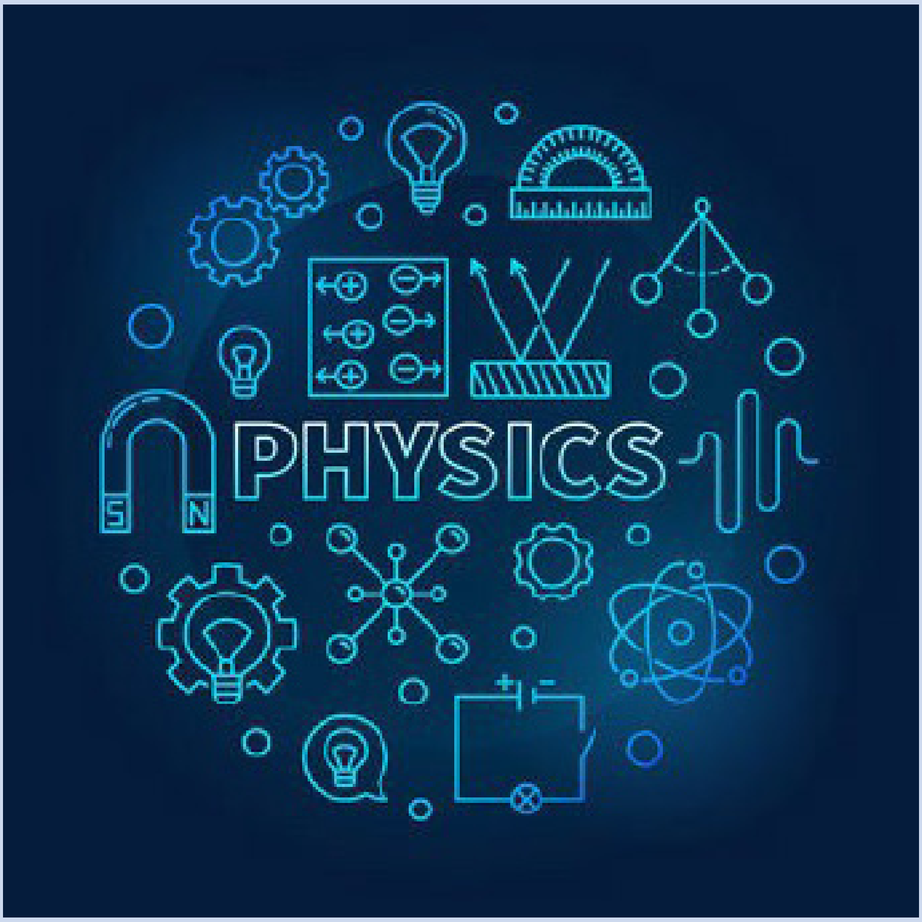
Physics A Level Essays 2025



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Contents

The physics of ferrofluids:

By Brian Waddelow,

What is ferrofluid?

A ferrofluid is a suspension of magnetic particles within a carrier liquid, that has a high "magnetic saturation" (1), the maximum magnetisation that can be induced across a material (2). It was first developed by NASA in 1963 (before it was fully known how liquid fuels would respond to the absence of gravity) by Stephen Papell , by adding small ground iron oxide particles to rocket fuel, so that in zero gravity, the fuel could be manipulated by an electromagnet and pulled into an engine to restart it in more complex missions in space (3). During the same period, it was discovered that under zero gravity conditions, fuels tended to gather at the centre of their tanks, allowing for simpler and cheaper methods of transporting them to be developed, making ferrofluids obsolete in this scenario.

The actual term ferrofluid was made official a few years later in 1967 by Dr. Ronald E. Rosensweig in a contract research report requested by NASA (5). A year later, both he and Ronald Moskowitz founded a business called the Ferrofluidics corporation. Which has now gone on to produce many commercialised pieces of technology that utilise ferrofluids.

(4) Ferrofluid being attracted to a magnetic cube through surface

In 2000, the Ferrofluidics corporation would merge and later share a name with another organisation known as Ferrotec (6), which was set up in 1980 in Minato Ward, Tokyo (7).

Ferrofluids are considered a colloidal substance (8). This means that it is a mixture of microscopic insoluble particles that are suspended within another substance. This means that when no magnetic field is applied, ferrofluids act like regular liquids and fill the bottom of their containers. However, underneath the effects of a magnet, the fluid's phase will change to mimic a solid, and its shape will follow the magnetic field. This is the effect that causes the signature spikes in the material, when magnetised.

(9) Ferrofluid pooling at the end of a screw and following its edge

This also influences the shape that it will take when it is applied directly onto a magnetised object. Instead of pouring over it as normal, a ferrofluid will follow the field lines produced by it, causing it to travel along and around ridges, as well as pooling at tips/points.

What is it used for?

In the modern day, Ferrotec and others use ferrofluid for a variety of different applications. For example, they are used in improving the efficiency of audio speakers. (10) Ferrofluids are used to make dampeners in the speakers that can be easily tailored by the production company, because the amount they dampen is proportional to the viscosity of the fluid. The viscosity of ferrofluids can be easily changed and modified, as it is influenced by the strength and angle of a magnetic field upon it. For maximum viscosity, and therefore maximum dampening, a magnetic field must be placed at 90 degrees to the fluid. (11) These dampeners then also help the speaker with heat dispersion as the ferrofluids can be around 5 times more thermally conductive than the air, allowing for easier dispersion of heat from the voice coil (12).

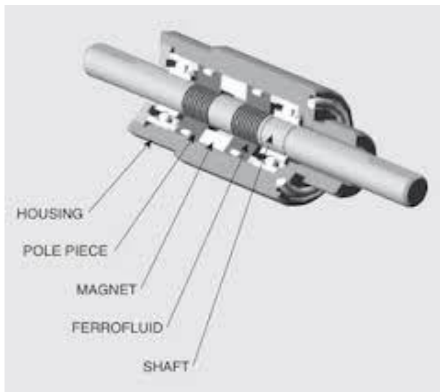
The voice coil is also centred by the ferro fluids, as it replaces the air around it. The ferro fluids produce a force constant on the voice coil that can be calculated with:

$$k = 2M_s H_m ht/r \text{ N/m} \quad (11)$$

where:
- Ms = saturation magnetization in tesla
- Hm = maximum field strength in the gap in ampere meter
- h = height of fluid in the gap in meter
- t = width of the gap in meter
- r = radius of the gap in meter

Because the force is calculated with the maximum field strength in the gap, that means that it can be easily manipulated by sound systems that utilise electromagnets, as the field strength can be altered to fit the system's needs.

(13) visualisation of a ferrofluidic seal

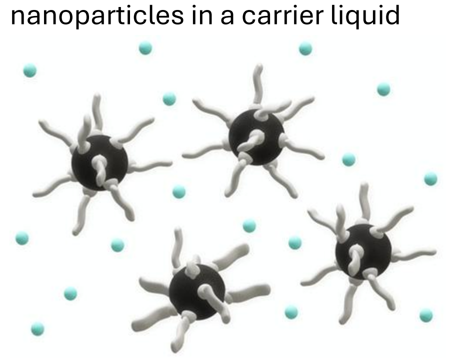


One other application of ferrofluids, utilised by Ferrotec, is within sealing technologies. A ferrofluidic seal. A ferrofluidic seal consists of a rotating shaft housed by a magnetic casing. Between the casing and shaft is a gap within which the ferrofluids are input. As the shaft begins to rotate, the ferrofluid forms a liquid O-ring around the shaft, under the influence of the magnetic field. This creates a hermetic (airtight) seal, that can withstand a pressure differential of up to 0.2 atms (200mbar) (13).

How is it made?

The basic synthesis of a ferrofluid is actually quite simple, as it consists of only a carrier liquid and ferrous particles. This lack of complexity means that it is possible for a ferrofluid to be produced outside of lab conditions in someone's home (14). A basic easily accessible recipe would be to mix a thin layer of vegetable or motor oil with iron filings. This would effectively produce a ferrofluid, that would interact with a magnet the same ways as described above.

(15) representation of iron oxide nanoparticles in a carrier liquid



In a more industrial setting, much more care will go into the production of ferrofluids. Considering the many options for each of the three components (the magnetic particles, the surfactant, and the carrier liquid) that make up a ferrofluid, a producer will consider the exact requirements of the product it will be utilised in and customise it accordingly (15). Most commonly the magnetic particles, or iron oxide nanoparticles (IONPs), are a mixture of magnetite

(Fe_3O_4) and maghemite (Fe_2O_3), which have highly magnetic properties. Other compounds of iron and +2 transition metals are also used but are less common.

These IONPS will often be prepared via processes such as coprecipitation or thermal decomposition, as they are easy and reliable (15). Coprecipitation is very low cost and has a simple methodology but does not provide much control over the size of the IONPs. In comparison, thermal decomposition requires much more equipment and expensive chemicals. However, it provides much more control over the size of nanoparticles produced. It also is better at producing lots of nanoparticles of very similar sizes (monodispersed).

The surfactants that are applied to the mixture help prevent the nanoparticles from agglomerating, helping make the fluids not break down quickly over time (15). The surfactant is somewhat dependant on the carrier fluid as they must have similar dielectric properties. The most common surfactant is oleic acid.

The carrier fluid the IONPs are mixed with is entirely dependent on the intended usage of the ferrofluid being produced, as the only requirement is that the fluid is non-magnetic. The material used will have physical properties such as boiling point that lends itself to the desired task (15).

Conclusion:

Ferrofluids are a highly versatile material that can be used in a myriad of different applications, from space travel to music. The quirks of a liquid being magnetic make it applicable in many scenarios, as it can be manipulated quickly and cheaply to swiftly change its physical properties, which lets it adapt to the scenario.

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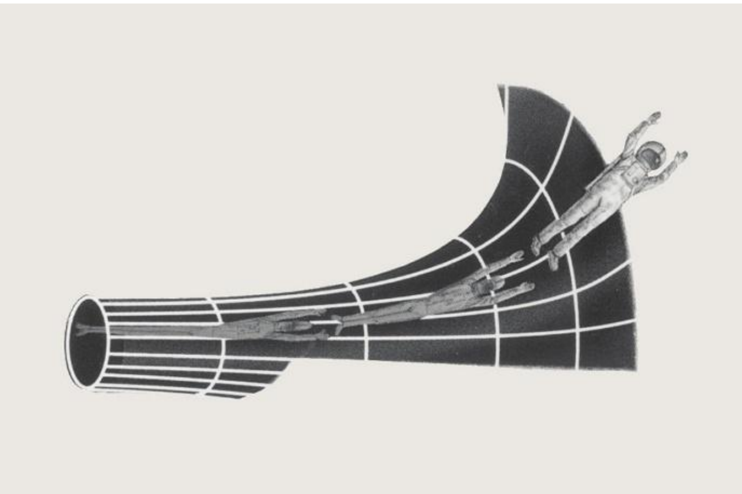
The Physics of Spaghettification in the vicinity of black holes

-By Cameron Sherlock

What does it mean?

Spaghettification is a term that typically describes what happens when you approach a black hole. It is defined as the tidal effect caused by strong gravitational fields, where the object falling into a black hole is stretched towards and compressed perpendicular to it, distorting into a long and thin shape (1). The gravitational fields in question are extraordinarily greater than that of Earth's, especially on the event horizon where not even rays of light can escape the boundary (2). The process of spaghettification detailed here isn't too complex to understand, but far more forces and other variables work in the background to make this happen. It should be noted that while spaghettification is still technically a theory, there is some evidence leaning towards it being a real occurrence (3). This refers to documented cases of spaghettification to be mentioned in this document.

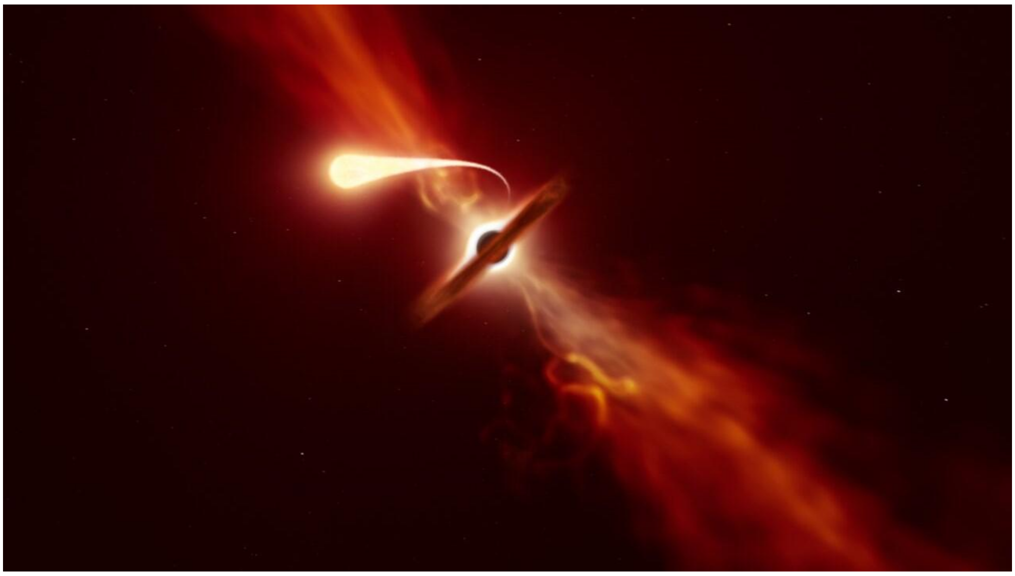


An illustration of Spaghettification (4)

How does spaghettification work?

To break down the process of spaghettification, we must understand fully what a black hole is. A black hole is a region in space where the pulling force of gravity is so strong even light cannot escape (5). This strength of gravity is due to matter collapsing into a tiny space. Objects of extreme mass will continue to collapse indefinitely, such as a massive star around 25 times heavier than our own sun (6). These stars essentially cannot withstand their own gravity as they die, forming a black hole usually after a supernova occurs. To summarise all this information, a black hole is basically a region of extreme gravity formed from an ever-collapsing star, which is how the gravitational fields needed for spaghettification come to be. Furthermore, this would explain where the inconsistency in the field strengths come from as well. If the black hole is constantly collapsing inwards, it can be safe to assume the core has the most density. This means that the field is strongest on the core, and weakest on the boundary.

Going back to the ‘’tidal effect’’ part of spaghettification, this refers to extreme tidal forces. As for what a tidal force is, it can be defined as the differences in the strength and direction of a gravitational force at one point compared to another neighbouring point (7). This can be linked to the information about blackholes, as the core’s force varies in strength to the event horizon boundary, creating one tidal force. Due to the black hole being very similar to a sphere in shape, moving only horizontally around the sphere without changing your vertical component will also cause a tidal force, as you get further/closer to the core of the black hole, decreasing/increasing the difference in the strength of the force and creating the tidal force. Certain parts of an object entering a black hole will be compressed with varying strengths as they may be at different proximities to the centre of the black hole, misshaping it. Overall, there are two tidal forces total that act on an object when approaching a black hole, one compressive force vertically and one horizontally which would thin an object out, causing spaghettification.



An illustration shows a star being ripped apart in a violent tidal disruption event (8)

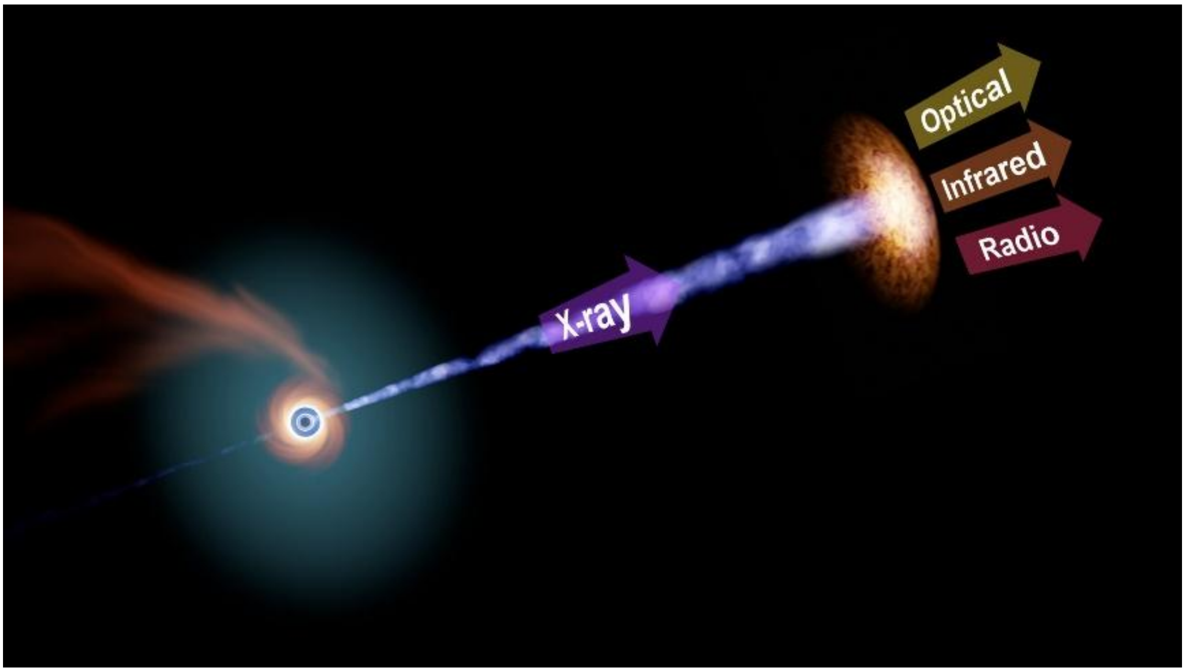
The aftermath of spaghettification – documented cases

Contary to popular belief, when an object in space is consumed by a black hole it does not entirely erase it or leave nothing behind at all. In fact, when a black hole destroys something like a star, some of the matter is kept near the event horizon where it is extremely energetic.This makes the matter heat up to millions of degrees as it resides here, causing the gas contained to rise while within the black hole(9). Although the hot gas itself does not escape, it rises enough to push the colder gas layers above it out. This causes a ring of debris to form around it, floating away from the black hole. Often when looking at an image of a black hole, people will skip over the streaks of colour in the background or the ring coloured black with an outline on it. The streak is usually the debris of an object that was devoured in the past, where dust has scattered over time. The ring can tell you that something has recently fallen victim to it.

Returning to the earlier statement about spaghettification being reality rather than a theory, there have been documented cases of incidents implied to be this concept at work. At the University of Birmingham, a team of researchers pointed the VLT (very large telescope) and NTT (new technology telescope) towards a flash of light that occurred in 2019 (10). This appeared near a supermassive blackhole. However, no matter how large the blackhole is, spaghettification is still rare to observe. This is due to debris being propelled outwards as stellar matter, meaning it belongs to a star in space (11), being devoured. Behind this dust curtain, it was recorded that the temperature suddenly dropped around the maximum light region (where light is the most potent) despite radius staying constant. This was evidence towards spaghettification occurring around the blackhole as, if an object was only being pulled directly towards it in one plane, the temperature would remain mostly identical in that column of space. If the object was moved away, such as it being stretched apart, then it would gradually lower as less of the object with heat to measure is physically present in that area.

Uncovering spaghettification: methods of research

Furthermore, brand new ways of discovering cases of spaghettification are being constantly researched, and one recent technology that has been introduced would be through radiation and light. This came into existence when the team at MIT began a hunt for tidal disruption events (extreme imbalance of tidal forces) after witnessing a flare of one from a galaxy named NGC 7392, 137 million light years away from Earth (12). It involves using a type of light called infrared (13) that is invisible to the human eye but can be felt as heat by humans. It is used to spot actively feeding blackholes by searching for brief bursts of infrared light with an algorithm which recognises patterns within them. After cross-referencing many galaxies within 600 million light years of Earth, they could zoom in more closely on galaxies that infrared light could be traced back to. Events where massive amounts of this light are emitted similarly to spaghettification are eliminated by checking for cases like supernovas (massive dying star collapsing on itself). With filtering for unrelated cases out of the way, 18 legitimate signals were found of tidal disruption events from the gravitational influence of blackholes (14), being vital evidence in proving the theory of spaghettification.



An artist's depiction of a beam of X-rays produced by a black hole devouring a star. The beam shocks material to release other types of light. Note the infrared light being generated here. (15)

<u>Conclusion</u>

To conclude, spaghettification is the idea that matter is compressed as it enters a black hole and thins out as it swirls around it and enters its core to be engulfed forever. While it has been backed up as a proper effect as opposed to being a theory, gathering the evidence for this has taken a long time due to how rare the process is to witness for us who are millions of light years away from the nearest black hole. This has spurred development in the methods used to track black holes over time to lead to what we know today about spaghettification.

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Physics in the automotive industry

By Ekraj Juttla

Introduction

The automotive industry is one of the biggest industries in the world with its market size, 2024, being calculated at over 4.3 trillion USD[1]. This ranks it as number one global manufacturing industry in terms of market size[2]. What is generally not known about the automotive industry is the role that physics plays in its success. Physics builds and puts together the fundamentals of the automotive industry through principles such as Newton's Laws playing as the basics behind car safety[3]. This outlines the ability to use forces to understand and further develop the movement of these vehicles. The automotive industry also maintains its safety through using millions of simulations which are backed by physics. With this, engineers can visualise the way that a vehicle will act in collisions and adjust the given safety system accordingly[4]. The understanding behind energy transformations and efficiency through physics has been huge key taken advantage of by the automotive industry through the use systems like KERS[5] and Regenerative Braking[6]. Furthermore, electric motors such as the PMSM motors heavily rely on electromagnetism to convert and store energy[7] which is crucial to the functioning of EVs. Finally, the fundamentals of further future projects such as self-driving cars rely on the current and always growing knowledge of nanotechnology and energy storage[8].

Figure 1

Virtual image of simulation technology

Forces

The fundamentals of physics lay behind Isaac Newton's three laws of motion and the forces involved. Each of the laws are entirely relevant to the braking, accelerating, stopping, and turning of the vehicles. Newton's first law of motion - inertia: An object at rest remains at rest, and an object in motion remains in motion at constant speed and in a straight line unless acted on by an unbalanced force[9]. In terms of automotive vehicles, Newton's first law can be seen through the braking and acceleration of the vehicles. This is through the braking and

Figure 2

Image of the different tyre compounds in Formula One acceleration creating the ‘unbalanced’ force. Through the laws of physics, this ‘unbalanced’ force causes the vehicle to change direction and speed. Newton’s second law of motion, states: the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass[10]. The equation related to this law is force = mass x acceleration, which hence goes to prove that the mass of the vehicle effects the acceleration and therefore the performance of the vehicle. By the rearrangement of the equation force = mass x acceleration, we can conduct that acceleration and mass are inversely proportional. This means that we can use the rearranged form of this equation to prove using physics, that mass affects the performance of the vehicle. The involvement of Newton’s third law of motion: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. The third law helps to tie in the involvement of the friction force between the tyres and the road which assists the grip and control of the vehicle. Along with Newton’s third law, there are multiple other factors which affect the grip and control of the vehicle through the tyres. The three main factors that impact on the levels of car tyre grip are the tyre tread pattern, the type of compound used, and the tread depth of the tyre[11]. The compound of the tyre relates to the softness/hardness of the tyre, with a softer compound harnessing more grip. Tyres with a softer compound can increase the contact area – and, therefore, the grip. Being softer means, they can also ‘adapt’ to irregularities on the road, deforming and then recovering to their shape as needed. Harder compounds are less malleable so tend to offer less grip. But they are more robust and durable. This affects the handling and stability of the vehicle, and therefore the safety.

Safety Systems

The safety of vehicles is also covered through systems within the vehicle. The involvements of physics in these systems are used to protect the occupant of the vehicle. Mechanisms such as airbags and seatbelts help to reduce the impact of an accident by increasing the impact time. The airbag increases the time over which the velocity of the head changes so that the acceleration is reduced, and thus the force is reduced. Ensuring that forces are applied to stronger parts of the body.[12] However, seatbelts work in a separate way. They work by preventing ejection and tumbling. They are designed to stretch a bit in collision. This increases the time taken for the body’s momentum to reach zero and so reduces the forces on it[13]. The impulse of an accident is the main reason which leads to injury for a passenger or driver. Increasing the time of impact can help to distribute force and reduce injury. This is a result of the impulse being reduced. We can prove this by using the physics equation of Impulse = force x change of time[14]. By rearranging this equation, we can deduct that to decrease the force, you must increase the change in time. This is because force is inversely proportional to change in time[15]. Seatbelts are used throughout the automotive industry all the way into the motorsport aspect. Another aspect of safety which is also used in motorsports are crumple zones. These were in fact first used in motorsports, then introduced in road cars[16]. These can most prominently be seen in Formula One cars with their long noses. They are designed to absorb impact energy during a crash; crumple zones were first introduced in racing to protect the drivers and have since become standard in road vehicles, reducing injury risks in collisions. Crumple zones have been engineered in a way that heavily relies on physics. The primary function of a crumple zone is to manage collisions energy. During an impact, the crumple zone gradually collapses, absorbing and redistributing the kinetic energy that would otherwise transfer directly to the passengers[17]. As a result, car occupant deaths and injuries have fallen 63 percent since the testing programmes began. These testing programmes employ advanced software to replicate real-world crash scenarios, providing engineers with a virtual testing environment to assess the safety and performance of vehicle designs[18].

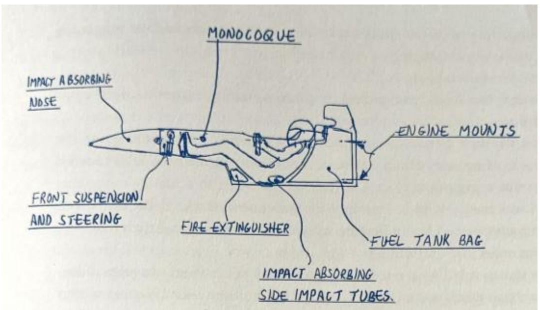

Image of a the monocoque with its many components

Figure 3

Image of the safety features in a car

Figure 4

Energy and Efficiency

There is argument that motorsport would not be where it is now without the intervention on physics-based research and equipment. For example, the KERS system developed and used in Formula one. The Kinetic Energy Recovery System, KERS, was introduced into Formula One in 2009[19]. The KERS system works by collecting the kinetic energy under braking, which would otherwise have been lost as kinetic energy[20], and converting it into electrical energy[21], or as mechanical energy in a flywheel[22]. The driver then presses a button on the steering wheel, discharging the battery to motion of the driveshaft and giving their vehicle a boost of power. There are three components to the system as a whole: the MGU converting energy into electrical energy, the PCU controlling the on/off switching of the electric current between the MGU and the battery, finally the storage the device which consists of a battery/super-capacitor and the flywheel. This results in up to 400 Kilojoules being stored in the battery per lap, giving Formula One drivers approximately an extra 82 Horsepower to access for 6.6 seconds per lap. As stated previously, there is an argument there that motorsport would not be where it is now without the intervention of physics within the sport. Without the intervention of physics knowledge, specifically knowledge on energy, KERS would not have been introduced, and the sport would be many steps behind where it is now. It has been proved that increased fuel efficiency is one of the most significant benefits of improved aerodynamics in the automotive industry[23], this could not have been done without the knowledge of air flow gained through physics. Due to improvements in aerodynamics, drag is reduced, and less energy is required to propel the vehicle forward. Resulting in lower fuel consumption[24]. Lower fuel consumption and therefore the intervention of physics in automotive has given more benefits than simply less money spent on fuel. Improved fuel economy leads to not only lower fuel expenses but also reduces dependence on oil[25]. Furthermore, a fuel-efficient vehicle can also benefit the vehicle's life span, reserving the need for increased manufacturing[26]. It is also possible to increase the fuel efficiency in automotive through using more lightweight materials to manufacture the vehicle, this is because extra weight means that the vehicle requires more energy to accelerate[27]. A 10% reduction in vehicle weight can result in a 6-8% fuel economy improvement[28]. Common lightweight materials include aluminium alloys, magnesium alloys, advanced high-strength steel (AHSS), carbon fibre-reinforced plastics, titanium, and polymer composites. These materials are chosen for their strength-to-weight ratio, helping to reduce vehicle weight and improve fuel efficiency without sacrificing safety[29]. All these materials are most common in everyday road vehicles. However, the most advanced of lightweight materials are used in motorsports, and most commonly Formula One. Around 80% of a Formula One car's volume is made from composite materials. These composite materials include carbon fibre, aramid (Kevlar), Zylon, Polyethylene, filaments, and epoxy resins[30].

Electromagnetism and Electronics

The alternative to having to worry deal with the issue of fuel efficiency is to turn to Electric Vehicles, EVs. The complication with EVs lies with the storage and conversion of energy rather than with fuel. Evs primarily use two types of AC motors: Permanent Magnet Synchronous Motors (PMSM) and Induction Motors[31]. PMSM first send the DC power from the EVs battery pack to the inverter[32], then the inverter converts the DC power into the AC power needed to drive the electric motor[33]. The AC motor then creates a rotating magnetic field inside the motor, causing the rotor to spin, providing torque to the transmission[34]. This direct method of converting energy into power is much more efficient than the methods used in petrol powered cars. We have seen the use of KERS in Formula One cars where it is used to harness what would otherwise be lost thermal energy into useful electrical energy, and although EVs experience a much lower level of energy loss, they still use a similar system. That system is called Regenerative braking[35]. This is conceptually the EV motor working in reverse. When lifting off the accelerator or applying the brakes, the electric motor reverses its function, effectively becoming a generator[36]. The motor then converts the vehicle's kinetic energy into electrical energy; the electrical energy is then sent back to the car's main battery to be stored and be used for propulsion later on[37]. Through this we can learn that physics has grown weaved into the automotive industry and the basics in recovering and storing potentially lost energy comes from the knowledge of energy which come from physics.

The role of physics in automotive does not end with advancements in systems due to physician knowledge of energy, physics also plays a huge role in technology advancement in vehicles. For example, the introduction of parking sensors in the 1970s[38]. These revolve around physics. The physics in car proximity sensors include ultrasonic and electromagnetic waves[39]. The sensor generates an electromagnetic field around the car's front and rear bumper. When a conductive object, such as a metal vehicle, enters this field, it disrupts or alters the electromagnetic field. The sensor detects this change in impedance or field properties, indicating the object's presence and proximity[40]. The concept of the electromagnetic field had emerged after several key discoveries from the likes of Hans Christian Orsted, Michael Faraday, and James Clerk Maxwell between 1820 and the 1860s[41].

Current developments in Automotive with Physics

Sensors continue to and will continue to aid the development of the automotive industry for the foreseeable future. The introduction of self-driving cars came in January 2014[42]. This could not have been done without the inclusion of sensors. For example, the use of LiDAR sensors in self-driving cars. LiDAR (Light Detection and Ranging) emits laser beams that bounce off surroundings to create detailed 3D maps and measure precise distances[43]. This is excellent for detecting road edges, lane markings, and other vehicles and objects[44]. Without LiDAR, self-driving cars would not be able to detect surroundings and create that image around them which allows the car to be aware of potential hazards to maintain the safety of its passengers. The development of sensors and other technologies through the knowledge of physics continues to propel the automotive in a forward direction.

The future of Nanotechnology in the Automotive Industry

The use of nanotechnology in the automotive industry[45] encourages the development of automotive in multiple factors. Nanotechnology enables the use of lighter and stronger materials, therefore offering a greater weight-to-strength ratio. A concept previously discovered through Formula One, lighter vehicles result in an increased fuel efficiency to benefit the environment and the economy[46]. With heavy investment into nanotechnology, money can be saved in the future in the form of materials in the automotive industry with materials being more lightweight and easier to access. Investment into nanotechnology can also boost performance and sustainability in the automotive industry. The introduction of nano-catalysts, nano-fluids, and nano-coatings on engine components can reduce friction and abrasion, leading to better engine performance, lower fuel consumption, and reduced harmful emissions[47]. Similar to issues with using materials that are not exactly lightweight, this can help boost the economy since the lifespan automotive engines will be increased, and fuel consumption will be reduced. Nanotechnology is also a contributing factor to increased energy efficiency, by being crucial for enhancing battery performance, energy density, and thermal management in electric vehicles[48]. However, nanotechnology is not the only route into enhancing battery performance and energy efficiency. Solid-state batteries have been seen as the “technological breakthrough” that electric car makers are striving to bring to the market[49]. So much so that Mercedes-Benz have have already run tests on this solid-state battery earlier this year in February[50]. These batteries offer significant advantages over current lithium-ion batteries in electric vehicles by replacing liquid electrolytes with solid ones, enabling higher energy density, longer range, faster charging, and improved safety – this is because solid-state batteries are less volatile[51]. They also require less expensive materials to put together, therefore reducing the costs, which could then be put towards improving other aspects of the vehicle[52]. The solid-state battery represents a new era for EVs since the first EV was introduced in 2008 with the Tesla Roadster [53].

Conclusion

Physics is and has always been a driving force in the Automotive Industry from the design all the way to the safety aspects and the performance. Basis principles of physics have been applied to maximise the output of automotive and has increased the development of the industry in hundreds of different ways. From Formula One, where physics is used to optimise the speed and balance of the car through aerodynamics, to EVs, where physics is used to develop batteries and revolutionary technology systems. In conclusion, physics has been a driving force of the automotive industry since its beginnings, and it will continue to be in the future with comprehensive research always being carried out to improve and optimise automotive performance.

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Misha Iunets

How electricity fundamentally changed how manufacturing is conducted

Introduction

In the modern era, electricity usage has become a standard in manufacturing. It will be difficult to name a single high precision manufacturing tool that does not utilise electricity. It has enabled new technologies, enhanced productivity and reshaped the whole profession and it continues to do this every day. In this essay, I will go over the limitations engineers had to face in the past as well as how the practical usage of electricity allowed them to make big limitations trivial

Issues with lighting

Firstly, factories relied on daylight or oil and gas lamps to provide the lighting[1]. This limited any significant work to daylight hours, as factories needed hundreds of lamps to provide meaningful lighting, but this was very inefficient due to uneven distribution of lighting and low overall light levels[2].

This made mass production of any product on a scale that it is today impossible, as manufacturing could not be done at night at the same efficiency as it was during daylight hours. This severely limited the availability of manufactured products, as well as making them a lot more expensive, meaning that only few rich people could afford to buy them.

While the existence of electricity was known, it could not be generated and distributed efficiently, making it mostly a scientific curiosity. Over time, electricity's potential for practical usage was recognised, leading to developments of electric powered light bulbs.

The first of these lamps were arc lamps, which worked by passing a large current between 2 electrodes, generating light in the process[3]. They were ideal for lighting streets and large halls, but had a short lifespan and were unsafe for indoor factory use due to harsh glare produced. [4]This was improved by Thomas Edison with his invention of the incandescent light bulb, which provided a safe, enclosed electric light. This significantly improved fire safety, as well as made air inside factories cleaner and reduced strain on the workers' eyes. These however were about 10% efficient at most, got very hot in a short period of time and had a short lifespan of about 40-200 hours. This made them expensive to sustain and quite unreliable.

[5]From 1890s-1910s electric power grids are expanded in cities and industrial centres, making electricity easier to access and utilise for practical applications. This allowed for electrical lighting systems to be installed for much cheaper and allowed them to become longer lasting by using bulbs with tungsten filaments. At this point, factories were able to operate at maximum efficiency at any time of the day and started to mass produce at a scale that is used today.

Power Transmission

Second problem was that factories' locations were constrained to be near rivers, as water was required to spin the waterwheel. While this problem was partially resolved by using steam engines, it had a lot of limitations. [6]Power was delivered through lines shafts, belts and pulleys, making it extremely dangerous. The whole factory was powered by a single steam engine, which meant that the whole factory could shut down if the engine failed. Power was also hard to regulate compared to electric motors, which meant that a sudden increase in power demand could not be quickly met.

[7]Some progress was made towards the solution of the problem in 1882 by Edison who set up the first commercial power station which supplied Direct Current to local buildings. [8]This only helped to remedy the problem on a short scale however, as direct current caused the transmission wires to heat up a lot which meant that a lot of power was wasted. The transmission wires could not be used to power non-local homes because it would be very costly and inefficient to do so. On top of this, unlike modern power grids, the voltage of the current could not be easily changed, which meant that multiple different generators had to be used to power different appliances, which was expensive and inefficient.

This model of electricity transmission was eventually replaced by Tesla's AC transmission model. [9]Even though this model was developed in the 1890s, it remains a backbone of modern transmission grids. It works by generating alternating current at a central station and using transformers to increase the voltage to hundreds of thousands of volts. The electricity would then be sent over transmission lines to consumers and transformers were used again to decrease the voltage to around 230 volts, which was a safe level for households and factories. [10]This model was a lot more efficient, as power dissipation was decreased significantly and it could be used to transmit power to large cities and rural areas. This made it a lot easier for factories to get a reliable, sustainable source of electricity, which ultimately allowed for the installation of electricity powered machinery, and carrying out mass production on a scale that it is today

[11]This model was refined further in the late 1880s with the invention of three-phase AC power supply. It improved the flaws of Tesla's original single phase power supply, such as: improved consistency of the power supply, provided a much more efficient power transmission and was a lot more scalable and flexible for supplying power to factories and households. This flexibility allowed factories to get a consistent and reliable supply of electricity, which allowed them to set up electricity powered high precision machinery, which were necessary in order to carry out mass production.

Accuracy and precision of manufacturing machines

The third problem was the inaccuracy of manufacturing machines. In order to carry out mass production, accurate and precise tooling is required to produce identical, complex parts with a consistent surface finish. [12]Before mass electrification, machines were partly hand driven, which meant that the quality of each piece was heavily dependent on operator's skill in driving the machine. This made manufacturing unreliable, as even if the most skilled operator produced all the parts, they would not be identical, and some would not fit inside the required tolerances. On top of this, the operator would slowly get increasingly tired, which would drastically decrease the quality of manufactured parts towards the end of the shift.

While this was partly solved by introducing steam engines to power the machines, the operator still needed to occasionally drive the machine manually, which still introduced errors in machine feed.

[13]In early 1821, Michael Faraday demonstrated the first electromagnetic rotation, where a current carrying wire rotated around a permanent magnet. This is the first example of the motor effect, which is utilised by every modern electric motor. While this was a scientific experiment and not a practical motor, it showed that it is possible to use electricity to generate consistent mechanical movement.

[14]In 1834, Moritz Von Jacobi built on Faraday's idea and created the first practical electric motor which could do real work. [15]It was used to power a boat carrying 14 people across the river Neva. [16]As well as this, Thomas Davenport patented a dc electric motor in United States, which was used to power small scale appliances, such as printing presses and model railways. This further proved that faraday's idea of using electricity to drive mechanical mechanisms worked and was effective, which in turn stimulated even further research into motors and eventual refinements to existing models.

[17]In 1866, Werner Von Siemens developed the first self-excited generator, which was a lot more efficient than earlier battery powered designs. This was a huge step towards

using motors in factories for mass production, as motors could now be powered via a generator that could provide an uninterruptable, consistent supply of electricity. This meant that workers had to spend less effort on trying to maintain a constant power output and could focus more on actual manufacturing, which would lead to better quality products being produced

[18]Between 1887-1888, Nikola Tesla made further refinements to existing models of motors, patenting the induction motor, which used alternating current. This paired well with his ac power supply model, [19]as motors could now be powered by electricity generated from a power station hundreds of kilometres away. This was revolutionary, as motors could now be used to reliably drive machinery at a consistent power output, regardless of where the factory was located and regardless of where motors were placed inside the factory. [20]This type of motor remains a backbone of modern industry

Conclusion

Overall, while electricity has fundamentally changed how manufacturing is conducted it was not a fast change that occurred over a single night. It took decades of research, experiments and refinements to invent the necessary tools, as well as develop the necessary infrastructure to power them. Without the discovery of electricity and inventions that harness and use it for a practical purpose, life would be very different compared to what it is today

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Physics in Motorsports

Nicholas Sysa

Introduction

Motorsport covers a wide range of different disciplines in the automotive industry. These can range from Formula One, Formula Drift, MotoGP, GT3 racing, Rally Racing, and many more with lower divisions. G-force is known as the side force[1] which pulls a driver away from their centre of mass. G-force plays a key role in motorsport racing specifically, because when drivers are cornering at high speeds, they can experience up to 5 times their weight (5g)[2], and in crashes they can reach up to 214g [3], which is the highest ever recorded in motorsport in IndyCar. This is why drivers train their necks by having their personal trainer place a band over their head, and the PT pulls the band whilst the F1 driver pulls against that force[4].Friction also plays an essential role in motorsport. For example, in Formula Drift, the driver needs to overcome the friction between the tires and the road, which is why the driver needs to go into a corner at high speed but also at an angle, then the driver needs to control it through clutch kicking[5] or using a handbrake to increase the angle of the drift to score more points. All these sides of motorsport cover the same aspects of aerodynamics but in each of their own separate ways.

Lando Norris' brutal neck training regime video[6]

Forces

Forces play a special role in motorsport racing as three main forces create three moments[7] around the axes. These forces are downforce in the vertical axes, drag in the longitudinal axes and side forces (G-force) in the lateral axes.

Downforce

Aerodynamics is a key concept in motorsport to gain speeds quicker but also maintain the vehicle on the road. Downforce is talked about mainly in Formula 1, but it is an important force for all motorsports. Downforce is a vertical aerodynamic force that pushes the car downward to create grip and allow for faster cornering. In road legal track cars, downforce is usually talked about being acted on the rear wing. However, this is far from the case, because components from all over the car contribute to downforce, like the front wing, underfloor, diffuser and rear wing. In Formula 1, cars can reach between 2400 kg to 3200 kg[8] of downforce at speeds of 155 mph. Whereas a normal road car produces only 68 kg of downforce at 120 mph[9].

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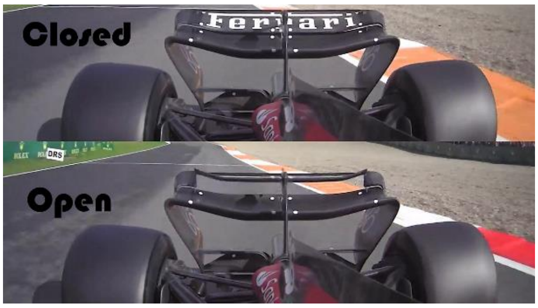
Drag



DRS rear wing open vs closed[1]

Drag is a force that opposes the car's motion, meaning drag slows the car down. This is why formula 1 cars are shaped as they are to reduce air resistance. Also drag can be minimised by using devices that redirect airflow, creating downforce while minimizing drag. Another way is using the Drag Reduction System (DRS). DRS can only be used in specific zones on different tracks, whilst also having to be within one second behind the driver in front. When activating DRS (driver presses a button on the steering wheel), a flap opens on the rear wing, changing its angle and reducing the pressure difference across the wing[2]. Simulators are used to show streamlines of how the air flows over/ under the cars. The use of these simulators, allows teams to analyse what should be modified on the car to enhance downforce, reduce drag and improve the overall aerodynamic efficiency.


Simulation of streamlining[3]

The colours in Photo 2 show velocity gradients, meaning that the colours signify what type of velocity the air is moving. For example, red/orange colours represent faster-moving air whilst the green shows slower-moving air. This diagram specifically shows that as the air moves through the car; the air becomes slower moving due to the air interacting with the surfaces of the car. The swirling pocket of air left at the back of the rear wing increases drag, which is why DRS reduces drag by opening a flap on the rear wing, allowing higher top speeds, though downforce is temporarily reduced.

Suspension

In GT3 racing, suspension is used to control the weight transfer of the car both laterally and longitudinally to improve cornering ability, and the other role is to control the impacts from bumps or kerbs to maintain constant contact between the tyre and the road surface[4]. This is why the ride height is very important in GT3 racing. If the ride height is too high, the underbody flow expands too much, reducing suction and downforce. But if the ride height is too low, the airflow under the body can stall, also reducing downforce[5]. There is an optimal ride height where the diffuser generates maximum low-pressure suction for grip. The images below show the big difference in ride height between a Porsche cup car and a regular Porsche.


Ride height comparison Porsche turbo S vs Porsche GT3 R rennsport[6]

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Gear Ratios

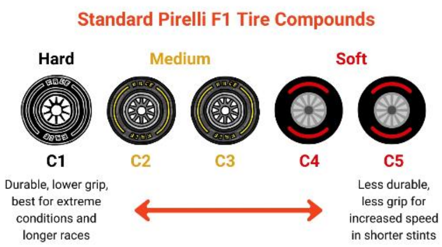
Gear ratios are important in motorsport racing; however, they can be seen in "normal" cars as well. For example, a shorter gear results in higher torque (quicker acceleration) but a lower top speed. On the other hand, a longer gear results in lower torque (slower acceleration) but a higher top speed[1]. In formula 1 specifically, if a new F1 track is created, simulations/ testing is taken place to find the right gear ratio for the track. On each track, F1 engineers must tune cars to different gears. If they have raced on the track before, they will use previous data from the events. All gears in high performance cars (track use only) ae straight cut to minimise power losses and to provide the maximum possible strength and durability.

Straight cut gears vs helical cut gears comparison[2]

When calculating the gear ratios, a power equation is used. ($P = \omega \times T$) This equation calculates power (Watts) through the product of rotational speed (rad s^{-1}) times by the torque (Nm). However, you must pass this through a reduction ratio of 2:1 where you end up with the equation:
$P = (\omega/2) \times (T/2)$, whereby you are moving at half the speed, but able to push more inertia/ accelerate quicker.

Tires and Friction

Tires in motorsport are key for planning out when the driver should pit due to the tires wearing out. For example, circuits like Bahrain, Abu Dhabi and Singapore are tracks that wear tires out quicker due to the high track temperatures. Additionally, tracks like Circuit de Spa Francorchamps and Suzuka, also cause tires to wear out faster due to the high-speed corners. These high-speed corners generate substantial forces that push the tires sideways, leading to increased grip and wear. Indentation is the roughness of the road excites the rubber and as the rubber does not immediately return to its original shape this leads to asymmetrical deformation and a friction force[3]. Adhesion is the rubber molecules bond to the road's surface and as the tyre rolls, these molecules are stretched. The rubber's viscosity resists this deformation, generating a friction force. In Formula 1, soft tyres create more grip than the hard tyre compound. This is due to the softer compound adhering better to the road surface where they create a larger contact area and a stickier surface[4]. This increased grip allows more power to be put down, therefore increasing the acceleration more, which allows for faster lap times and overtaking positions. MotoGP have the exact same compounds as Formula 1 but in MotoGP tyres usually last one full race session, whereas in Formula 1 there are usually one or two pitstops in a race session. However, in MotoGP each driver gets two bikes, one for a wet session and another for a dry session; in Formula 1 it's one car but they have a choice of intermediate tyres for wet conditions. Both motorsports have no set limits on the times the tyres can be changed, but regulations in Formula 1 state that two different types of compounds must be used in a race.



Tyre compound comparison Formula 1[5]

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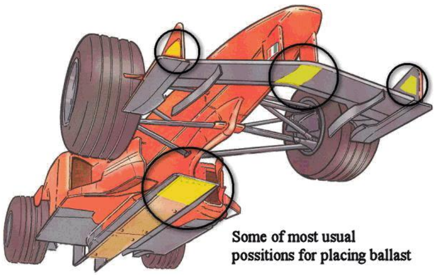
Weight Distribution and Vehicle Balance

A vehicle's centre of gravity is crucial as weight transfer occurs around it, altering the load on each tyre. The higher the car's centre of gravity and the harder the turn, the greater this weight transfer will be. This can feel like a sideways force pushing you towards the outside of the car[1]. Understeer refers to a situation where the front tires lose traction before the rear tires. Hence, it causes the car to keep moving straight ahead, even if the driver attempts to turn. Conversely, oversteer occurs when the rear tires lose grip before the front tires. As a result, the end tends to slide out, making it difficult to maintain control[2]. These terms (understeer and oversteer) aren't just talked about in motorsport, but also in the real world. In the real world, understeer and oversteer can be a result of a crash due to the driver losing control of the steering. Ballast is a F1 specific tuning option. Ballast allows you to add weight to an already light car, with the specific intention of altering the weight distribution of the car. This works hand in hand with weight balance. Modern F1 cars have ballast of more than 150 Kg on the as lowest place as possible to further lower the centre of gravity[3].



Ballast placement on Formula 1 cars[4]

Ballast in Formula 1 framework[5]

Formula 1 cars are low to the ground to have the centre of gravity as close to the ground as possible, meaning the less leverage weight transfer has during acceleration, braking and cornering. This means the load on each tyre becomes more evenly distributed, so the car maintains grip better leading to less risk of understeer/ oversteer. On the other hand, in Rallying the ride height is set to a high position to absorb the rough, uneven terrain of off-road stages. The impact of a bump compresses the spring but to ensure that your car doesn't turn into a 200 kph trampoline the spring is not allowed to decompress immediately. Instead, the damper (the oil in the damper, to be more specific) releases the compression gradually to get the car back to its normal ride height[6].

Ride height of a Formula 1 car[7]

Ride height of a Rally car[8]

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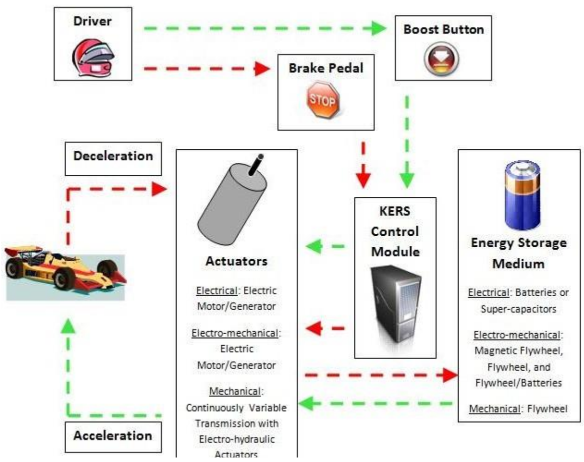
Energy and Efficiency

Kinetic energy is the energy a moving object possesses, defined by the formula: $KE = 1/2mv^2$. When a driver applies the brakes to the vehicle, friction between the brake pads and the rotors performs work. This work converts the vehicle's kinetic energy into other forms of energy, mainly thermal energy in the brakes and environment but also some sound energy. However, this thermal energy created from the brakes can become a significant concern in motorsport, because the brakes can overheat, meaning brake performance is affected negatively and reducing their overall efficiency. The Kinetic Energy Recovery Systems (KERS) was introduced to Formula 1 in 2009[1] which are devices used for converting some of the waste energy from the braking process into more useful types of energy which can then be used to give the cars a power boost. The additional 60 kW[2] boost (which equates to 80 HP), limited to 400 kJ per lap, will reduce lap times by between 0.2-0.3 seconds. But to get the most from KERS, the whole system needs to be as lightweight and compact as possible; otherwise, this advantage can quickly disappear. However, this power boost could only be used 6.7[3] seconds a lap. Meaning, KERS was only able to be used during crucial moments and had to be used strategically.

KERS Schematic



KERS schematic[4]

Energy Recovery Systems (ERS) is the next generation system that replaced KERS becoming a central part of the Formula 1 power units from 2014[5] onwards. In contrast to KERS, the deployment of ERS occurs by 'engine maps'. This is essentially pre-set modes that dictate how to use the engine, and exactly where to use ERS, rather than the driver. ERS can provide up to 120 kw (approx. 160 bhp)[6] of power for approximately 33 seconds per lap. The main difference between KERS and ERS is that KERS recovers only the kinetic energy from braking, whereas ERS recovers both kinetic energy from braking and heat energy[7] from the turbocharger. In F1, the fuel flow rate is limited to a maximum of 100 kg[8] per hour, so the only factor the teams can influence is the efficiency of the engine. A more efficient engine therefore means more power output and thus better on-track performance. ERS inside the engine looks complicated but it shows the transfers between the Motor Generator Unit-Kinetic (MGU-K), the Motor Generator Unit-Heat (MGU-H) and the turbocharger.

How ERS looks inside the Formula 1 engine[9]

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Driver Safety and Crash Physics

In motorsport, the difference between a survivable crash and a fatal one often comes down to physics. The safety of the driver relies on understanding how forces act during high-speed crashes and how designing safety systems can reduce the impact on a human. Momentum is a key term when talking about crashes. Momentum is defined as the quantity of motion an object has, with equation p=mv. Conservation of momentum states that the total momentum before the crash is equal to the total momentum after the crash. However, during the crash the momentum becomes zero, which results in a large change in momentum (impulse), which is a force that acts over time. The impulse is what creates the large forces that cause injuries. Car safety features are very important to protect the driver from large impacts, and possibly death. One example is the halo in Formula 1. There have been many speculations whether to get rid of the halo or keep it due to aesthetic concerns[1], but it should be kept for safety reasons. One very popular example is the crash that happened at Silverstone in Formula 1, where Zhou Guanyu was hit and flipped upside down, and he survived because of the halo protecting him when the car went upside down, however he did hit the wall very hard (there was never an official g-force reading).

Zhou Guanyu crash at Silverstone[3]

Car safety features aren't only in motorsport, but also in normal cars. For example, each car has seatbelts, airbags and crumple zones all work to change the shape of the car, which increases the time taken for the collision. These crumple zones refer to the areas of a car that are designed to deform or crumple on impact. These different safety features decrease the rate of change of momentum, which decreases the force of the collision[2] on any people within the car.

One of the most extreme physical challenges faced by motorsport drivers is the effect of g-forces, which is a physical force equivalent to one unit of gravity that is multiplied during rapid changes of direction or velocity[4]. The accelerations acting on the body come from the stem of Newton's 2nd law: F=ma. For example, if the average person (70 kg in mass) went under 5g, they would feel the effective force of approximately 3435 N. As mentioned earlier, g-forces can spike massively in crashes. There are also human limits when it comes to g-force. If a driver sustains 4-6g for more than a few seconds, symptoms can range from blackouts to total death[5]. The Head and Neck Support (HANS) is a device that was introduced to minimise the effects of extreme G-forces and the risk of severe or even fatal head and neck injuries in crashes, such as basilar skull fractures[6]. The HANS device is a lightweight carbon fibre collar that is custom-made for each driver to ensure a perfect fit. Designed in the shape of a 'U', the curvature is positioned at the back of the neck with two adjacent arms resting on the top of the chest. The collar, supported by the shoulders, is secured under the driver's safety belts and tethered to the helmet. Another piece of safety equipment is the racing uniform as they are all fireproof. One evidence shown that the racing suits are fireproof is when Romain Grosjean crashed into a wall in 2020 Bahrain, splitting his car into two pieces and setting alight. Luckily Grosjean walked out alive with only burns on his hands[7].

Romain Grosjean's crash in 2020 Bahrain[8]

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Case Studies in Motorsport Physics

Tracks like Silverstone have many high-speed straights. One famous example is known as Copse Corner. The Formula One cars will approach Copse Corner at close to 190 mph[1] from the National Pit Straight. In qualifying Copse is flat out. The car's downforce will keep it glued to the road but will slow it down slightly as it corners. It will hit the apex at around 180 mph. At that speed, the lateral (sideways) force needed to turn is enormous. The formula for this would be $F= mv^2/r$. This is the equation to calculate the centripetal force[2]. With a small radius and huge velocity, the force is huge; if there was no downforce and tire grip, F1 cars would not be able to corner this fast. Downforce and tire friction are what make such speeds possible, otherwise cars would slide off easily. Copse Corner is also famous for the Max Verstappen crash where he sustained 51g[3] after being hit by Lewis Hamilton whilst turning into the corner. If the car goes too fast or loses too much downforce, the centripetal force generated by the tyres will be exceeded, leading to a loss of grip and a skid.

Max Verstappen crash at Copse Corner Silverstone[4]

Another famous track which is physical is Monza, specifically the Parabolica (Curva Alboreto) section. The last corner of the Temple of Speed was renamed as "Curva Alboreto", exactly twenty years after the death of the Milanese driver, which took place in 2001 during some test tests at the Lausitzring[5]. This part of the track also requires a centripetal force to turn into the corner. This corner specifically requires significant lateral force from the tires to maintain traction by applying the throttle progressively[6], which then allows drivers to accelerate out towards the finish line.

Monza Turn 11 Curve Parabolica[7]

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Conclusion

Overall, it has become obvious that physics is at the heart of both performance and safety on track. Many people think that motorsport is only about speed, but it's about applying physics to push limits whilst keeping drivers safe. Throughout I have talked about the different aspects which are shaped by physics. Aerodynamics determines how cars cut through the air while generating downforce, vehicle dynamics such as suspension and weight distribution affect cornering and stability, power and efficiency explain how energy is transmitted and managed, and crash physics shows how drivers are kept safe through modern technology. Motorsport is currently evolving, especially with new regulations coming through to make the sports become more environmentally friendly. For example, from 2026 in Formula 1, cars will have new power unit rules, which include increased battery power and the use of 100% sustainable fuels[1]. This shows motorsport will continue evolving to become more strategic, sustainable and innovative.

1. Formula 1 - **FIA unveils Formula 1 regulations for 2026 and beyond featuring more agile cars and active aerodynamics** Date Accessed (27/08/2025) https://www.formula1.com/en/latest/article/fia-unveils-formula-1-regulations-for-2026-and-beyond-featuring-more-agile.75qJiYOHXgeJqsVQtDr2UB

What does the future look like for deep space propulsion?

By Oliver Stowe

Chemical rockets have been the primary propulsion method for space exploration since the space race in the late 1950s to early 1960s. Combustion rockets have been continuously improved over time to improve efficiency and the overall thrust. However, chemical combustions limitations arise during deep space exploration. But what if there was an engine that could operate over greater distances? This essay focus on the growth and development of the innovative technology of magneto-plasma dynamic thrusters (MPD thruster) and how they compare with chemical rockets of today.

Origins of the Lorentz force

Self-field and applied field MPD thrusters both rely on the principle of Lorentz force and its effects to expel the ionised plasma at the high exhaust velocities to generate thrust (1). The Lorentz force was derived by Hendrick Lorentz in 1895 with the equation. **F = q (E + v*B).** (2)The Lorentz force describes the effect of an electrically charged particle as it travels through and interacts with both an electric and magnetic field. In the equation the F represents the total Lorentz force on the particle, with q representing the charge of the particle v represents the velocity of the particle through the electric field E and B being the strength of the magnetic field. In a self-field MPD thruster the magnetic field is purely created by the interaction of the electric current and the ionized plasma forming an azimuthal magnetic field in concentric circles around the central cathode of the thruster (3). There is also an applied field MPD thruster that works the same as a self-field MPD. However, it has an external electromagnet to generate the magnetic field therefore increasing thrust, but it is unrelated to the overall function and principle of how it works. However, the analysis will talk about using applied field MPD's.

Plasma physics

Plasma is the main source of propulsion due to the way it can be manipulated by the electromagnetic fields. Plasma is defined as a mixture of an element that consists of an ionised atoms, free electrons, and neutral atoms (4). Plasma by this definition is classified as one of the four states of matters in our universe that we are aware of so far. With it being one of the states of matter, it is a shock to us that we see so little natural plasma in the earth with the nearest source being the sun. For how rare plasma is in our solar system, you would expect it to be quite uncommon in the universe. However, the opposite is true with plasma being the most abundant states of matter in the universe with over 99% of all matter being plasma (5). Plasma being uncommon on earth provides challenges for its containment in our thrusters. The plasma is referred to as a quasi-neutral where the ratio of positive ions to negative electrons is almost equal giving a small charge density. Another important property of the quasi-plasma is it is treated as an electrically conducting fluid due to the electrons and ions in the plasma. This fact about the plasma allows it to be manipulated by the electric and magnetic fields created externally and induced from within the component, this allows it to be expelled at high velocities creating thrust (6). With the promises of plasma, it also comes with some significant drawbacks including component erosion at low power which causes a reduction in efficiency. Overall, the plasma part of our thrusters poses many benefits but not without its fair share of challenges.

How does it work?

Regarding the basic principles as aforementioned how do they turn a propellant into thrust for the potential for deep space exploration? Regarding MPD thrusters they have the option of using a metal or gas as a propellant. Whilst both have their own advantages and disadvantages the most efficient thrusters use a metallic propellant, with the most common being lithium. The first step in creating thrust is gathering a cylinder of the metal propellant that will be used. The metal rod is fed into the thruster where a small amount of energy is used to heat and vaporise the metal, turning it into a gas. Now the propellant has been vapourised, it performs the same steps as if a gaseous propellant were used. The now gaseous propellant is injected into the engines discharge chamber. The engine discharge chamber consists of three main components including: the cathode, anode, and the rear insulator. The cathode is a cylinder in the centre of the thruster made of variants of tungsten metal, with the most ideal being impregnated thorium tungsten electrode, an alloy of tungsten made with 2% thorium oxide (7). The anode is made of a water-cooled copper that is created into a cylinder and a ring around the central cathode with a sheet at the back acting as a rear insulator and the point of injection for the gaseous propellant.

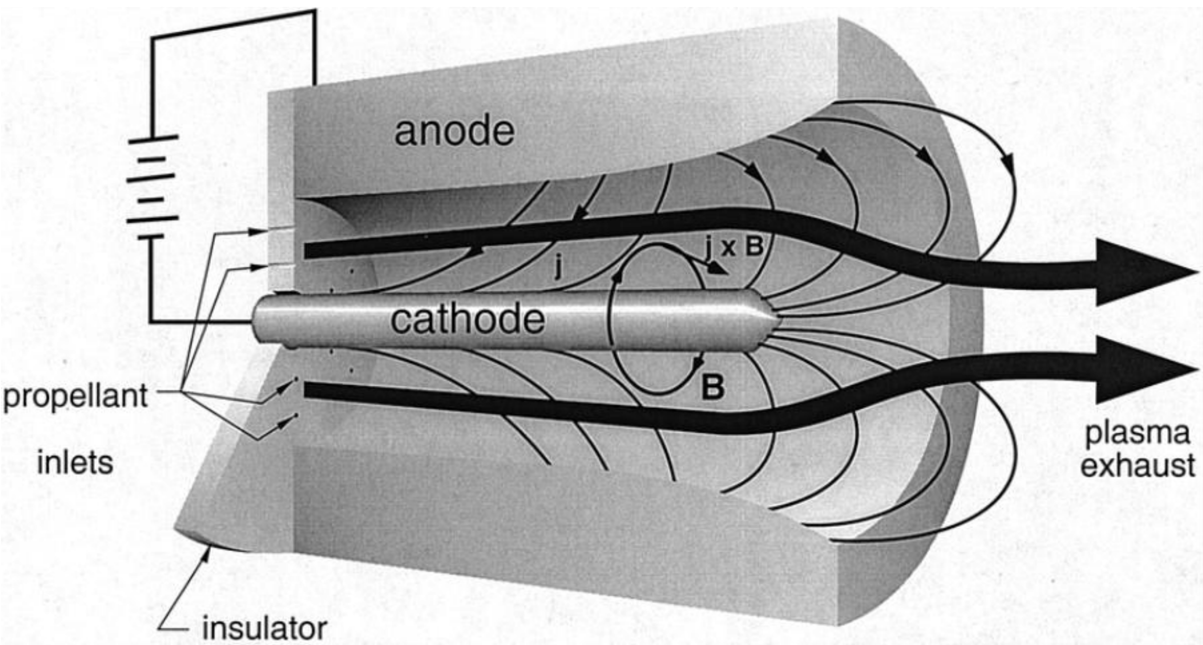

Image 1 – Diagram of an engine discharge chamber (8)

How gas is converted to thrust

The ionised gas is injected into the discharge chamber though the rear insulator. A compromise is established between the rate the propellant is flowed into the discharge chamber so all the gas can be ionised to generate the maximum thrust. The gas passes between the anode and cathode where a high current electrical discharge is passed between the two components causing the gas to heat up and ionise becoming plasma. Regarding the physics of plasma properties as mentioned earlier it is then manipulated through the magnetic field generated by the cathode and the external electromagnet. The current flows radially from the anode to the central cathode. From the currents interaction with the central cathode is creates a self-induced magnetic field that wraps around the cathode in a circular motion in concentric circles. The magnetic field, and the current interact perpendicularly to each other causing the Lorentz force to act along the thruster causing the ions to be expelled at velocities between 15 and 60 kilometres per second.

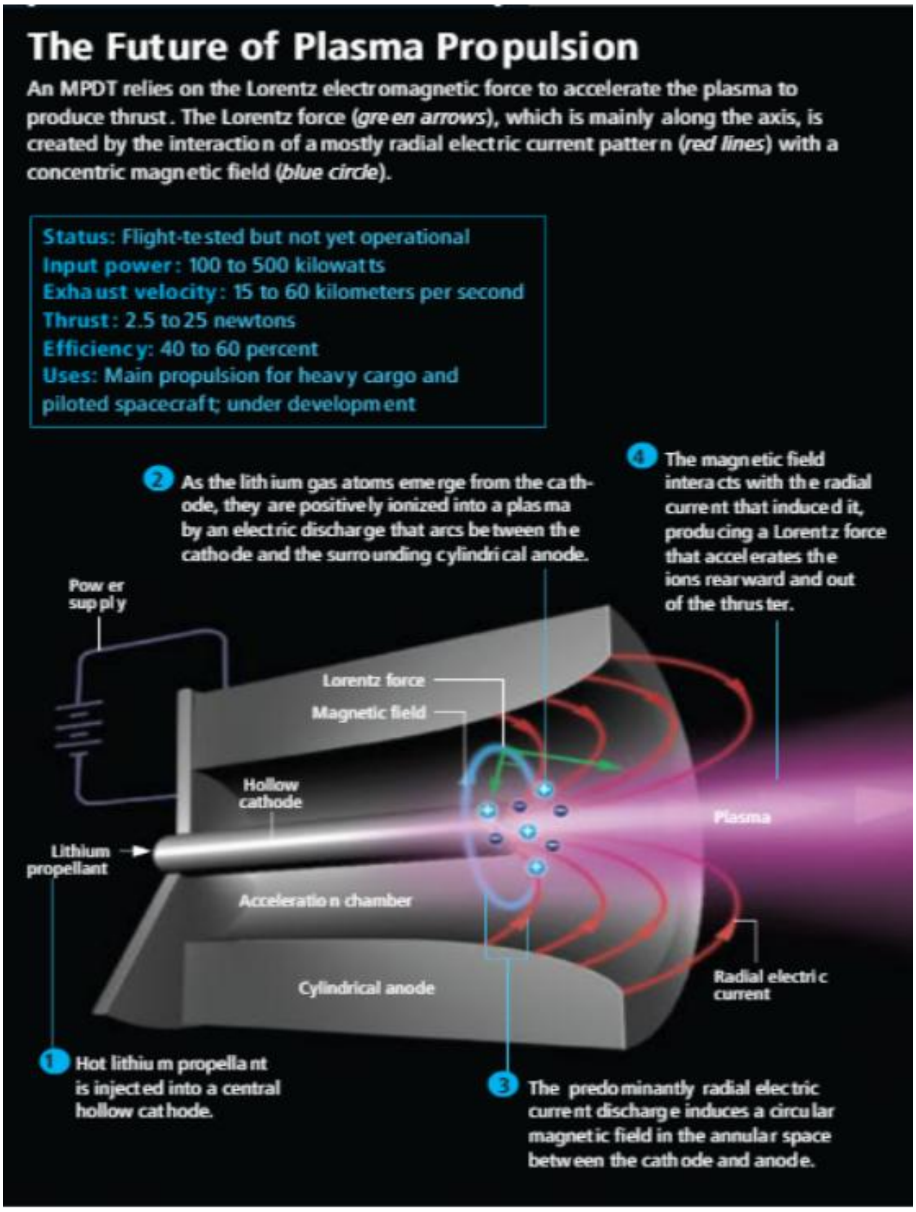

Diagram 3 - A diagram to show how an MPD thruster works. (9)

Why is each component chosen?

Lithium metal as the propellant - the most common is lithium dues to a few factors including a low ionisation energy reducing power consumption in ionising and allowing a larger power percentage to go towards accelerating the plasma.

Copper and thoriated tungsten – Both metals are classed as refractory metals. Due to this classification, the metals have characteristics that allow it to be adapted for its purpose. One property is their high melting and boiling point allowing them to operate at elevated temperatures. A benefit of tungsten as a central cathode is they have low wear from the continuous electron bombardment allowing a longer operating lifetime. Copper has a high thermal conductivity allowing it to absorb and dissipate heat without damaging internal components. Thoriated tungsten is used for many reasons including a low specific heat capacity and melting point allowing it to hold its shape with the surrounding heat, the thoriated part of it allows the tungsten to carry a larger current through it and has a slower work function compared to pure tungsten. The benefit of a lower work function is a drop in surface temperature of the material causing a better electron emission rate whilst also lengthening the life of the thrusters as it slows down the evaporation rate of the cathode itself (10).

Boron Nitride- The main function of the insulator is to isolate the anode and to cathode to ensure there is the electrical discharge between the two. It is the subject to the injection of the gas into the chamber. The roles of the rear insulator provide challenges to the design and choice of a material as it must be able to withstand the conditions inside the chamber and provide structural support for the thruster itself. The most common material chosen for this role is a ceramic of boron nitride which at high operating temperatures has a high electrical resistance reducing the chance of a short at the rear. It also has a high resistance to heat and ion bombardment erosion improving and extending the thrusters lifespan (11).

Challenges

With the great promise of this type of thruster it comes with its own set of challenges and complications. One such complication compared to the more chemical combustions rockets one major difference between the two types of rockets is the volume of thrust they both provide. An MPD thrusters provides up to 2.5N in a vacuum (12). This indicates one of the challenges of MPD thrusters is spaceflight as the average minimum escape force with Saturn V using around 3.4 million kg of thrust which converts to 33,000,000N of thrust (13). and the latest of the Artemis SLS system providing an initial thrust or around 39,000,000 newtons of thrust,8.8 million pounds of thrust (14). As a complication it must be part of another stage of a rocket that is deployed in orbit. This means it can only be compared to an upper stage of a rocket with the upper stage of the Artemis rocket being where the MPD thruster would perform best. However, the upper stage of the Artemis rocket provides around about 110,000N (15) which is 45,000x more powerful than the MPD thruster. Another challenge is the generation of the 100-150KW as they do not generate their own power. and to generate through solar it would take 2 or 3 10x10 metre solar arrays with current technology (16). Based on current designs and models however breakthroughs with fission reactors provide promising results. However, due to elevated operating temperatures and the energy required to vaporise the metallic propellant MPD thrusters operate at an efficiency between 40% and 60% as illustrated in diagram 3.

Success

However, with all the challenges the technology presents it does have some fundamental success that could lead it to be the future of deep space propulsion. One successful feat of the engine is the reduction if fuel it requires allowing a larger cargo to be able to move the same distance. Another benefit of MPD thrusters is that they have a higher specific impulse which is a measure of how much thrust is produced per unit of propellant (17). Chemical rockets top out around 400 isp which indicates they can generate high thrust for shorter periods making them useful for launch and rapid orbital changes whilst current MPD thrusters have a specific impulse of on average 5000 isp (18). This provides an advantage for deep space missions as they have low thrust, but they can burn over greater distances. This benefit allows probes or landers to embark on deep space mission whilst constantly acceleration and reaching greater speed with less fuel making MPD suited to deep space exploration.

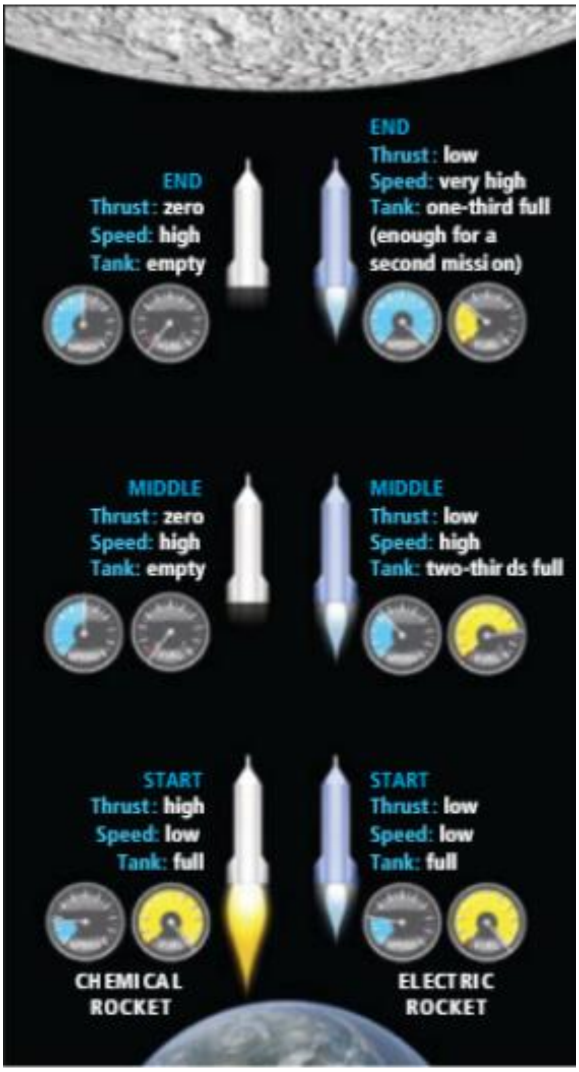

Image 4 – illustration comparing thrust of chemical vs electrical rockets (19)

Conclusion

Whilst MPD thruster have immense potential for space exploration, the current technology has its limitations. They excel in deep space and will have a substantial impact for mars mission and future exploration to furth out or beyond our solar system. With continued development a new technological development. However, for the moment they are more of a sci-fi reach than a practical propulsion system.

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In Formula 1, tyres are one of the most essential components of the car. While the power unit and aerodynamics often receive the most attention, it is ultimately the tyres that transfer every bit of power, braking force and cornering grip to the track. Each tyre has a contact patch with the road surface roughly the size of a postcard, yet this small area must withstand forces of several tonnes when a car is travelling over 300 km/h (The Times, 2025). Without tyres, no amount of engine power or aerodynamic downforce can be used effectively.

The physics behind the tyres is both complex and essential. At its simplest level, the performance of a tyre can be linked to the force of friction, given by the equation:

$$\boldsymbol{F = \mu R}$$

Where F is the maximum frictional force, μ is the coefficient of friction, and R is the normal force acting on the tyre (Physics in Formula 1, 2025). In Formula 1, the normal force is a combination of the car's weight and the aerodynamic downforce produced by wings and the car's bodywork. This equation highlights why tyres are central to performance – if a team can increase μ through compound chemistry or optimise R through aerodynamics, the car can accelerate, corner and brake faster.

However, the physics of Formula 1 goes far beyond this simple formula. The viscoelastic (of a substance exhibiting both elastic and viscous behaviour when deformed) (Collins Dictionary, 2025) nature of rubber, the effects of temperature on grip, the way tyres deform under load, and the processed of heat transfer all influence how the tyres behave during a race. The "operating window" of tyres – the narrow temperature range in which grip is maximised – is an application of thermodynamics and materials science. Toto Wolff described the need to "put the tyre in the window", which in physics terms means raising the rubber's temperature to achieve a higher coefficient of friction without overheating it (Motorsport, 2017).

1. Fundamental Physics of Tyres

The performance of a Formula 1 tyre can initially be explained through one of the most fundamental equations in mechanics:

$$F = \mu R$$

Where F is the maximum frictional force, μ is the coefficient of friction, and R is the normal force acting on the tyre (Young & Freedman, 2012). For a racing car, R is not just the car's mass x gravitational acceleration, but also includes aerodynamic downforce generated by wings and the car's bodywork. This is why F1 cars can corner at forces exceeding 5g – the downforce increases the effective load on the tyres, which in turn increases frictional grip.

1.1 Static vs Kinetic Friction

Grip depends on static friction, where the tyre surface is not sliding relative to the track. Once the tyre begins to slide, the coefficient of kinetic friction applies, which is lower than statice friction. This explains why a car that locks its brakes cannot stop as quickly: by moving into the sliding regime, the available frictional force is reduced (Tipler & Mosca, 2007).

For example, drivers often “trail brake” (continuing to apply the front brakes) into corners to keep tyres within static friction, maximising grip while decelerating and turning.

1.2 Contact Patch and Pressure

The contact patch is the small area of tyre rubber that actually touches the track surface. The pressure acting on this area can be described by:

$$P = \frac{F}{A}$$

Where P is the pressure, F is the force (normal load), and A is the area of contact. A larger contact patch increases the number of molecular interaction between tyre and track, which generally improves grip. However, it also increases rolling resistance. Tyre designers balance this by adjusting tyre width, pressure, and compound stiffness (Wright, 2001).

For example, the move from narrow tyres in the 1960s to wide “slicks” in the 1970s increased contact patch area, raising available grip and cutting lap times significantly (Wright, 2001).

1.3 Rolling Resistance and Energy Losses

Rolling Resistance arises due to hysteresis - the energy lost when rubber deforms as it rolls over the track surface (ScienceDirect, 2025). This energy loss converts mechanical work into heat, which is why tyres warm up over the course of a lap.

The rolling resistance force can be expressed as:

$$F_r = C_r R$$

Where C_r is the rolling resistance coefficient. Minimising rolling resistance improves straight-line efficiency, but too little deformation reduces grip. F1 engineers accept higher rolling resistance in exchange for greater adhesion in corners.

1.4 Heat Generation and Thermodynamics

When tyres are forced against the track under high load, microscopic slip occurs within the contact patch, The work down by friction ($W = F \times d$) is partly converted into heat. The increase in tyre temperature can be modelled by:

$$Q = mc\Delta T$$

Where Q is the heat absorbed, m is the mass of the rubber affected, c is the specific heat capacity of rubber, and ΔT is the change in temperature (IFAT, 2020)

This explains why drivers need "warm-up laps": cold tyres have lower μ, giving less grip. Once they reach the correct operating window, molecular interactions improve adhesion and μ increases.

In qualifying sessions, drivers often complete a slow out-lap followed by a push lap to ensure their tyres are in the correct temperature window before attempting a flying lap. Lewis Hamilton described this process at Silverstone: *"You have to get the tyres switched on – it's a fine balance of not overheating but making sure they're alive when you start the lap"* (BBC Sport, 2019).

1.5 Application to Formula 1 Strategy

Higher μ (softer compounds) means faster lap times but greater heat generation and quicker degradation.

Lower μ (harder compounds) means slower lap times but longer durability.

Teams must choose the optimal balance depending on race distance, track temperature, and aerodynamic setup (IFAT, 2020).

2. Tyre Evolution in Formula 1

2.1 The Early Years (1950s-1960s)

In the first decade of Formula 1, cars used narrow cross-ply tyres which were similar to road cars. Grip relied almost entirely on the frictional force equation:

$$F_{friction} = \mu N$$

with very low coefficients of friction (μ) compared to today's tyres (Ludvigsen, Classic Racing Cars, 2001).

At this stage, mechanical grip was limited; drivers would report they were "sliding through corner," as tyres could not generate much lateral force. Cross-ply construction also meant larger slip angles (the angle between the tyre's pointing angle and its actual motion), reducing precision in high-speed corners. These tyres operated at relatively low temperatures, with limited focus on heat cycles (the process of tyres going from hot to cold, cold to hot) or pressure adjustments.

"Tyre development in Formula One began with narrow treaded cross-ply tyres, offering limited grip and relying heavily on mechanical suspension setup for handling" (Ludvigsen, Classic Racing Cars, 2001).

2.2 The Radial Revolution (1970s-1980s)

In 1977, Michelin introduced radial tyres into F1, a huge step forward. Radials reduced rolling resistance and allowed better heat distribution. Radial construction minimised deformation, reducing hysteresis loss, lowering rolling resistance ($F_r = C_r R$) (Motorsport Magazine, 2020).

This efficiency allowed higher straight-line speeds and improved durability. Grip also increased because radials allowed tyres to run with larger, more stable contact patches. Radials require higher operating pressures, changing the car suspension tuning.

Michelin's introduction of the radial tyre in Formula One in 1977 revolutionised grip and reduced rolling resistance compared to cross-ply designs.

The effect of the radials was proven in 1978, when Ferrari switched from Goodyear cross-ply tyres to Michelin radials and immediately gained a performance advantage, leading to multiple wins.

2.3 The Tyre War (1990s-2006)

During this period, multiple supplies – Goodyear, Michelin, Bridgestone - competed in F1. This meant that compound development became central, e.g. softer compounds increased μ in the friction equation but wore out faster due to greater heat build-up ($Q = mc\Delta T$). Teams began optimising operating windows, with suppliers tailoring tyres for specific circuits depending on whether they are high-wear tracks like Suzuka or low-wear tracks like Monza.

"The tyre war between Michelin and Bridgestone produced compounds optimised for specific circuits," often determining varied race outcomes (Collins, The Science of Formula 1 Design, 2008).

A famous example of the close competition was when Michelin's performance advantage in 2005 led to a safety issue at the US Grand Prix, where their tyres overheated and failed due to excessive lateral loads in Indianapolis' high-banked final corner (Motorsport, 2023).

This period showcased how thermodynamics and material science drove tyre performance, as much as aerodynamics or engines.

2.4 The Pirelli Era (2011-present)

Since 2011, Pirelli has been F1's sole supplier, tasked with designing tyres that degrade predictably to create strategic variation. Pirelli introduced compounds with deliberate thermal degradation, when heat generated exceeds the tyre's optimal operating window, grip falls off sharply.

$$Q = mc\Delta T$$

When ΔT pushes the rubber beyond its designed glass transition range, the rubber loses elasticity, reducing grip.

An example of this is, at Silverstone 2020, Lewis Hamilton suffered a tyre delamination (a blown tyre) on the final lap due to extreme loading. This is a clear reminder of how forces interact with heat build-up in modern tyres. Current tyres also incorporate low-profile 18-inch designs since 2022, changing sidewall stiffness, reducing deformation, and therefore, altering rolling resistance and suspension physics (FIA Technical Briefing, 2022).

Conclusion

Together, these developments show that the physics of tyres is not static but evolves as regulations, materials, and demands change. Formula 1 has repeatedly highlighted that tyres are not just passive components but dynamic systems where friction, deformation, and heat flow decide outcomes as much as driver skill or engine power. By tracing tyre evolution through the lens of physics, this essay demonstrates that progress in Formula 1 has always been as much about mastering forces, energy, and materials as it has been about speed. Tyres will continue to evolve with new materials and sustainability demands, but the physics underpinning them will remain the key to unlocking performance.

This analysis shows that a deep understanding of physics is essential not only in motorsport but also in engineering more broadly, where applying principles of force, energy, and material behaviour can directly determine the success of technological innovations.

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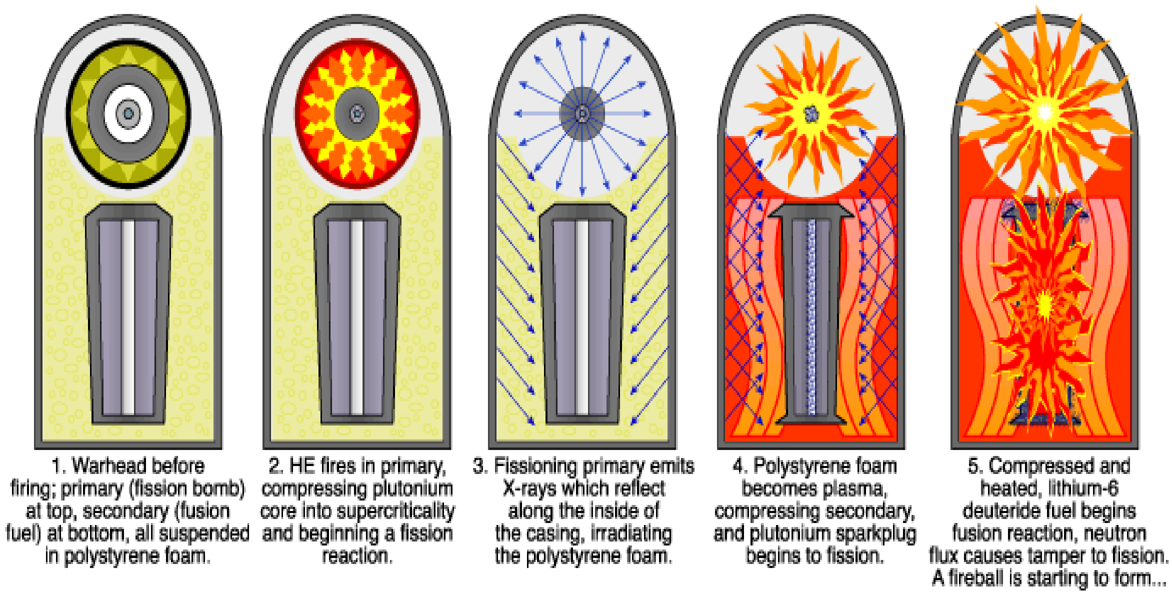
Sebastian Pickford- An analysis of the destructive potential of neutron bombs

The neutron bomb was a concept first created by the US in the 1950s which was then built upon and used for the first time in the 1960s. The neutron bomb was even considered by America as a new form of deterrent specifically for armoured ground invasion with this new fear of neutron bomb counterattack [1]. However, others at the time worried that deploying a cleaner nuclear weapon would heighten the possibility of a nuclear scale war. Fortunately, these weapons were never deployed in any other circumstance than testing and the US stopped production in the 1980s and by the end of the Cold War they were withdrawn.

What is a Neutron Bomb?

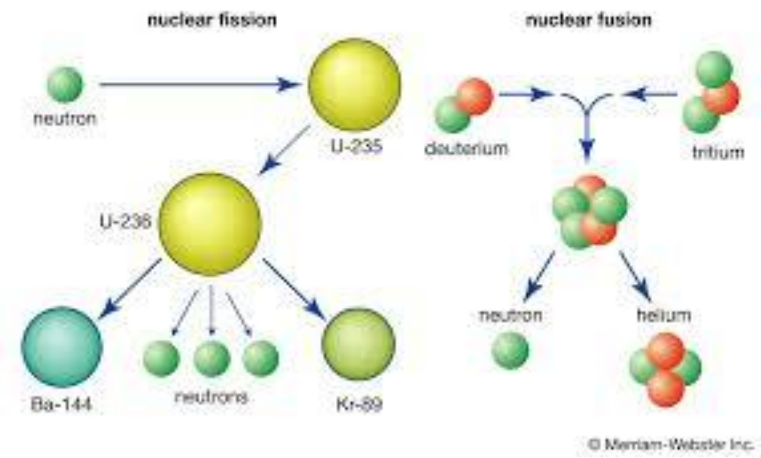
Explosion within the capsule containing several grams of Actinides [2]



A neutron bomb is a type of nuclear weapon with the distinct effect of having a minimal physically damaging blast radius whilst having a much larger scale and much more lethal amount of radiation released [3]. It uses a few kilograms of either Uranium or Plutonium that are ignited by a conventional explosion. This begins the fission which is the primary stage of activation. This is then followed up with the secondary stage, fusion, which occurs within the capsule containing several grams of hydrogen isotopes deuterium and tritium. The scale of this bomb is minimal in comparison to most other types of nuclear bombs, only reaching a few hundred metres in scale of physical damage but up to an intense 2000 metre range of powerful neutron and gamma radiation.

Fission and Fusion Cycle

The differences of the Fission-Fusion-reaction [4]



The primary stage of the explosion is the fission; this is the process of a heavy atomic nucleus dividing into two or more smaller nuclei and releasing a large amount of energy [5]. This occurs in neutron bombs with the bombardment of neutrons. This splits them apart into several differently charged nuclei. This causes them to experience the electrostatic force of repulsion due to their varying nuclear charges. This means they repel from each other with kinetic energies determined by the nuclei's varying charges. This variation leads to a difference in kinetic energies which causes each nucleus to have a fast initial velocity. This initial velocity from is too fast for the outer electrons to keep pace, so the nuclei lose them which, in return, makes the different nuclei to have a charge, so they scatter as very high velocities charged atoms. This releases a significant number of neutrons which carries on the cycle to the secondary stage of the cycle.

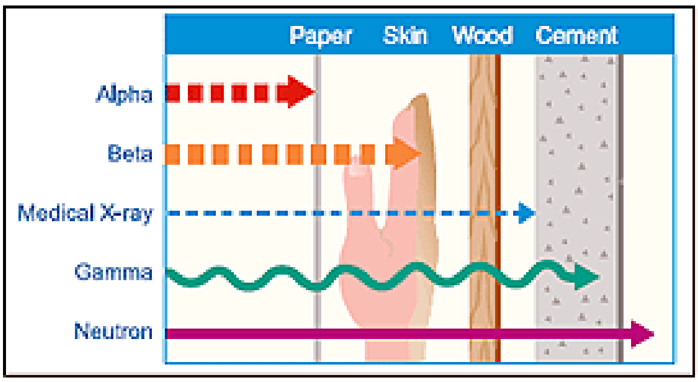
Fast vs Slow Neutrons

A nucleus becomes unstable by the size or imbalance of neutrons/protons. Another factor, which is the main factor relied on in this instance is the energy of the neutron in the nucleus of an atom [6]. This instability creates the probability for a fission reaction to take place. These varying causes a split between two different forms of classification based off this energy. This being the fast and slow neutrons. After many collisions with nuclei, the energy produced by neutrons by their collisions is drastically smaller than originally. They now inhabit an energy range of only a few electron-volts and are labelled as slow. The slower neutrons allow for control over the reaction. These types of neutrons are much better suited for nuclear reactors to run on typically used nuclear power plant elements like uranium. The slowdown of these neutrons means that the neutron Bomb cannot maximise the lethal amount of radiation. With the intent of penetrating through and be absorbed by as much as possible, using such low energy neutron would make the bomb redundant. Unlike slow neutrons, fast neutrons maintain a large amount of kinetic energy reaching up to 2-3 mega electron-volts [7]. This is because they have not undergone a large amount of fissions reactions yet. They still have a large amount of kinetic energy allowing for fast neutrons to fission much more easily. The use of fast neutrons is much better suited for reactions without a moderator element involved. This is suited perfect for a Neutron Bomb whose purpose it minimal blast but large radiation coverage. The small amount of fuel in the bomb allows much more high energy neutron beams to jet out much further with a much higher penetrative power.

Neutron Radiation

Not only are they rapidly fired with high energy levels, but they can also cover a significantly long distance. This also means that neutron beams can attack your body and ionise the cells of your body [8]. Ionization in the human body is the process of electrons being removed from the atoms of your body due to a high amount of energy being transferred to the electrons that allows them to overcome the electrostatic force of attraction which creates charged ions. Neutron radiation is an incredibly highly ionising form of radiation that can penetrate almost any material including lead. Ionizing radiation can penetrate the human body, and the radiation energy can be absorbed in tissue. This has the potential to cause harmful effects to people, especially at elevated levels of exposure. It would take only 1 kiloton of an Enhanced Radiation tactical warhead to deliver a dose of 80 gray to an armoured tank crew at a range of 690 m, and a lethal 6 gray dose at 1.1 km with protection or 1.35km without protection. Even with this it still manages to have a minimal heat and blast effect making it so deadly [9]. The process of ionization of a living organism can cause damage to cells and DNA which can cause mutations, cancer, and cell death [10]. The gray is conventionally used to express the severity of what are known as "tissue effects" from doses received in acute exposure to elevated levels of ionizing radiation. These are effects that are certain to happen, as opposed to the uncertain effects of low levels of radiation that have a probability of causing damage. A whole-body acute exposure to 5 gray's or more of high-energy radiation usually leads to death within 14 days. LD_1 is 2.5 Gy, lead-50 is 5 Gy and lead-99 is 8 Gy. The lead-50 dose represents 375 joules for a 75 kg adult [11].

Several types of radiation and their penetrative power [12]



This is the intentionally design of a Neutron Bomb; to minimise physical damage but do maximise the amount of radiation damage. Using a thin tamper is intentional to maximise the release of neutron radiation as opposed to being absorbed by other components [13]. Moreover, other bombs use thick layers dense metallic materials that can contain the force of the explosion such as alloys such as lead-bismuth alloy with a beryllium deflector. This would also help other bombs to reduce the output of X-rays that range up to a few rads which is not too far off the 100 rads to cause Acute Radiation Syndrome (ARS) which can be fatal in people. An important development after World War II was the lightweight beryllium tamper. In a boosted device the thermonuclear reactions increase the production of neutrons, which makes the inertial property of tampers less important. Beryllium has a low slow neutron absorbency cross section but an extremely high scattering cross section. When struck by high energy neutrons produced by fission reactions, beryllium emits neutrons.

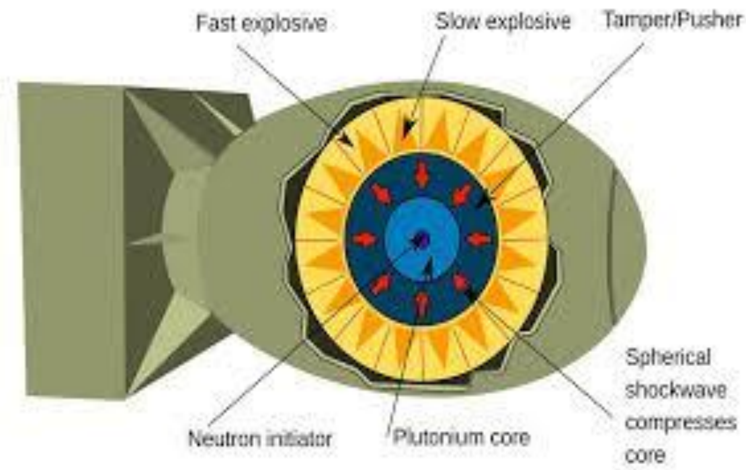
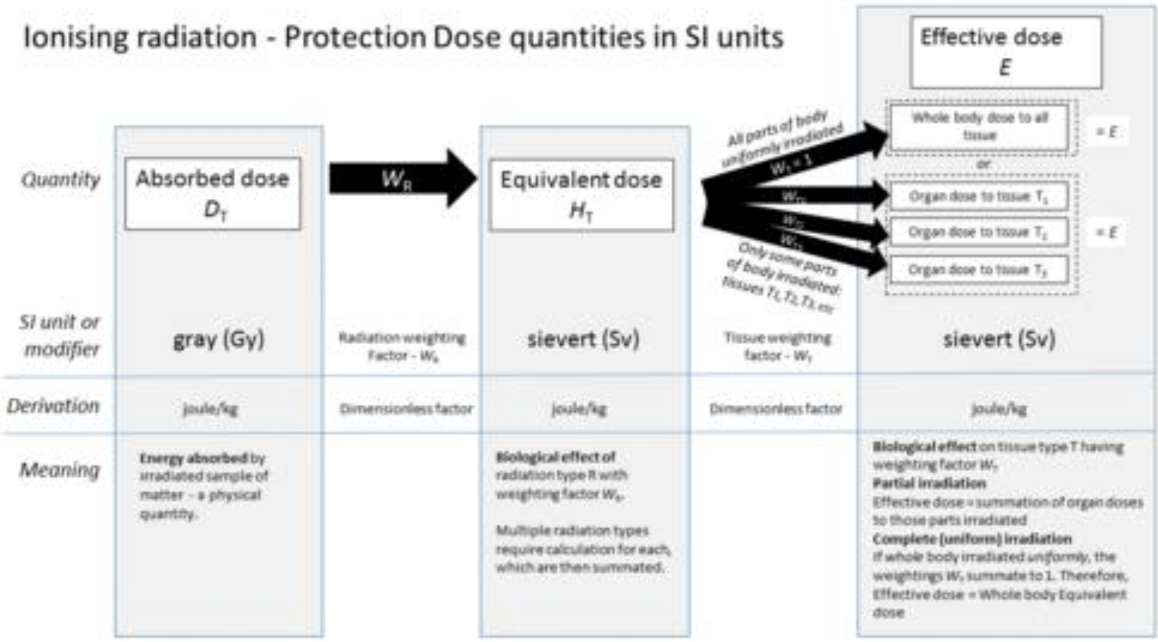


Diagram of a neutron bomb [14]

When using a 10 centimetre beryllium reflector, the critical mass of highly enriched uranium is 14.1 kg, compared with 52.5 kg in an untampered sphere [15]. A beryllium tamper also minimizes the loss of X-rays, which is important for a thermonuclear primary which uses its X-rays to compress the secondary stage. What makes a neutron bomb different is how it thrives on the thin tampering line. In a nuclear weapon, a tamper is an optional layer of dense material surrounding the material used for fission typically uranium-235 (U-235) or plutonium-239 (Pu-239). It is used in nuclear weapon design to reduce the critical mass and to delay the expansion of the reacting material through its inertia, which delays the thermal expansion of the fission fuel mass, keeping it supercritical longer. Often the same layer serves both as tamper and as neutron reflector [16]. Unlike typical nuclear weapons that use uranium-238, neutron bombs use uranium-235 or plutonium-239. This is because unlike typical fission isotopes like U-238 that can only undergo fission with fast neutrons' emission and speed. Fissionable isotopes, like U-235 and Pu-239, can work with slow or fast neutrons to undergo fission [17].

Radiation protection

The absorbed dose also plays a key role irradiation protection, as it is the starting point for calculating the health risk of low levels of radiation, which is defined as the probability of cancer induction and genetic damage [18]. The gray measures the total absorbed energy of radiation, but the probability of stochastic damage also depends on the type and energy of the radiation and the types of tissues involved. This probability is related to the equivalent dose in sieverts (Svi), which has the same dimensions as the gray. It is related to the Gray by weighting factors such as effective does and equivalent dose. The International Committee for Weights and Measures, states: "In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of ab sorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H [19]. (1 Gray=1 Joule kilogram=1 m2s2)



Relationship of ICRU/ICRP computed Protection dose quantities and units [20]

The accompanying diagrams show how absorbed dose is first obtained by computational techniques, and from this value the equivalent doses are derived. For X-rays and gamma rays the gray is numerically the same value when expressed in sieverts, but for 1 gray is equivalent to 20 sieverts, and a radiation weighting factor is applied accordingly.

Conclusion

To conclude, neutron bombs are a very dangerous nuclear weapon. Due to the high intensity neutron radiation beams emitted that can cover a huge area of land which is due to the thin tamper line used within the bomb. Despite these bombs never being used, they have been tested to lethal effects. The existence of these bombs is a deterrent in modern society. However, if this bomb is to be utilised properly then it can be a serious threat to life.

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