not expected to start research operations until 2034, fully operational in 2039. We saw the machine currently under construction.

Fusion 101: can we recreate the sun's process to transform energy on earth?

Nuclear fusion is the process that powers the sun and stars, the methods of recreating it on earth are by fusing isotopes of hydrogen to form larger atoms creating lots of energy in the process. Achieving the engineering to capture that energy at the scale and cost effectiveness required to make it commercially viable remains the key challenge. The process requires fusing light atoms together releasing energy, as described by Albert Einstein's E=mc2 equation on conversion of mass into energy. The process requires very high temperature (10x hotter than the sun: 150m degrees celsius), high particle density and time. These factors can be traded off against each other in different devices, most of which use either magnetic confinement of plasma, or inertial fusion using lasers or electromagnetic pulses fired at hydrogen fuel targets.

- **Magnetic fusion**: using a machine such as a Tokamak to confine plasma in a donut shape (torus), heated to millions of degrees and using magnetic fields to hold it together for long enough for fusion to happen and obtain useful amounts of energy from it. It's a continuous process like a furnace, drip feeding fuel to keep the reaction going at very low density for a long period of time. Key challenges include the materials required (e.g. superconducting magnets that are complex and expensive to produce) and complex calculations to enable it. AI, simulation and in future quantum computing may mitigate this. Both CEA and ITER that we visited adopt this approach.

- **Inertial Fusion**: taking a fuel pellet and crushing it quickly (e.g. with powerful lasers or pulsed power) to heat and compress it to create the plasma, with the energy released from the high temperature and density created being captured. This is a repetitive pulse process, much like an internal combustion engine – you drop in a fuel, compress it, energy gets released, and then repeat that process. Key challenges are obtaining sufficient energy in the short window of time the reaction occurs, and the engineering required to develop the repetitive process. CEA also has ongoing inertial fusion research at an alternative site to the one we visited.

The easiest fuel mix to enable fusion is deuterium and tritium (both isotopes of hydrogen). Deuterium is found in water and is thus abundant. Some Tritium is added to the process initially but then regenerated in the fusion process. Plasma physics is at the core of this; separating electrons from nuclei create a plasma, which produces significant amounts of energy if it can be contained and confined for long enough. The latter is what several research projects and companies are trying to achieve.

Why fusion? Clean baseload energy with unique characteristics…and heat!

In discussing the benefits of nuclear fusion energy could provide, both CEA/ITER highlighted it could overcome several shortcomings that exist with alternative forms of energy today. Specifically fusion would be zero carbon, deployable in any location, dispatchable at any time, and thus provide energy security. Furthermore it can also be used as a source of heat energy for industrial and energy intensive processes such as metals production, desalination, or hydrogen production in future. Key to all of this would be not just developing the engineering required to achieve fusion, but doing so cost competitively – something only possible when fusion reactors moved to the nth of a kind. The first deployments would likely be far more expensive than alternatives owing to the significant technology developments incorporated in them. However, the ongoing operational cost could be relatively low given the abundant fuel source (deuterium, available from seawater), and low maintenance cost. Once in place, the ITER tokamak should last up to 100 years for example.

ITER: world's largest Fusion research project

Visiting ITER: International Thermonuclear Experimental Reactor

ITER is the world's largest nuclear fusion research project, with the goal of demonstrating the feasibility of fusion power at scale. It's a multinational collaborative project with funding both directly from contributing partner countries governments, and in kind through private sector manufacturing of the required parts and consultancy expertise required.

In a presentation and tour hosted by the Head of Communications Laban Coblentz and his team, we saw the ongoing construction of the Tokamak that will be used to create the fusion process, and assembly of several related components including the cryostat, vacuum chamber and superconducting magnets.

Exhibit 1: The ITER Worksite

ITER is a 180-hectare site with 39 buildings to house the Tokamak device and related systems

Source: ITER

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The Geopolitics of a Clean Energy future

The seven contributors to the project are the European Union, United States, China, India, Japan, South Korea, and Russia, sharing the project costs, and the experimental results and any intellectual property generated by the project. The success of the project will be dependent on collaboration between the contributing nations; whilst tough in the current geopolitical climate,

Coblentz stated the common goal of the partners is to make a machine that will change history in his view, not only in accelerating clean energy but also breakthrough technologies that are learnt through the project in e.g. robotics, material science (particularly use of magnets), and use of AI & simulation. Furthermore, he stated part of the rationale for using the magnetic confinement of plasma method to attempt fusion (rather than inertial) was that no enriched materials like plutonium or enriched uranium would be created in the reactor that could be exploited to make nuclear weapons.

Exhibit 2: International Collaboration key to project success

ITER is an international collaboration research project with direct and in kind funding contributions from country partners

Source: ITER

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Exhibit 3: ITER organisation

Europe as host contributes 45% to the project, with Non-EU members contributing 9% each

Source: ITER

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Fusion on earth: 10x hotter than the core of the sun

Fusion is the process that powers stars and the sun, converting mass into energy produced by gravitational force. Recreating that on earth needs higher temperatures than the core of the sun to compensate for the lower gravitational force. This is done using a precision controlled magnetic field to control a burning plasma. The intended outcome is to use the heat created to generate electricity.

Exhibit 4: Fusion in the Universe produced by gravitational force

Fusion is the process that powers stars and the sun, converting mass into energy produced by gravitational force

Source: ITER

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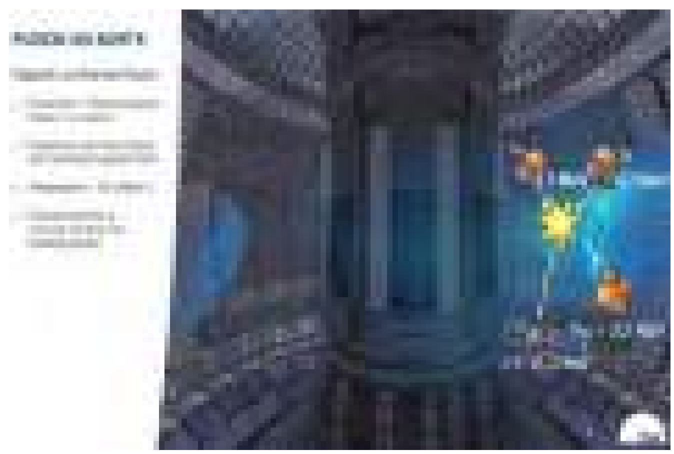
Exhibit 5: Fusion on earth: recreated with heat & magnets to control it

Recreating fusion on earth uses higher temperatures in the absence of the same gravitational force the sun has, with magnets to control it



Source: ITER

Towards clean abundant energy, if we can contain and shape very hot plasma

The key rationale for fusion research is pursuing a source of baseload dispatchable power that can be generated on demand, created from an abundant fuel source – deuterium from seawater, and tritium that's recreated in the fusion reaction process – without the risks of chain reaction leading to thermal runaway or long-lived radioactive waste (the key challenges in deploying nuclear fission). To do so requires the manipulation of gas into a plasma 10x hotter than the sun, by injecting deuterium and tritium gas, electric current, electromagnetic waves and high energy particles for the process to occur. The engineering challenges of doing so remain significant, particularly around the creation of materials capable of handling this process, hence the long timelines for the project.

Exhibit 6: Why fusion? Carbon free energy abundance
The key rationale for fusion research is to create a carbon free constant dispatchable power with abundant fuel supply

Source: ITER

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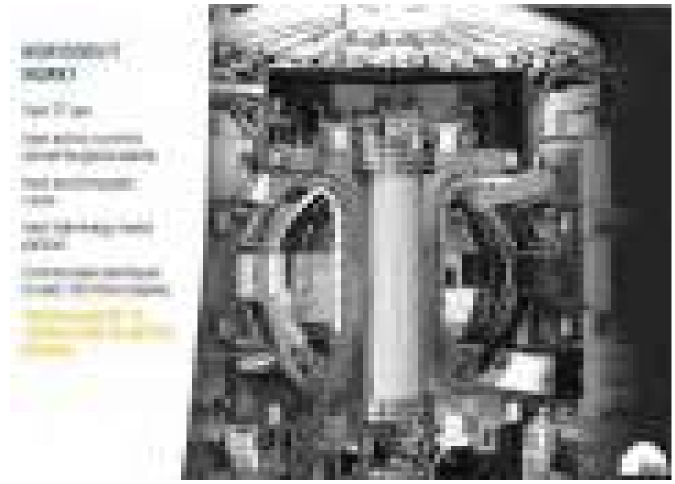
Exhibit 7: The challenge: Contain plasma 10x hotter than the sun
Fusion works by manipulating deuterium and tritium gas into a plasma 10x hotter than the sun; the key challenge being to contain and shape it



Source: ITER

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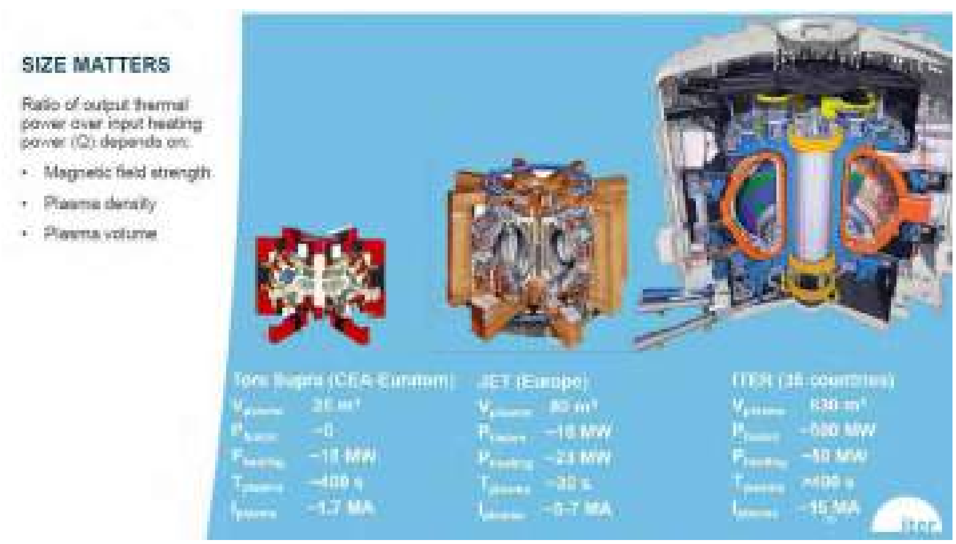
Raising the bar of Energy Gain

Whilst several Tokamak reactors have achieved fusion in the past few years, none have reached significant energy gain, referred to as the triple product - a measure (Q) of magnetic field strength, density and volume. ITER is aiming to achieve a ratio of 10:1, achieved by increasing the size and scale of the machine relative to those that have been used to date, including the Tore Supra/WEST at CEA that we also visited.

Exhibit 8: Energy Gain: ratio of output thermal power over input heating
Whilst fusion has been achieved in several research and private companies in the last few years, the ratio of output thermal power to input heating (Q) has remained at or lower than 1; ITER is aiming for at least 10



Source: ITER

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Material science, fuel cycling and heat management key remaining challenges

The key remaining challenges to successfully achieve fusion at larger scale and towards commercially viable reactors (in terms of energy gain and cost) per ITER are 1) creating the materials resistant to the extreme heat and potential damage from neutrons, 2) heat management (both diverting from the reaction as well as the heat removal for electricity generation), and 3) fuel cycle – creating the conditions for tritium to regenerate itself in the reaction, which has not been done continuously at scale.

Exhibit 9: Materials, fuel cycle, and heat management key challenges to achieve fusion commercially
ITER cited several remaining challenges to achieving fusion at scale, particularly around the materials, fuel and heat management

Source: ITER

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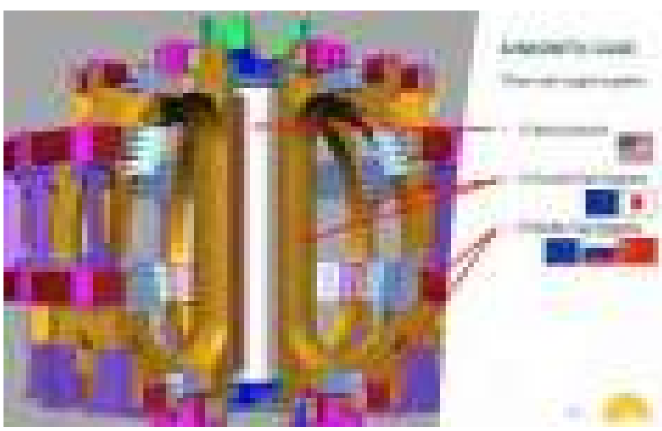
Superconducting magnets powerful enough to lift aircraft carriers

Superconducting magnets are used to contain and control the plasma in the fusion process. Per ITER the magnets under construction would achieve a magnetic field of 13 tesla, so powerful the central soleroid alone could theoretically lift an aircraft carrier. We saw this under construction, with 6 of the 7 modules currently now assembled.

Exhibit 10: Creating a Magnetic Cage
Magnets are used in the core and surrounding the tokamak device with the aim of controlling and shaping the plasma



Source: ITER

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Exhibit 11: 1 Million components in the ITER Tokamak
The vast scale of construction requires international expertise, with >1m components

Source: ITER

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Power Supply: up to 620MW at peak periods

In order to operate the vast scale of equipment under construction at ITER, the site has a dedicated high voltage (400kv) power line, extended from the nearby CEA site linking ITER to the network. Electricity requirements will range from 110MW to 620MW for peak periods of plasma operation. A dedicated substation transforms the electricity to an intermediate level (69kv). The cooling water and cryogenic systems will require ~80% of that supply, but during plasma operation a second pulsed power system will be needed to provide the superconducting magnets and heating systems sufficient energy. Two diesel generators can provide alternative power in emergencies.

Exhibit 12: Power Supply Crucial to deliver scale of energy required
ITER has a substation on site to transform electricity from the 400kv power lines to provide ITER's significant power needs: ranging from 110MW to 620MW for peak periods during plasma operation.

Source: ITER

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ITER timelines: 10-15 years until operational

ITER's project timelines were recently delayed owing to equipment and technical issues such as leakage in the thermal shields and cracking of pipes due to stress corrosion, in addition to regulatory and delivery delays. The original goal of 2035 plasma operational phase is now 2039 as a result. However, the project is already creating commercial potential for the technologies and materials that are under development, such as superconducting magnets being used to advance mapping of the human brain, run magnetically levitating trains, and use the high strength components in demanding industries such as aerospace and high precision diagnostics.

Exhibit 13: Operational fusion delayed until 2039...
ITER's project timelines were delayed from an initial 2035 target to 2039

Source: ITER

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Exhibit 14: ...but commercialisation of related tech already emerging
Use of the technologies under development may come prior to fusion energy, e.g. using superconducting magnets and precision diagnostics

Source: ITER

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Inside the ITER Construction Site

As part of the visit we toured inside the Tokamak Assembly room and Tokamak building, with a bus tour of the key other buildings including power source, cryostat workshop and cryogenics plant.

Exhibit 15: ITER Worksite Construction
When completed the ITER site will have 39 buildings for the fusion reactor and various inputs/processes

Source: ITER

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The key two highlights of the site visit were accessing the:

- **Assembly Hall:** Tokamak components are being assembled in a 100m long/60m high dedicated building that we saw as part of the visit, as well as the assembly of the magnet coils
- **Tokamak pit**: the vacuum vessel when complete will measure 19m wide by 11m high weighing 5,200 tons, rising to 8,500 tons when the heat diversion/other equipment are completed. One ninth of the sections is currently in place which we saw being assembled.

Exhibit 16: Inside the Tokamak Assembly
BofA Global Research team hosted a group of investors to visit ITER's nuclear fusion site under construction

Source: BofA Global Research

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Exhibit 17: Tokamak Building under construction
The Tokamak building under construction at ITER has separate diagnostics and fuel (to access Tritium) buildings either side

Source: BofA Global Research

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Picturing the future of Nuclear Fusion

Pictures from the visit are included below.

Exhibit 18: Tokamak Assembly Room

ITER's Tokamak components are being assembled in a 100m long/60m high dedicated building that we saw as part of the visit

Source: BofA Global Research

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Exhibit 19: ITER Assembly Room

Over 1m components will be in the final ITER Tokamak device. We visited the hall observing the vacuum vessel and magnets being assembled

Source: BofA Global Research

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Exhibit 20: Tokamak Assembly Room: adding thermal shield and field coils to vacuum vessel sectors
Two of the nine segments of the Tokamak are currently being assembled, each taking 6 months to complete

Source: BofA Global Research

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Exhibit 21: Tokamak Assembly Room
Assembly of the vacuum vessel sections began in 2021; there will be 9 in total, each weighing 500 tons

Source: BofA Global Research

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Exhibit 22: Superconducting Magnet Construction
ITER are constructing superconducting magnets so powerful they could lift an aircraft carrier

Source: ITER

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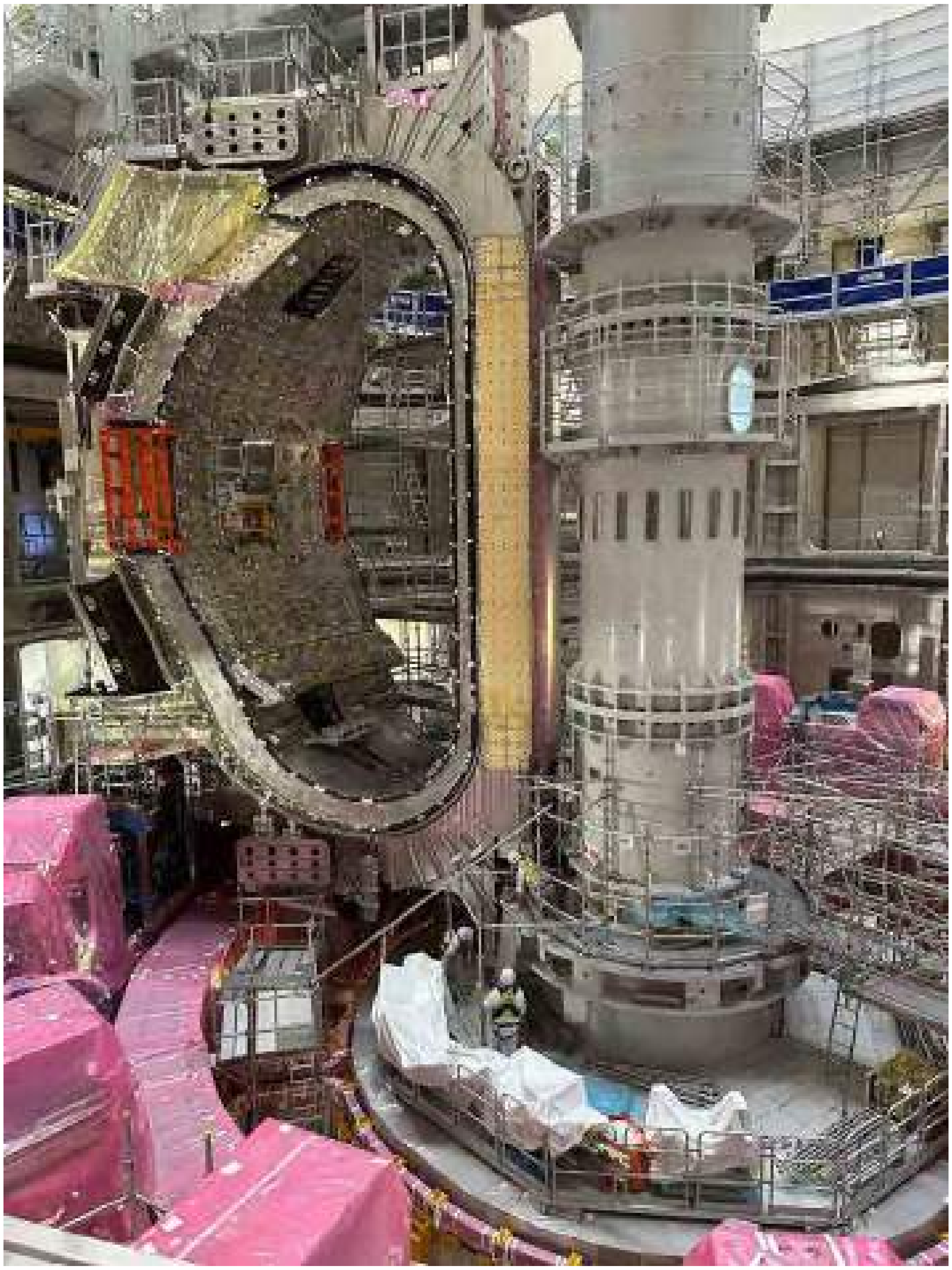
Exhibit 23: Inside the ITER nuclear fusion reactor

We visited ITER's Tokamak construction site that will house the world's largest Tokamak fusion reactor; one of the nine vacuum vessel sections in place which we saw as part of the tour



Source: BofA Global Research

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Exhibit 24: Inside the Tokamak pit
Several supporting systems will surround the tokamak including cryostat, heat exhaust and cooling

Source: BofA Global Research

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Exhibit 25: Power Supply Crucial to deliver scale of energy required
ITER has a substation on site to access and convert high voltage energy

Source: BofA Global Research

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Exhibit 26: Cryostat Lid: Final piece of the tokamak jigsaw
The 665 ton lid to the world's largest cryostat will complete the construction of the vacuum chamber surrounding the ITER Tokamak

Source: BofA Global Research

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CEA: the City of Low Carbon Energy

Visiting CEA: International R&D Centre for low-carbon energy

We visited IRFM (Institut de Recherche sur la Fusion par confinement Magnétique/Institute for Magnetic Fusion Research), part of the CEA (French Alternatives Energies and Atomic Energy Commission). Based in Cadarache, Southern France, next to ITER, Tore Supra is a nuclear fusion project managed by the IRFM that began operations in 1988, becoming the world's first tokamak to successfully use superconducting magnets alongside actively cooled plasma-facing components.

The Institute do research on Magnetic Fusion as a potential future energy source. We saw their R&D site for low carbon energy, with lab tours of the biotechnologies facilities creating energy from algae and other materials, and a visit to the WEST tokamak nuclear fusion reactor that recently achieved the world record for holding a fusion plasma (22 minutes, at 50m degrees Celsius).

Material Choices enabled fusion breakthrough

Decades of tokamak development have narrowed viable divertor material choices to just two: carbon-fibre composites (CFC) and tungsten. Between 2000 and 2002, Tore Supra was upgraded with a new CFC limiter, serving a similar function to the ITER divertor and designed to handle ITER-relevant heat loads of up to 10 megawatts per square metre. This upgrade showed that while CFC materials are highly effective at managing power loads and maintaining plasma compatibility, they also suffer from significant erosion resulting from chemical interactions between the carbon in the limiter, and hydrogen isotopes such as deuterium in the plasma.

In 2012, a decision was made to modify Tore Supra into a testbed to support ITER development, renaming the project WEST (W Environment in Steady-state Tokamak, where W is the symbol for Tungsten). This transformation aims to mitigate risks and accelerate ITER's progress while reducing both time and expenses. As part of the WEST upgrade, all carbon materials were removed from the vessel. Magnetic coils were installed inside the vacuum chamber to reshape the plasma from circular to a D-shape, and the heating systems were reconfigured accordingly. From a limiter configuration, Tore Supra was transformed to a divertor configuration and initial experimental campaigns began in 2016.

WEST as a test for components ITER will need

Initially, ITER planned to start with a CFC divertor and later switch to tungsten before beginning nuclear operations with deuterium and tritium in 2027. By installing a tungsten divertor from the outset however, ITER could lower costs and gain earlier operational experience with tungsten in the non-nuclear phase – a direct outcome of the WEST project progress, validated by the recent world record plasma duration.

One of the largest operational tokamaks in the world

We accessed the site, visited the control room and tokamak hall. With a radius of 2.4m at the centre of the plasma, WEST is one of the largest operational tokamaks in the world currently. The end goal is to control the plasma for longer periods while ensuring components are able to withstand the radiation, and increase the temperature in the reaction from 50m degrees achieved so far towards >100m.

Exhibit 27: CEA WEST project in Cadarache (France)
Site finalized and experiencing nuclear fusion

Source: CEA-IRFM

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Exhibit 28: CEA WEST project in Cadarache (France)
Site when under construction

Source: CEA-IRFM

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Fusion at €20k a shot

The control room observes the conditions prior to a fusion shot, prepare parameters before discharge, during discharge and monitor all parameters. A team of plasma diagnostic physicists oversee all the measurement instruments. Each fusion shot currently costs €20k, limiting the volume of testing that the site can do. Much of the cost arises from the significant energy requirements to undertake each plasma operation.

Exhibit 29: Command control room
Control screens of one of the long duration plasma pulses trial

Source: CEA-IRFM

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Exhibit 30: Inside ToreSupra/WEST tokamak
The WEST tokamak from the inside

Source: CEA-IRFM

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