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RESOURCES FOR SCHOOL TEACHERS

NUCLEAR FUSION

Nuclear fusion is the process that powers the Sun and the stars. In this reaction, light atomic nuclei combine to form a heavier nucleus, releasing enormous amounts of energy in the process. Because fusion can produce vast energy with very little fuel and without the long-lived radioactive waste associated with traditional nuclear fission, it has long been considered one of the most promising potential energy sources for the future. Nuclear fusion generates four million times more energy per kilogram of fuel than burning coal or oil - making it very attractive for climate change mitigation.

However, reproducing fusion on Earth is very challenging. The atomic nuclei involved naturally repel each other due to their electric charge, also known as Coulomb repulsion, so they must be forced together at extremely high temperatures (*100 million K*) and confined pressures – conditions similar to those found in the core of stars. Scientists use powerful magnetic fields and advanced reactor designs, such as tokamaks and stellarators, to confine and control superheated plasma (the fourth state of matter) so that they collide and “fuse”.

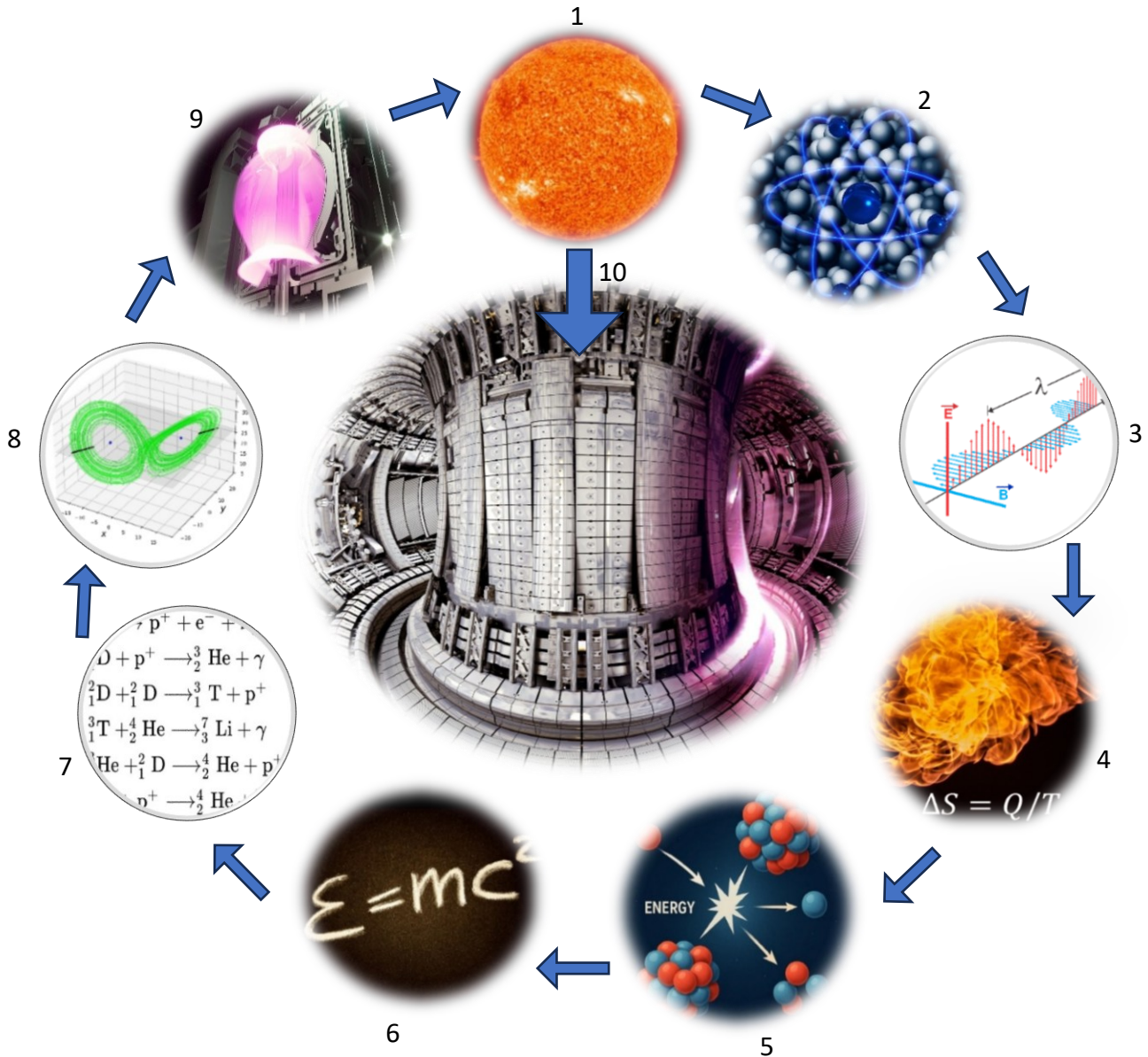
Due to these extreme challenges, the development of fusion energy has required contributions from many areas of science, including astronomy, atomic physics, quantum mechanics, thermodynamics, electromagnetism, materials science, advanced computing, numerical modelling and systems engineering. Modern experimental reactors, such as the Joint European Torus (JET) shown overleaf, represent many decades of global research and technological progress. Together, these advances are bringing humanity ever closer to achieving controlled fusion as a practical and sustainable source of energy.

This document explains some of the key concepts and breakthroughs, spanning 2,500 years of human thought, that will make nuclear fusion a practical and commercial reality.

Nuclear Fusion – The Conceptual Blueprint

The key scientific discoveries that make controlled fusion conceivable at all

Natural philosophy → atoms → electromagnetism → thermodynamics → nuclear physics → quantum mechanics → stellar fusion → simulation → fusion reactor designs → practical reality



Using this image, one can see that many areas of scientific understanding had to emerge in order for fusion to become conceivable, let alone practicable. These areas are chronologically numbered from 1-10 and will be further explained overleaf.

1) The Sun is a Physical Object, not a Deity

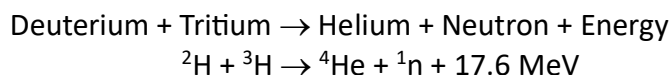
There was a time in history when the Sun was regarded as being a divine object or a Deity. However, early philosophers from Ancient Greece challenged this and proposed that the Sun is indeed a natural object governed by physical laws.

- *Thales* (600 BC) – encouraged natural explanations of celestial phenomena rather than mythological ones; made solar observations and even predicted an eclipse
- *Anaxagoras* (450 BC) – argued the Sun is a hot physical body rather than a divine object
- *Aristarchus* (270 BC) – proposed a heliocentric model placing the Sun at the centre of the Solar System, and made solar measurements accordingly.

2) Atomic Theory & Matter: The universe is made of atoms of distinct elements

Matter consists of discrete atoms that combine to form chemical elements.

- *Democritus* (400 BC) – proposed that matter is composed of indivisible atoms
- *John Dalton* (1808) – formulated the first modern atomic theory and chemical laws based on atoms
- *Gustav Kirchhoff* (1859) – working with Robert Bunsen, he developed spectroscopy to identify elements through their light spectra, and used this technique to measure the composition of the Sun from afar
- *Dmitri Mendeleev* (1869) – correctly organised all the elements into the Periodic Table based on their chemical properties and atomic mass
- *Heike Kamerlingh Onnes* (1911) – discovered superconductivity in certain elements and alloys, essential materials for future magnetic systems in tokamaks and stellarators
- *Ernest Rutherford* (1911) – discovered the atomic nucleus at the heart of an atom
- *Mark Oliphant* (1934) – the first artificial fusion reactions involving deuterium (D, or ^2H) and tritium (T, or ^3H), the most practical route for fusion on Earth:



3) Electromagnetism: Electricity and magnetism are a single unified force

Charged particles and magnetic fields govern the behaviour of plasmas (or charged gases).

- *Charles-Augustin de Coulomb* (1785) – discovered the strong repulsive force of two electrically charged objects of similar charge, relevant to positive nuclei
- *Michael Faraday* (1831) – discovered electromagnetic induction and field concepts
- *James Clerk Maxwell* (1873) – unified electricity and magnetism mathematically in the four Maxwell's equations
- *Nikola Tesla* (1888) – developed practical systems for generating and controlling alternating electromagnetic fields; the SI unit for magnetic field strength, the tesla (T), is named in his honour.

4) Thermal and Energy: Energy cannot be created or destroyed, only transformed

Thermodynamics governs heat, energy flow, and temperature.

- *James Prescott Joule* (1843) – demonstrated the equivalence of heat and mechanical energy, and therefore the ‘conservation of energy’ law
- *Lord Kelvin* (1848) – developed thermodynamic temperature and formalised thermodynamic theory
- *Rudolf Clausius* (1865) – formulated the second law of thermodynamics and the concept of entropy.

5) Nuclear Phenomena: Radioactivity originates from the atomic nucleus

Radioactive decay revealed that atoms have internal structure and nuclear processes.

- *Marie Curie* (1898) – pioneered the study of radioactivity and discovered new radioactive elements, like radium (Ra) and polonium (Po)
- *Frederick Soddy* (1913) and *Francis Aston* (1919) – proposed and experimentally confirmed the existence of isotopes using mass spectrographs
- *James Chadwick* (1932) – discovered the neutron, confirming the nucleus contained neutral particles
- *Lise Meitner* (1938) – explained the physical mechanism of nuclear fission, which is different to fusion, but essential nuclear physics nonetheless.

6) Quantum Theory: Nuclear processes follow quantum laws

Quantum mechanics explains how nuclei interact and how fusion becomes possible.

- *Max Planck* (1900) – introduced quantised energy ($E = hf$) for the first time
- *Albert Einstein* (1905) – established mass-energy equivalence ($E = mc^2$)
- *Erwin Schrödinger* (1926) – developed wave mechanics describing particle behaviour
- *Paul Dirac* (1928) – unified quantum mechanics with relativity in the Dirac equation
- *George Gamow* (1928) – applied quantum tunnelling to nuclear processes such as alpha decay and later models of nuclear fusion
- *Lev Landau* (1946) – contributed to the merger of quantum physics and plasma physics, which explains how plasma heating works inside tokamak reactors
- *Richard Feynman* (1949) – developed quantum field theory tools and Feynman diagrams for calculating particle interactions and tunnelling probabilities.

7) Fusion in the Sun: The Sun generates energy through nuclear fusion

Stellar physics demonstrated that fusion powers stars, all across the universe.

- *Hans Bethe* (1939) – explained the proton-proton chain and CNO cycle, the nuclear reactions that power stars; later he worked on deuterium-tritium (D-T) reactions of high relevance to terrestrial fusion in tokamaks and stellarators.

8) Computer Modelling: Simulating the unseeable

Modern fusion relies on computers to predict plasma behaviour, heat flow and material behaviour and to optimise reactor designs.

- *Henri Poincaré* (1905) – developed the mathematical foundations of chaos and dynamical systems, important for understanding plasma instabilities
- *Alan Turing* (1936) – laid the theoretical foundation for programmable computers; his ideas make numerical simulations possible
- *Hannes Alfvén* (1942) – his pioneering work on magnetohydrodynamics (MHD) underpins plasma simulation codes for tokamaks and stellarators
- *John von Neumann* (1945) – developed early digital computing architectures and numerical methods for solving complex physical equations of nuclear reactions
- *Grace Hopper* (1952) – developed early computer programming languages like COBOL and compilers that make industrial simulations possible today.

9) Tokamak and Stellarator Designs: ‘Putting the Sun in a bottle’

First magnetic confinement designs are made that would permit fusion reactions.

- *Igor Tamm and Andrei Sakharov* (1950) – first conceptual design of a magnetically confined tokamak (a toroidal, doughnut-shaped chamber)
- *Lyman Spitzer Jr.* (1951) – first conceptual design of a stellarator using a complex, twisted magnetic coil.
- *John Lawson* (1955) – defined the *Lawson criterion* above which a fusion reactor generates net energy (i.e. when the rate of energy production is higher than the rate of losses)

10) Practical reality: Can we get it to work?

These are a selection of 10 programmes and developers making great strides to unlock nuclear fusion for the benefit of humanity.

- Joint European Torus (JET) in Culham, UK
- ITER in Cadarache, France
- Spherical Tokamak for Energy Production (STEP) in West Burton, UK
- SPARC in Devens, Massachusetts, USA
- National Ignition Facility (*inertial*) in Livermore, California, USA
- Gauss Fusion in Hanau, Germany
- Proxima Fusion in Munich, Germany
- Experimental Advanced Superconducting Tokamak (EAST) in Hefei, China
- Korea Superconducting Tokamak Advanced Research (K-STAR) in Daejeon, South Korea
- JT-60SA in Naka, Ibaraki, Japan

These projects represent humanity’s current attempt to translate centuries of scientific insight into a practical energy source.

Conclusion

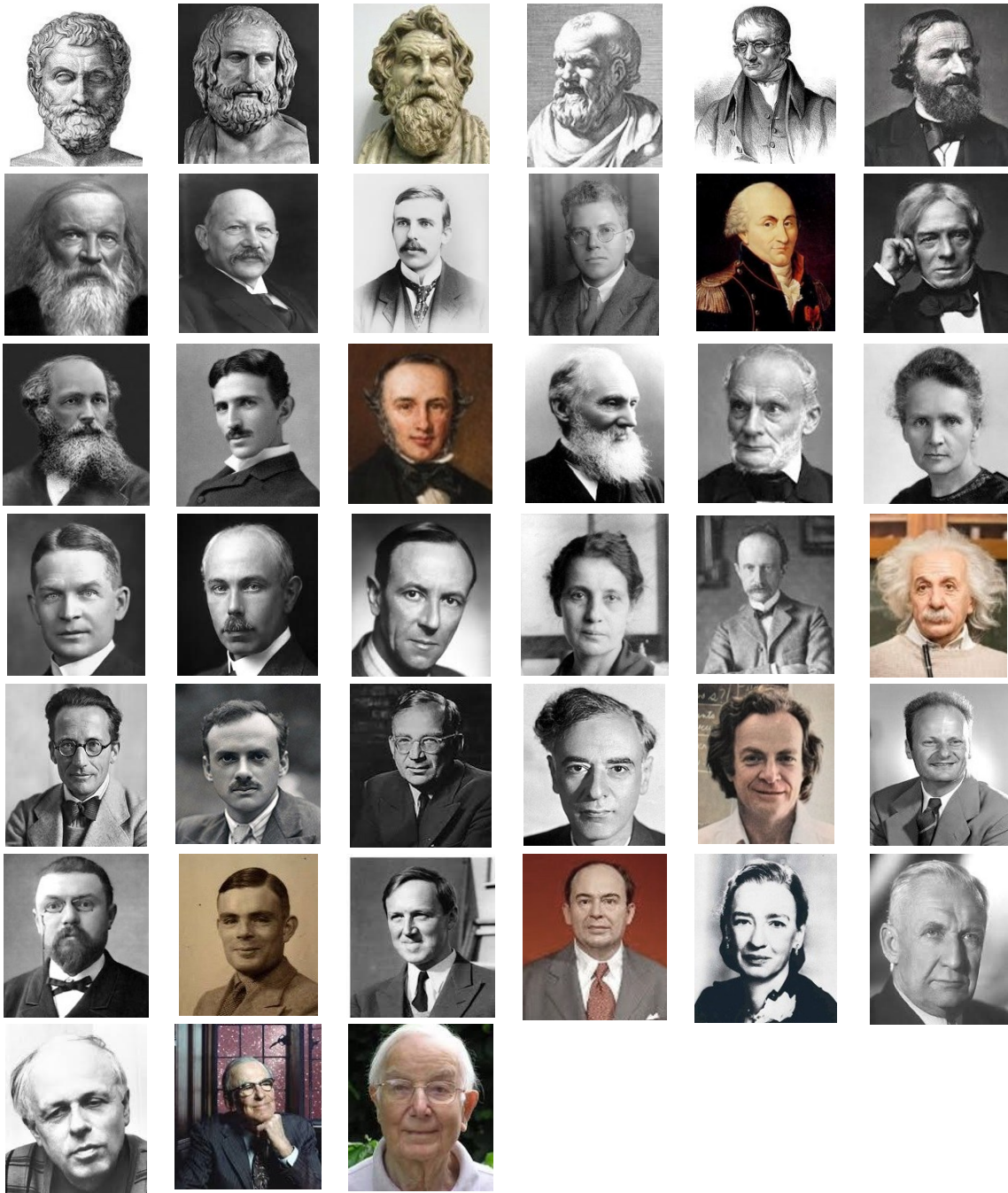
The stars shine because of nuclear fusion — the process in which light atomic nuclei combine and release enormous amounts of energy. Bringing this stellar power under our control is one of the most ambitious goals in modern science.

Yet fusion only became imaginable after centuries of discoveries by philosophers, astronomers, physicists and mathematicians who uncovered the laws of atoms, energy, electromagnetism, quantum mechanics and engineering. Their ideas form the intellectual foundation of the fusion reactors that scientists are building today.

Harnessing fusion is proof that human imagination can reach the stars — and bring their power down to Earth as truly limitless, clean energy.

David Jarvis

Thinkers and pioneers who, in some way, made nuclear fusion possible



1st row: Thales, Anaxagoras, Aristarchus, Democritus, John Dalton, Gustav Kirchhoff
 2nd row: Dmitri Mendeleev, Heike Kamerlingh Onnes, Ernest Rutherford, Mark Oliphant, Charles-Augustin de Coulomb, Michael Faraday
 3rd row: James Clerk Maxwell, Nikola Tesla, James Prescott Joule, Lord Kelvin, Rudolf Clausius, Marie Curie
 4th row: Frederick Soddy, Francis Aston, James Chadwick, Lise Meitner, Max Planck, Albert Einstein
 5th row: Erwin Schrödinger, Paul Dirac, George Gamow, Richard Feynman, Hans Bethe
 6th row: Henri Poincaré, Alan Turing, Hannes Alfvén, John von Neumann, Grace Hopper, Igor Tamm
 7th row: Andrei Sakharov, Lyman Spitzer Jr., John Lawson

FOR TEACHERS

Using the *Atlas of Human Imagination* in Lessons - 5 Physics Projects related to Nuclear Fusion Concepts (15-18 year olds)

1) Plasma as the Fourth State of Matter

- using a plasma globe (commercial), show students that noble gases like neon, krypton and xenon can be turned into plasma in a high-voltage field. Explain the concept of electrically charged gas and ionisation
- observe the plasma filaments and their motion. See what happens when you put your hand on the globe, or you wave a charged comb or magnet nearby

Concepts: plasma, electromagnetism, ionisation of gas

2) Coulomb repulsion

- using plastic polystyrene balls, get the students to charge them up electrostatically and hang them near each other. Watch them repel as they approach
- discuss how positive nuclei in a plasma also repel each other: linked with $F = k(q_1 \cdot q_2)/r^2$
- mention that quantum tunnelling can overcome this repulsive force under certain conditions

Concepts: electrical charge, repulsion, quantum effects

3) Magnetic repulsion

- using bar magnets, get the students to place the similar poles of the magnets near each other (N-N and S-S). Again, watch them repel as they approach
- visualise the field lines and the repulsive magnetic fields with paper and iron filings
- discuss how magnetism could be used to confine a plasma inside a tokamak reactor

Concepts: magnetism, repulsion, confinement

4) Mass-Energy Conversion: $E=mc^2$ Exercise

- using the Einstein equation and the nuclear masses for deuterium (^2H), tritium (^3H), helium (^4He) and the neutron, calculate the mass difference between reactants (D + T) and products (He + n)
- calculate energy released per fusion reaction
- explain that mass defect is tiny but produces huge energy because of c^2
- compare the energy released by burning 1 kg of oil and 1 kg of fusion fuel

Concepts: mass defect, Einstein's equation, energy density

5) Build a Simple Tokamak Model

- using thin cardboard, glue and staples, get students to build a torus-shaped object (50cm diameter) and explain the geometrical features of a torus
- using some copper wire, get them to wrap wire to simulate where the magnetic coils would go
- get them to put a red LED light inside the tokamak to represent the plasma ring and reactions
- proudly display the tokamak in the school reception area

Concepts: spatial understanding, torus shapes, reactor design, system engineering

Cross-curricular connection and discussions: tie nuclear fusion physics to other areas like chemistry (isotopes, materials science), maths (geometry of torus, energy calculations, $1/r^2$ graphs), geography (climate change), computing (chaos, instabilities) and environmental science (clean energy benefits).