Wireless Energy Transfer

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First Edition, 2012

ISBN 978-81-323-2438-6

Published by:
Library Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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Wireless Energy Transfer

Wireless energy transfer or **wireless power** is the transmission of electrical energy from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible. The problem of wireless power transmission differs from that of wireless telecommunications, such as radio. In the latter the proportion of energy received becomes critical only if it is too low for the signal to be distinguished from the background noise. With wireless power, efficiency is the more significant parameter. A large part of the energy sent out by the generating plant must arrive at the receiver or receivers to make the system economical.

The most common form of wireless power transmission is carried out using direct induction followed by resonant magnetic induction. Other methods under consideration include electromagnetic radiation in the form of microwaves or lasers.

Electric energy transfer

An electric current flowing through a conductor carries electrical energy. When an electric current passes through a circuit there is an electric field in the dielectric surrounding the conductor; magnetic field lines around the conductor and lines of electric force radially about the conductor.

In a direct current circuit, if the current is continuous, the fields are constant; there is a condition of stress in the space surrounding the conductor, which represents stored electric and magnetic energy, just as a compressed spring or a moving mass represents stored energy. In an alternating current circuit, the fields also alternate; that is, with every half wave of current and of voltage, the magnetic and the electric field start at the conductor and run outwards into space with the velocity of light. Where these alternating fields impinge on another conductor a voltage and a current are induced.

Any change in the electrical conditions of the circuit, whether internal or external involves a readjustment of the stored magnetic and electric field energy of the circuit, that is, a so-called transient. A transient is of the general character of a condenser discharge through an inductive circuit. The phenomenon of the condenser discharge through an inductive circuit therefore is of the greatest importance to the engineer, as the foremost cause of high-voltage and high-frequency troubles in electric circuits.

Electromagnetic induction is proportional to the intensity of the current and voltage in the conductor which produces the fields and to the frequency. The higher the frequency the more intense the induction effect. Energy is transferred from a conductor that produces the fields (the primary) to any conductor on which the fields impinge (the secondary). Part of the energy of the primary conductor passes inductively across space into secondary conductor and the energy decreases rapidly along the primary conductor. A high frequency current does not pass for long distances along a conductor but rapidly transfers its energy by induction to adjacent conductors. Higher induction resulting from the higher frequency is the explanation of the apparent difference in the propagation of high frequency disturbances from the propagation of the low frequency power of alternating current systems. The higher the frequency the more preponderant become the inductive effects that transfer energy from circuit to circuit across space. The more rapidly the energy decreases and the current dies out along the circuit, the more local is the phenomenon.

The flow of electric energy thus comprises phenomena inside of the conductor and phenomena in the space outside of the conductor—the electric field—which, in a continuous current circuit, is a condition of steady magnetic and dielectric stress, and in an alternating current circuit is alternating, that is, an electric wave launched by the conductor to become far-field electromagnetic radiation traveling through space with the velocity of light.

In electric power transmission and distribution, the phenomena inside of the conductor are of main importance, and the electric field of the conductor is usually observed only incidentally. Inversely, in the use of electric power for *radio* telecommunications it is only the electric and magnetic fields outside of the conductor, that is electromagnetic radiation, which is of importance in transmitting the message. The phenomenon in the conductor, the current in the launching structure, is not used.

The electric charge displacement in the conductor produces a magnetic field and resultant lines of electric force. The magnetic field is a maximum in the direction concentric, or approximately so, to the conductor. That is, a ferromagnetic body tends to set itself in a direction at right angles to the conductor. The electric field has a maximum in a direction radial, or approximately so, to the conductor. The electric field component tends in a direction radial to the conductor and dielectric bodies may be attracted or repelled radially to the conductor.

The electric field of a circuit over which energy flows has three main axes at right angles with each other:

1. The *magnetic field*, concentric with the conductor.
2. The *lines of electric force*, radial to the conductor.
3. The *power gradient*, parallel to the conductor.

Where the electric circuit consists of several conductors, the electric fields of the conductors superimpose upon each other, and the resultant magnetic field lines and lines of electric force are not concentric and radial respectively, except *approximately in the immediate neighborhood* of the conductor. Between parallel conductors they are conjugate of circles. Neither the power consumption in the conductor, nor the magnetic field, nor the electric field, are proportional to the flow of energy through the circuit. However, the product of the intensity of the magnetic field and the intensity of the electric field is proportional to the flow of energy or the power, and the power is therefore resolved into a product of the two components **i** and **e**, which are chosen proportional respectively to the intensity of the magnetic field and of the electric field. The component called the current is defined as that factor of the electric power which is proportional to the magnetic field, and the other component, called the voltage, is defined as that factor of the electric power which is proportional to the electric field.

In *radio* telecommunications the electric field of the transmit antenna propagates through space as a radio wave and impinges upon the receive antenna where it is observed by its magnetic and electric effect. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays and gamma rays are shown to be the same electromagnetic radiation phenomenon, differing one from the other only in frequency of vibration.

Electromagnetic induction

Energy transfer by electromagnetic induction is typically magnetic but capacitive coupling can also be achieved.

Electrodynamic induction method

The electrodynamic induction wireless transmission technique is near field over distances up to about one-sixth of the wavelength used. Near field energy itself is non-radiative but some radiative losses do occur. In addition there are usually resistive losses. With electrodynamic induction, electric current flowing through a primary coil creates a magnetic field that acts on a secondary coil producing a current within it. Coupling must be tight in order to achieve high efficiency. As the distance from the primary is increased, more and more of the magnetic field misses the secondary. Even over a relatively short range the inductive coupling is grossly inefficient, wasting much of the transmitted energy.

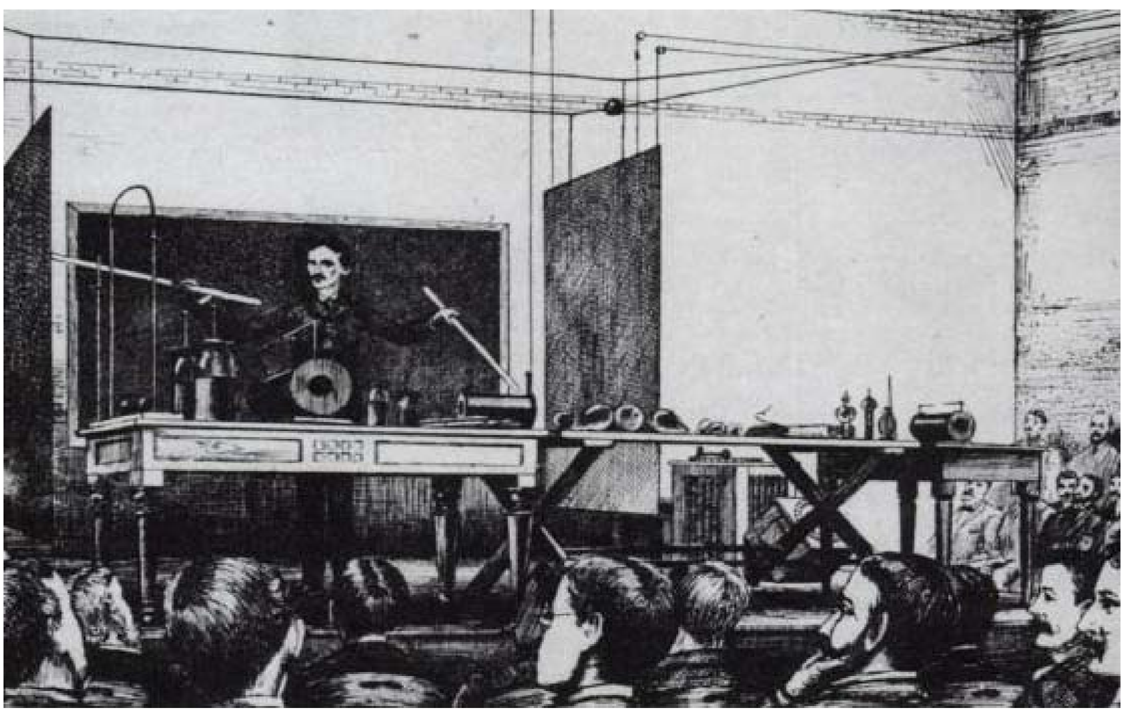
This action of an electrical transformer is the simplest form of wireless power transmission. The primary and secondary circuits of a transformer are not directly connected. Energy transfer takes place through a process known as mutual induction. Principal functions are stepping the primary voltage either up or down and electrical isolation. Mobile phone and electric toothbrush battery chargers, and electrical power distribution transformers are examples of how this principle is used. Induction cookers use this method. The main drawback to this basic form of wireless transmission is short range. The receiver must be directly adjacent to the transmitter or induction unit in order to efficiently couple with it.

The application of resonance improves the situation somewhat. When resonant coupling is used the transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a nonsinusoidal transient waveform. Pulse power transfer occurs over multiple cycles. In this way significant power may be transmitted over a distance of up to a few times the size of the primary coil. Transmitting and receiving coils are usually single layer solenoids or flat spirals with series capacitors, which, in combination, allow the receiving element to be tuned to the transmitter frequency.

Common uses of resonance-enhanced electrodynamic induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad (the transmitter circuit) and the receiver module (embedded in the load) to maximize energy transfer efficiency. This approach is suitable for universal wireless charging pads for portable electronics such as mobile phones. It has been adopted as part of the Qi wireless charging standard.

It is also used for powering devices having no batteries, such as RFID patches and contactless smartcards, and to couple electrical energy from the primary inductor to the helical resonator of Tesla coil wireless power transmitters.

Electrostatic induction method



The **Tesla effect**. is the illumination of two exhausted tubes by means of a powerful, rapidly alternating electrostatic field created between two vertical metal sheets suspended from the ceiling on insulating cords. It exploits the physics of electrostatic induction.

Electrostatic or capacitive coupling is the passage of electrical energy through a dielectric. In practice it is an electric field gradient or differential capacitance between two or more insulated terminals, plates, electrodes, or nodes that are elevated over a conducting ground plane. The electric field is created by an alternating current of high potential and high frequency. The capacitance between fixed plates and the powered device form a voltage divider.

The electric energy transmitted through the atmosphere can be utilized by receiving devices. Tesla demonstrated the illumination of wireless lamps by energy that was coupled to them through an alternating electric field.

"Instead of depending on *electrodynamic induction* at a distance to light the tube . . . [the] ideal way of lighting a hall or room would . . . be to produce such a condition in it that an illuminating device could be moved and put anywhere, and that it is lighted, no matter where it is put and without being electrically connected to anything. I have been able to produce such a condition by creating in the room a powerful, *rapidly alternating electrostatic field*. For this purpose I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets . . . each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous."

The principle of electrostatic induction is applicable to the electrical conduction wireless transmission method.

Electromagnetic radiation

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s). The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or well-collimated Laser Beam) thereby delivering almost all emitted power at long ranges. The maximum directivity for antennas is physically limited by diffraction.

Beamed power, size, distance, and efficiency

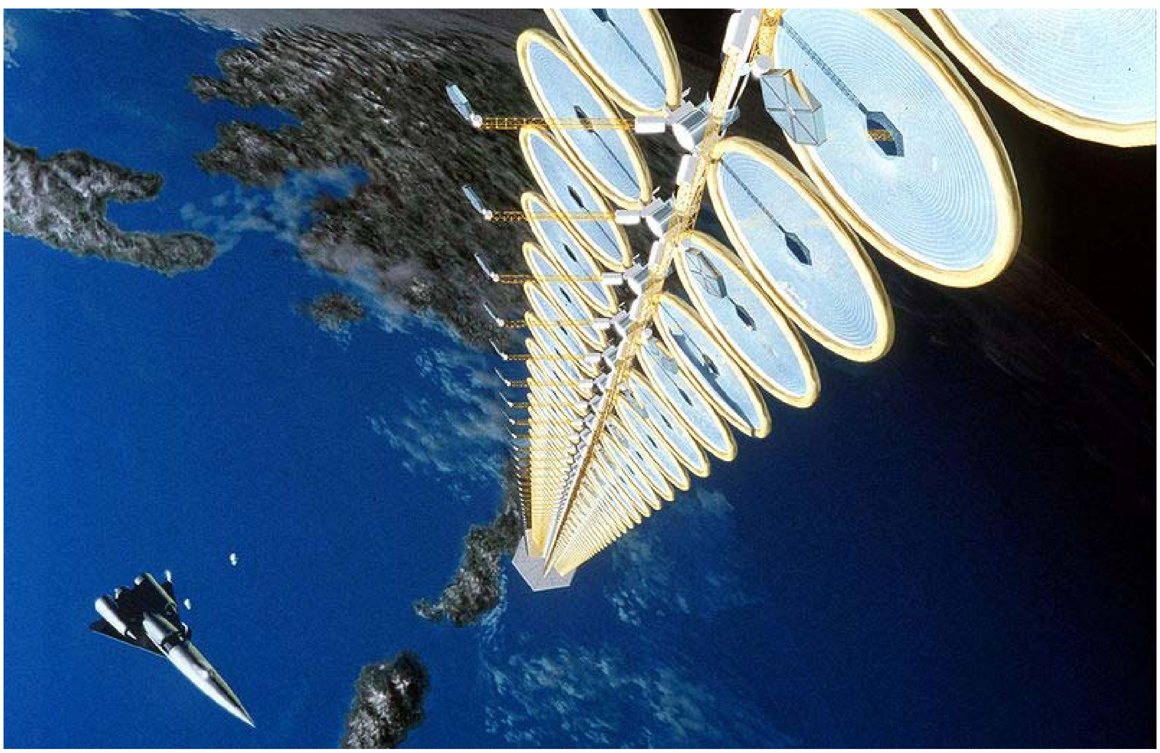
The size of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. In addition to the Rayleigh criterion Airy's diffraction limit is also frequently used to determine an approximate spot size at an arbitrary distance from the aperture.

The Rayleigh criterion dictates that any radio wave, microwave or laser beam will spread and become weaker and diffuse over distance; the larger the transmitter antenna or laser aperture compared to the wavelength of radiation, the tighter the beam and the less it will spread as a function of distance (and vice versa). Smaller antennae also suffer from excessive losses due to side lobes. However, the concept of laser aperture considerably differs from an antenna. Typically, a laser aperture much larger than the wavelength induces multi-moded radiation and mostly collimators are used before emitted radiation couples into a fiber or into space.

Ultimately, beamwidth is physically determined by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. Microwave power beaming can be more efficient than lasers, and is less prone to atmospheric attenuation caused by dust or water vapor losing atmosphere to vaporize the water in contact.

Then the power levels are calculated by combining the above parameters together, and adding in the gains and losses due to the antenna characteristics and the transparency and dispersion of the medium through which the radiation passes. That process is known as calculating a link budget.

Microwave method



An artist's depiction of a solar satellite that could send electric energy by microwaves to a space vessel or planetary surface.

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA Study of solar power satellites required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned array curse," it is not possible to make a narrower beam by combining the beams of several smaller satellites.

For earthbound applications a large area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety. A human safe power density of 1 mW/cm^2 distributed across a 10 km diameter area corresponds to 750 megawatts total power level. This is the power level found in many modern electric power plants.

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. By 1964 a miniature helicopter propelled by microwave power had been demonstrated.

Japanese researcher Hidetsugu Yagi also investigated wireless energy transmission using a directional array antenna that he designed. In February 1926, Yagi and Uda published their first paper on the tuned high-gain directional array now known as the Yagi antenna. While it did not prove to be particularly useful for power transmission, this beam antenna has been widely adopted throughout the broadcasting and wireless telecommunications industries due to its excellent performance characteristics.

Wireless high power transmission using microwaves is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. These methods achieve distances on the order of a kilometer.

Laser method

In the case of electromagnetic radiation closer to visible region of spectrum (10s of microns (um) to 10s of nm), power can be transmitted by converting electricity into a laser beam that is then pointed at a solar cell receiver. This mechanism is generally known as "powerbeaming" because the power is beamed at a receiver that can convert it to usable electrical energy.

Advantages of laser based energy transfer compared with other wireless methods are:

1. collimated monochromatic wavefront propagation allows narrow beam cross-section area for energy transmission over large ranges.
2. compact size of solid state lasers-photovoltaics semiconductor diodes fit into into small products.
3. no radio-frequency interference to existing radio communication such as Wi-fi and cell phones.
4. control of access; only receivers illuminated by the laser receive power.

Its drawbacks are:

1. Conversion to light, such as with a laser, is inefficient
2. Conversion back into electricity is inefficient, with photovoltaic cells achieving 40%-50% efficiency. (Note that conversion efficiency is rather higher with monochromatic light than with insolation of solar panels).
3. Atmospheric absorption causes losses.
4. As with microwave beaming, this method requires a direct line of sight with the target.

The laser "powerbeaming" technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics Low-Power applications. Wireless energy transfer system using laser for consumer space has to satisfy Laser safety requirements standardized under IEC 60825.

To develop an understanding of the trade-offs of Laser ("a special type of light wave"-based system):

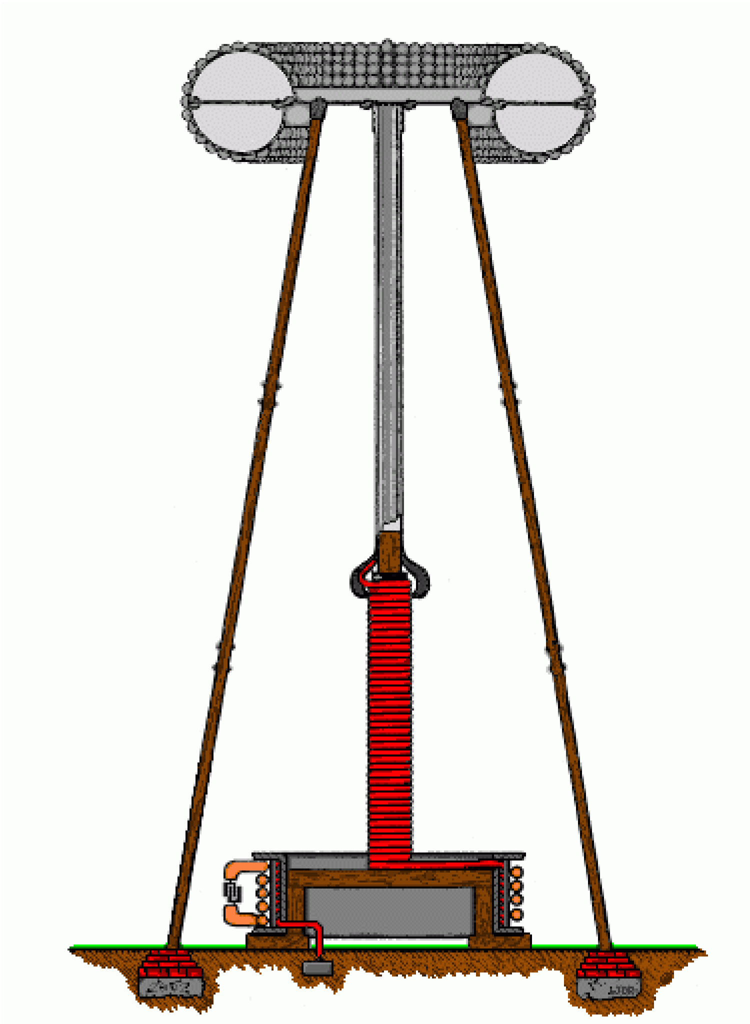
1. Propagation of a laser beam (on how Laser beam propagation is much less affected by diffraction limits)
2. Coherence and the range limitation problem (on how spatial and spectral coherence characteristics of Lasers allows better distance-to-power capabilities)
3. Airy disk (on how wavelength fundamentally dictates the size of a disk with distance)
4. Applications of laser diodes (on how the laser sources are utilized in various industries and their sizes are reducing for better integration)

Geoffrey Landis is one of the pioneers of solar power satellite and laser-based transfer of energy especially for space and lunar missions. The continuously increasing demand for safe and frequent space missions has resulted in serious thoughts on a futuristic space elevator that would be powered by lasers. NASA's space elevator would need wireless power to be beamed to it for it to climb a tether.

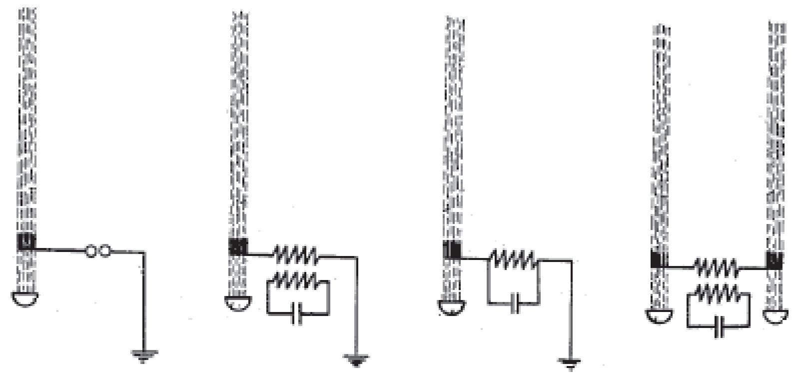
NASA's Dryden Flight Research Center has demonstrated flight of a lightweight unmanned model plane powered by a laser beam. This proof-of-concept demonstrates the feasibility of periodic recharging using the laser beam system and the lack of need to return to ground.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power a small UAV. Since 2006, "PowerBeam" which originally invented the eye-safe technology and holds all crucial patents in this technology space, is developing commercially ready units for various consumer and industrial electronic products.

Electrical conduction



The Tesla coil wireless power transmitter
U.S. Patent 1,119,732



Means for long conductors of electricity forming part of an electric circuit and electrically connecting said ionized beam to an electric circuit. Hettinger 1917 -(U.S. Patent 1,309,031)

Disturbed charge of ground and air method

Single wire with Earth return electrical power transmission systems rely on current flowing through the earth plus a single wire insulated from the earth to complete the circuit. In emergencies high-voltage direct current power transmission systems can also operate in the 'single wire with earth return' mode. Elimination of the raised insulated wire, and transmission of high-potential, high-frequency alternating current through the earth with an atmospheric return circuit has been investigated as a method of wireless electrical power transmission. Transmission of electrical energy through the earth alone, eliminating the second conductor is also being investigated.

Low frequency alternating current can be transmitted through the inhomogeneous earth with low loss because the net resistance between earth antipodes is considerably less than 1 ohm. The electrical displacement takes place predominantly by electrical conduction through the oceans, and metallic ore bodies and similar subsurface structures. The electrical displacement is also by means of electrostatic induction through the more dielectric regions such as quartz deposits and other non-conducting minerals.

Alternating current can be transmitted through atmospheric strata having a barometric pressure of less than 135 millimeters of mercury. Current flows by means of electrostatic induction through the lower atmosphere up to about two or three miles above the plants (this is the middle part in a three-space model) and the flow of ions, that is to say, electrical conduction through the ionized region above three miles. Intense vertical beams of ultraviolet light may be used to ionize the atmospheric gasses directly above the two elevated terminals resulting in the formation of plasma high-voltage electrical transmission lines leading up to the conducting atmospheric strata. The end result is a flow electrical current between the two elevated terminals by a path up to and through the troposphere and back down to the other facility. Electrical conduction through atmospheric strata is made possible by the creation of capacitively coupled discharge plasma through the process of atmospheric ionization.

Terrestrial transmission line with atmospheric return

Tesla discovered that electrical energy can be transmitted through the earth and the atmosphere. In the course of his research he successfully lit lamps at moderate distances and was able to detect the transmitted energy at much greater distances. The Wardenclyffe Tower project was a commercial venture for trans-Atlantic wireless telephony and proof-of-concept demonstrations of global wireless power transmission. The facility was not completed because of insufficient funding.

Earth is a naturally conducting body and forms one conductor of the system. A second path is established through the upper troposphere and lower stratosphere starting at an elevation of approximately 4.5 miles (7.2 km).

A global system for "the transmission of electrical energy without wires" called the World Wireless System, dependent upon the high electrical conductivity of plasma and the high electrical conductivity of the earth, was proposed as early as 1904.

Terrestrial single-conductor surface wave transmission line

The same transmitter used for the atmospheric conduction method is used for the terrestrial single-conductor earth resonance method.

The fundamental earth resonance frequency is claimed to be approximately 11.78 Hz. With the earth resonance method some harmonic of this fundamental frequency is used. "I would say that the frequency should be smaller then twenty thousand per second, through shorter waves might be practicable" and on the low end, "a frequency of nine hundred and twenty-five per second" is used, "when it is indispensable to operate motors of the ordinary kind."

Observations have been made that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials that are presently considered to be *nonphysical.*

Timeline of wireless power

- **1820**: André-Marie Ampère develops Ampere's law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday develops Faraday's law of induction describing the electromagnetic force induced in a conductor by a time-varying magnetic flux.
- **1836**: Nicholas Callan invents the electrical transformer.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory and mathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz's "*apparatus for generating electromagnetic waves*" was a VHF or UHF "radio wave" spark gap transmitter.

- **1891**: Tesla improves Hertz-wave wireless transmitter RF power supply or exciter in his patent No. 454,622, "System of Electric Lighting."
- **1893**: Tesla demonstrates the wireless illumination of phosphorescent lamps of his design at the World's Columbian Exposition in Chicago.
- **1893**: Tesla publicly demonstrates wireless power before a meeting of the National Electric Light Association in St. Louis.
- **1894**: Tesla lights incandescent lamps wirelessly at the 35 South Fifth Avenue laboratory in New York City by means of "electro-dynamic induction" or resonant inductive coupling.
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they received U.S. Patent # 527,857 describing a system for power transmission at 3 kHz.
- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1896**: Tesla demonstrates wireless transmission over a distance of about 48 kilometres (30 mi).
- **1897**: Tesla files his first patent application dealing specifically with wireless transmission.
- **1899**: Tesla continues his wireless power transmission research in Colorado Springs and writes, "the inferiority of the induction method would appear immense as compared with the *disturbed charge of ground and air method*."
- **1902**: Nikola Tesla vs. Reginald Fessenden - U.S. Patent Interference No. 21,701, System of Signaling (wireless); wireless power transmission, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.
- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) airship motor by energy transmitted through space at a distance of at least 100 feet (30 m).
- **1916**: Tesla states, "In my [*disturbed charge of ground and air*] system, you should free yourself of the idea that there is [electromagnetic] radiation, that energy is radiated. It is not radiated; it is conserved."
- **1917**: Tesla's Wardenclyffe tower is demolished. . . .

- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's *"tuned high-gain directional array"* better known as the Yagi antenna.

- **1961**: William C. Brown publishes an article exploring possibilities of microwave power transmission.
- **1964**: Brown demonstrates on CBS News with Walter Cronkite a model helicopter that receives all of the power needed for flight from a microwave beam. Between 1969 and 1975, Brown is technical director of a JPL Raytheon program that beams 30 kW over a distance of 1 mile at 84% efficiency.
- **1968**: Peter Glaser proposes wirelessly transmitting solar energy captured in space using "Powerbeaming" technology. This is usually recognized as the first description of a solar power satellite.

- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: The world's first passive RFID system is demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that power transmission by means of electrodynamic induction should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, patents the technology.
- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd. to develop technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using electrodynamic induction to charge (30-60 kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **1998**: RFID tags are powered by electrodynamic induction over a few feet.
- **1999**: Dr. Herbert L. Becker powers a lamp and a hand held fan from a distance of 30 feet.
- **1999**: Prof. Shu Yuen (Ron) Hui and Mr. S.C. Tang of the City University of Hong Kong file a patent on "Coreless Printed-Circuit-Board (PCB) transformers and operating techniques", which form the basis for future planar charging surface with "vertical flux" leaving the planar surface. The circuit uses resonant circuits for wireless power transfer. EP(GB)0935263B
- **2000**: Prof. Shu Yuen (Ron) Hui invent a planar wireless charging pad using the "vertical flux" approach and resonant power transfer for charging portable consumer electronic products. A patent is filed on "Apparatus and method of an inductive battery charger," PCT Patent PCT/AU03/00 721, 2000.
- **2000**: Based on the coreless PCB transformer developed by Prof. Ron Hui, Prof. B. Choi and his team at Kyungpook National University publish a paper on "A new contactless battery charger for portable telecommunication/computing electronics," in Proc. ICCE'00 Int. Conf. Consumer Electron., 2000, pp. 58–59. The coreless PCB transformer is used to wirelessly charge a mobile phone.
- **2001** Prof. Shu Yuen (Ron) Hui and Dr. S.C. Tang file a patent on "Planar Printed-Circuit-Board Transformers with Effective Electromagnetic Interference (EMI) Shielding". The EM shield consists of a thin layer of ferrite and a thin layer of copper sheet. It enables the underneath of the future wireless charging pads to be shielded with a thin EM shield structure with thickness of typically 0.7mm or less. Patent: US6, 501,364.

- **2001**: Prof. Ron Hui's team demonstrate that the coreless PCB transformer can transmit power close to 100W in ‘A low-profile low-power converter with coreless PCB isolation transformer, IEEE Transactions on Power Electronics, Volume: 16 Issue: 3, May 2001. A team of Philips Research Center Aachen, led by Dr. Eberhard Waffenschmidt, use it to power an 100W lighting device in their paper "Size advantage of coreless transformers in the MHz range" in the European Power Electronics Conference in Graz.
- **2001**: Splashpower formed in the UK. Uses coupled resonant coils in a flat "pad" style to transfer tens of watts into a variety of consumer devices, including lamp, phone, PDA, iPod etc.
- **2002**: Prof. Shu Yuen (Ron) Hui extends the planar wireless charging pad concept using the vertical flux approach to incorporate free-positioning feature for multiple loads. This is achieved by using a multilayer planar winding array structure. Patent were granted as "Planar Inductive Battery Charger", GB2389720 and GB 2389767.
- **2004**: Electrodynamic induction used by 90 percent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof. Shu Yuen (Ron) Hui and Dr. W.C. Ho of City University of Hong Kong publish their work in the IEEE Transactions on a planar wireless charging platform with free-positioning feature. The planar wireless charging pad is able to charge several loads simultaneously on a flat surface.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transmission of power to moving vehicles in the lab.
- **2007**: A localized charging technique is reported by Dr. Xun Liu and Prof. Ron Hui for the wireless charging pad with free-positioning feature. With the aid of the double-layer EM shields enclosing the transmitter and receiver coils, the localized charging selects the right transmitter coil so as to minimize flux leakage and human exposure to radiation.
- **2007**: Using electrodynamic induction a physics research group, led by Prof. Marin Soljacic, at MIT, wirelessly power a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance with two 60 cm-diameter coils.
- **2008**: Bombardier offers a new wireless power transmission product PRIMOVE, a system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University make a wireless lamp incorporating a high efficiency 3W LED.
- **2008**: Intel reproduces Tesla's original 1894 implementation of electrodynamic induction and Prof. John Boys group's 1988 follow-up experiments by wirelessly powering a nearby light bulb with 75% efficiency.
- **2008**: Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on Tesla's *disturbed charge of ground and air method* of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the electrodynamic induction method.

- **2009**: A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power inductive charging
- **2009**: Palm (now a division HP) launches the Palm Pre smartphone with the Palm Touchstone wireless charger.
- **2009**: An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.
- **2009**: A simple analytical electrical model of electrodynamic induction power transmission is proposed and applied to a wireless power transfer system for implantable devices.
- **2009**: Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.
- **2009**: Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010**: Haier Group debuts “the world's first” completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's follow-up research on Tesla's electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).
- **2010**: System On Chip (SoC) group in University of British Columbia develops an optimization tool for the design of highly efficient wireless power transmission systems using multiple coils. The design is optimized for implantable applications and power transfer efficiency of 82% is achieved.
- **2010**: The Wireless Power Consortium launches the world's first wireless power transfer standard "Qi", that governs wireless power transfer applications up to 5W.
- **2010**: The US company Energizer launches the first Qi-certified wireless charging pad with free-positioning and localized charging features in October 2010.

Chapter- 2

Coupling (electronics)

In electronics and telecommunication, **coupling** is the desirable or undesirable transfer of energy from one medium, such as a metallic wire or an optical fiber, to another medium, including fortuitous transfer.

Coupling is also the transfer of electrical energy from one circuit segment to another. For example, energy is transferred from a power source to an electrical load by means of conductive coupling, which may be either resistive or hard-wire. An AC potential may be transferred from one circuit segment to another having a DC potential by use of a capacitor. Electrical energy may be transferred from one circuit segmant to another segment with different impedance by use of a transformer. This is known as impedance matching. These are examples of electrostatic and electrodynamic inductive coupling.

Types of coupling

Electrical conduction:

- hard-wire
- resistive
- natural conductor

Electromagnetic induction:

- electrodynamic -- commonly called inductive coupling, also magnetic coupling
- electrostatic -- commonly called capacitive coupling
- evanescent wave coupling

Electromagnetic radiation:

- radio -- wireless telecommunications
- electromagnetic interference (EMI) -- Sometimes called radio frequency interference (RFI), is unwanted coupling. Electromagnetic compatibility (EMC) requires techniques to avoid such unwanted coupling, such as electromagnetic shielding.
- Microwave power transmission

Other kinds of energy coupling:

- acoustic

Capacitive coupling

In electronics, **capacitive coupling** is the transfer of energy within an electrical network by means of the capacitance between circuit nodes. This coupling can have an intentional or accidental effect. Capacitive coupling is typically achieved by placing a capacitor in series with the signal to be coupled.

Use in analog circuits

In analog circuits, a coupling capacitor is used to connect two circuits such that only the AC signal from the first circuit can pass through to the next while DC is blocked. This technique helps to isolate the DC bias settings of the two coupled circuits. Capacitive coupling is also known as *AC coupling* and the capacitor used for the purpose is known as a *coupling or DC blocking capacitor*. Capacitive coupling has the disadvantage of degrading the low frequency performance of a system containing capacitively coupled units. Each coupling capacitor along with the input electrical impedance of the next stage forms a high-pass filter and each successive filter results in a cumulative filter with a -3dB frequency that may be higher than each individual filter. So for adequate low frequency response the capacitors used must have high capacitance ratings. They should be high enough that the reactance of each is at most a tenth of the input impedance of each stage, at the lowest frequency of interest. This disadvantage of capacitively coupling DC biased, transistor amplifier circuits is largely minimized in directly coupled designs.

Use in digital circuits

AC coupling is also widely used in digital circuits to transmit digital signal with a zero DC component, known as DC-balanced signals. DC-balanced waveforms are useful in communications systems, since they can be used over AC-coupled electrical connections to avoid voltage imbalance problems and charge accumulation between connected systems or components.

For this reason, most modern line codes are designed to produce DC-balanced waveforms. The most common classes of DC-balanced line codes are constant-weight codes and paired-disparity codes.

Gimmick

A "gimmick" is a very simple kind of capacitive coupling: a piece of wire that is placed in proximity to another one, providing a capacitive coupling between two nodes of a few picofarads in value. Sometimes the wires are twisted together for physical stability.

Parasitic capacitive coupling

Capacitive coupling is often unintended, such as the capacitance between two wires or PCB traces that are next to each other. Often one signal can capacitively couple with another and cause what appears to be noise. To reduce coupling, wires or traces are often separated as much as possible, or ground lines or ground planes are run in between signals that might affect each other. Breadboards are particularly prone to these issues due to the long pieces of metal that line every row creating a several-picofarad capacitor between lines. To prototype high-frequency (10s of MHz) or high-gain analog circuits, often the circuits are built over a ground plane so that the signals couple to ground more than to each other. If a high-gain amplifier's output capacitively couples to its input it often becomes an electronic oscillator.

Electromagnetic interference

Electromagnetic interference in analog TV signal

Electromagnetic interference (or **EMI**, also called **radio frequency interference** or **RFI**) is a disturbance that affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted from an external source. The disturbance may interrupt, obstruct, or otherwise degrade or limit the effective performance of the circuit. The source may be any object, artificial or natural, that carries rapidly changing electrical currents, such as an electrical circuit, the Sun or the Northern Lights.

EMI can be intentionally used for radio jamming, as in some forms of electronic warfare, or can occur unintentionally, as a result of spurious emissions for example through intermodulation products, and the like. It frequently affects the reception of AM radio in urban areas. It can also affect cell phone, FM radio and television reception, although to a lesser extent.

Types

Radiated EMI or RFI may be broadly categorized into two types; narrowband and broadband.

Narrowband interference usually arises from intentional transmissions such as radio and TV stations, pager transmitters, cell phones, etc. Broadband interference usually comes from incidental radio frequency emitters. These include electric power transmission lines, electric motors, thermostats, bug zappers, etc. Anywhere electrical power is being turned off and on rapidly is a potential source. The spectra of these sources generally resemble that of synchrotron sources, stronger at low frequencies and diminishing at higher frequencies, though this noise is often modulated, or varied, by the creating device in some way. Included in this category are computers and other digital equipment as well as televisions. The rich harmonic content of these devices means that they can interfere over a very broad spectrum. Characteristic of broadband RFI is an inability to filter it effectively once it has entered the receiver chain.

Conducted electromagnetic interference is caused by the physical contact of the conductors as opposed to radiated EMI which is caused by induction (without physical contact of the conductors). Electromagnetic disturbances in the EM field of a conductor will no longer be confined to the surface of the conductor and will radiate away from it. This persists in all conductors and mutual inductance between two radiated electromagnetic fields will result in EMI.

Susceptibilities of different radio technologies

Interference tends to be more troublesome with older radio technologies such as analogue amplitude modulation, which have no way of distinguishing unwanted in-band signals from the intended signal, and the omnidirectional dipole antennas used with broadcast systems. Newer radio systems incorporate several improvements that enhance the selectivity. In digital radio systems, such as Wi-Fi, error-correction techniques can be used. Spread-spectrum and frequency-hopping techniques can be used with both analogue and digital signalling to improve resistance to interference. A highly directional receiver, such as a parabolic antenna or a diversity receiver, can be used to select one signal in space to the exclusion of others.

The most extreme example of digital spread-spectrum signalling to date is ultra-wideband (UWB), which proposes the use of large sections of the radio spectrum at low amplitudes to transmit high-bandwidth digital data. UWB, if used exclusively, would enable very efficient use of the spectrum, but users of non-UWB technology are not yet prepared to share the spectrum with the new system because of the interference it would cause to their receivers. The regulatory implications of UWB are discussed in the ultra-wideband article.

Interference to consumer devices

Complex electronic circuitry is found in all sorts of devices used in the home. This results in a vast interference potential that didn't exist in earlier, simpler decades. In the United States, Public Law 97-259, enacted in 1982, gave the Federal Communications Commission (FCC) the authority to regulate the susceptibility of consumer electronic equipment sold in the country. The FCC, working with equipment manufacturers, decided to allow them to develop standards for EMI immunity and implement their own voluntary compliance programs.

Broadcast transmitters, two-way radio transmitters, paging transmitters, and cable TV are potential sources of RFI and EMI. Other possible sources of interference include a wide variety of devices, such as doorbell transformers, toaster ovens, electric blankets, ultrasonic pest control devices, electric bug zappers, heating pads, and touch controlled lamps. Multiple CRT computer monitors or televisions sitting too close to one another can sometimes cause a "shimmy" effect in each other, due to the electromagnetic nature of their picture tubes, especially when one of their de-gaussing coils is activated.

Electromagnetic interference at 2.4 GHz can be caused by 802.11b and 802.11g wireless devices, Bluetooth devices, baby monitors and cordless telephones, video senders, and microwave ovens.

Switching inductive loads, such as electric motors, often cause interference, but it is easily suppressed by connecting a snubber network, a resistor in series with a capacitor, across the switch. Exact values can be optimised for each case, but 100 ohms in series with 100 nanofarads is usually satisfactory.

Switched-mode power supplies can be a source of EMI, but have become less of a problem as design techniques have improved, such as integrated power factor correction.

Most countries have legal requirements that mandate electromagnetic compatibility: electronic and electrical hardware must still work correctly when subjected to certain amounts of EMI, and should not emit EMI which could interfere with other equipment (such as radios).

Standards

The International Special Committee for Radio Interference sets standards for radiated and conducted electromagnetic interference.

EMI in integrated circuits

Integrated circuits are often a source of EMI, but they must usually couple their energy to larger objects such as heatsinks, circuit board planes and cables to radiate significantly.

On integrated circuits, important means of reducing EMI are: the use of bypass or decoupling capacitors on each active device (connected across the power supply, as close to the device as possible), rise time control of high-speed signals using series resistors, and V_{CC} filtering. Shielding is usually a last resort after other techniques have failed, because of the added expense of shielding components such as conductive gaskets.

The efficiency of the radiation depends on the height above the ground plane or power plane (at RF one is as good as the other) and the length of the conductor in relation to the wavelength of the signal component (fundamental frequency, harmonic or transient (overshoot, undershoot or ringing)). At lower frequencies, such as 133 MHz, radiation is almost exclusively via I/O cables; RF noise gets onto the power planes and is coupled to the line drivers via the V_{CC} and ground pins. The RF is then coupled to the cable through the line driver as common-mode noise. Since the noise is common-mode, shielding has very little effect, even with differential pairs. The RF energy is capacitively coupled from the signal pair to the shield and the shield itself does the radiating. One cure for this is to use a braid-breaker or choke to reduce the common-mode signal.

At higher frequencies, usually above 500 MHz, traces get electrically longer and higher above the plane. Two techniques are used at these frequencies: wave shaping with series resistors and embedding the traces between the two planes. If all these measures still leave too much EMI, shielding such as RF gaskets and copper tape can be used. Most digital equipment is designed with metal, or conductive-coated plastic, cases.

RF immunity and testing

Integrated circuits tend to demodulate high-frequency carrier signals commonly found in regular environment due presence of cell phones. These ICs demodulate the high frequency cell phone carrier (e.g., GSM850 and GSM1900, GSM900 and GSM1800) and produce low-frequency (e.g., 217 Hz) demodulated signals. This demodulation manifests itself into unwanted audible buzz in audio appliances such as microphone amplifier, speaker amplifier, car radio, telephones etc. Adding on-board EMI filters or special layout techniques help in bypassing EMI or improving RF immunity. Some ICs are designed (e.g., LMV831-LMV834, MAX9724) to have integrated RF filters and/or special design which prevent demodulation of high frequency carrier. These ICs are also subjected to tests for measuring their capability to reject RF.

Designers often need to carry out special tests for testing the RF immunity of the parts to be used in the system. These tests are usually carried inside a special anechoic chamber with a controlled RF environment where the test vectors produce RF field similar to that produced in an actual environment.

Acoustic coupler

The Novation CAT acoustically coupled modem

In telecommunications, the term **acoustic coupler** has the following meanings:

1. An interface device for coupling electrical signals by acoustical means—usually into and out of a telephone instrument.
2. A terminal device used to link data terminals and radio sets with the telephone network.

The link is achieved through acoustic (sound) signals rather than through direct electrical connection.

History and applications

Prior to its breakup in 1982, Bell System's monopoly over telephony in the United States allowed the company to impose strict rules on how consumers could access their network. Customers were prohibited from connecting phones not made or sold by Bell to the network, and for a long time the phone itself was owned by the phone company and leased to customers. In many households, telephones were hard-wired to wall terminals before connectors like RJ11 and BS 6312 became standardised. The telephone network was essentially a closed system wholly controlled and owned by Bell end-to-end. Interconnection of outside phones or other terminal equipment to the telephone system was not allowed.

It was not until a landmark court ruling regarding the Hush-A-Phone in 1956 that the use of a phone attachment (by a third party vendor) was allowed for the first time; though AT&T's right to regulate any device connected to the telephone system was upheld by the courts, they were instructed to cease interference towards Hush-A-Phone users. A second court decision in 1968 regarding the Carterphone further allowed *any device not harmful to the system* to be connected directly to the AT&T network. This decision enabled the proliferation of later innovations like answering machines, fax machines, and modems.

The earliest third-party terminal equipment, such as the Hush-A-Phone and the Carterphone, were all acoustically, rather than electrically, connected to the phone system. With the increased use of computing, acoustic couplers were used to connect early modems to the telephone network. Speeds were typically 300 bits per second, achieved by modulating a carrier at 300 baud. The practical upper limit for acoustic-coupled modems was 1200-baud, first made available in 1973 by Vadic and 1977 by AT&T. It became widespread in 1985 with advent of the Hayes Smartmodem 1200A. Such devices facilitated the creation of dial-up bulletin board systems, a forerunner of modern internet chat rooms, message boards, and e-mail.

Design

Usually, a standard telephone handset was placed into a cradle that had been engineered to fit closely (by the use of rubber seals) around the microphone and earpiece of the handset. A modem would modulate a loudspeaker in the cup attached to the handset's microphone, and sound from the loudspeaker in the telephone handset's earpiece would be picked up by a microphone in the cup attached to the earpiece. In this way signals could be passed in both directions.

Acoustic couplers were sensitive to external noise and depended on the widespread standardisation of the dimensions of telephone handsets. Direct electrical connections to telephone networks, once they were made legal, rapidly became the preferred method of attaching modems, and the use of acoustic couplers dwindled. Acoustic couplers are still used by people travelling in areas of the world where electrical connection to the telephone network is illegal or impractical. Many models of TDDs (Telecommunications Device for the Deaf) still have a built-in acoustic coupler, which allow more universal use with pay phones.

An acoustic coupler is prominently shown early in the 1983 film "WarGames", when character David Lightman (depicted by actor Matthew Broderick) places a telephone handset into the cradle of a film prop acoustic modem to accentuate the act of using telephone lines for interconnection to the developing computer networks of the period, in this case, a military command computer.

Chapter- 3

Resonant Inductive and Inductive Coupling

Resonant inductive coupling

Resonant inductive coupling or **electrodynamic induction** is the near field wireless transmission of electrical energy between two coils that are highly resonant at the same frequency. The equipment to do this is sometimes called a **resonant or resonance transformer**. While many transformers employ resonance, this type has a high *Q* and is often air cored to avoid 'iron' losses. The two coils may exist as a single piece of equipment or comprise two separate pieces of equipment.

Resonant transfer works by making a coil *ring* with an oscillating current. This generates an oscillating magnetic field. Because the coil is highly resonant any energy placed in the coil dies away relatively slowly over very many cycles; but if a second coil is brought near to it, the coil can pick up most of the energy before it is lost, even if it is some distance away. The fields used are predominately non-radiative, near field (sometimes called evanescent waves), as all hardware is kept well within the 1/4 wavelength distance they radiate little energy from the transmitter to infinity.

One of the applications of the resonant transformer is for the CCFL inverter. Another application of the resonant transformer is to couple between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by tuned transformers in the intermediate-frequency amplifiers. Resonant transformers such as the Tesla coil can generate very high voltages with or without arcing, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaff generator. Resonant energy transfer is the operating principle behind proposed short range wireless electricity systems such as WiTricity and systems that have already been deployed, such as some types of RFID tags and contactless smart cards.

These types of systems generate magnetic fields that are unlikely to cause health issues in humans.

Resonant coupling

Non-resonant coupled inductors, such as typical transformers, work on the principle of a primary coil generating a magnetic field and a secondary coil subtending as much as possible of that field so that the power passing though the secondary is as close as possible to that of the primary. This requirement that the field be covered by the secondary results in very short range and usually requires a magnetic core. Over greater distances the non-resonant induction method is highly inefficient and wastes the vast majority of the energy in resistive losses of the primary coil.

Using resonance can help efficiency dramatically. If resonant coupling is used, each coil is capacitively loaded so as to form a tuned LC circuit. If the primary and secondary coils are resonant at a common frequency, it turns out that significant power may be transmitted between the coils over a range of a few times the coil diameters at reasonable efficiency.

Energy transfer and efficiency

The general principle is that if a given oscillating amount of energy (for example alternating current from a wall outlet) is placed into a primary coil which is capacitively loaded, the coil will 'ring', and form an oscillating magnetic field. The energy will transfer back and forth between the magnetic field in the inductor and the electric field across the capacitor at the resonant frequency. This oscillation will die away at a rate determined by the *Q* factor, mainly due to resistive and radiative losses. However, provided the secondary coil cuts enough of the field that it absorbs more energy than is lost in each cycle of the primary, then most of the energy can still be transferred.

The primary coil forms a series RLC circuit, and the *Q* factor for such a coil is:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}},$$

Because the *Q* factor can be very high, (experimentally around a thousand has been demonstrated with air cored coils) only a small percentage of the field has to be coupled from one coil to the other to achieve high efficiency, even though the field dies quickly with distance from a coil, the primary and secondary can be several diameters apart.

Coupling coefficient

The coupling coefficient is the fraction of the flux of the primary that cuts the secondary coil, and is a function of the geometry of the system. The coupling coefficient is between 0 and 1.

Systems are said to be tightly coupled, loosely coupled, critically coupled or overcoupled. Tight coupling is when the coupling coefficient is around 1 as with conventional transformers. Overcoupling is when the secondary coil is close enough that it tends to collapse the primary's field, and critical coupling is when the transfer in the passband is optimal. Loose coupling is when the coils are distant from each other, so that most of the flux misses the secondary, in Tesla coils around 0.2 is used, and at greater distances, for example for wireless power transmission, it may be lower than 0.01.

Power transfer

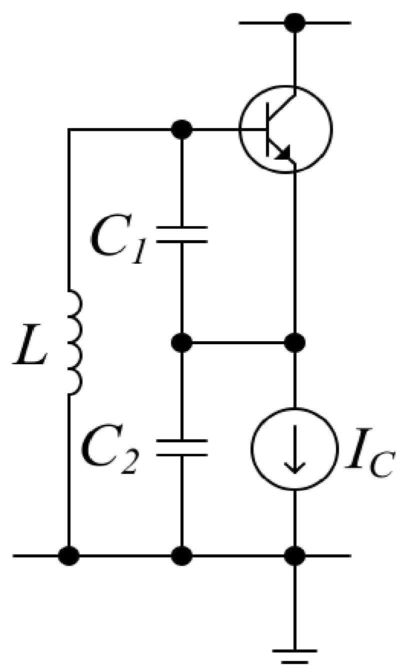
Because the *Q* can be very high, even when low power is fed into the transmitter coil, a relatively intense field builds up over multiple cycles, which increases the power that can be received—at resonance far more power is in the oscillating field than is being fed into the coil, and the receiver coil receives a percentage of that.

Voltage gain

The voltage gain of resonantly coupled coils is proportional to the square root of the ratio of secondary and primary inductances.

Transmitter coils and circuitry

Unlike the multiple-layer secondary of a non-resonant transformer, coils for this purpose are often single layer solenoids (to minimise skin effect and give improved *Q*) in parallel with a suitable capacitor, or they may be other shapes such as wave-wound litz wire. Insulation is either absent, with spacers, or low permittivity, low loss materials such as silk to minimise dielectric losses.

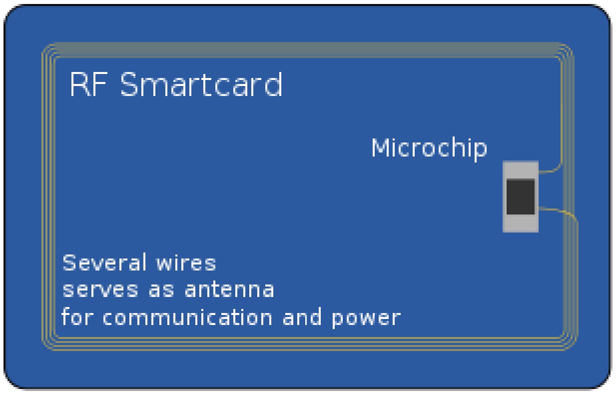


Colpitts oscillator. In resonant energy transfer the inductor would be the transmitter coil and capacitors are used to tune the circuit to a suitable frequency.

To progressively feed energy/power into the primary coil with each cycle, different circuits can be used. One circuit employs a Colpitts oscillator.

In Tesla coils an intermittent switching system, a "circuit controller or "break," is used to inject an impulsive signal into the primary coil; the secondary coil then rings and decays.

Receiver coils and circuitry

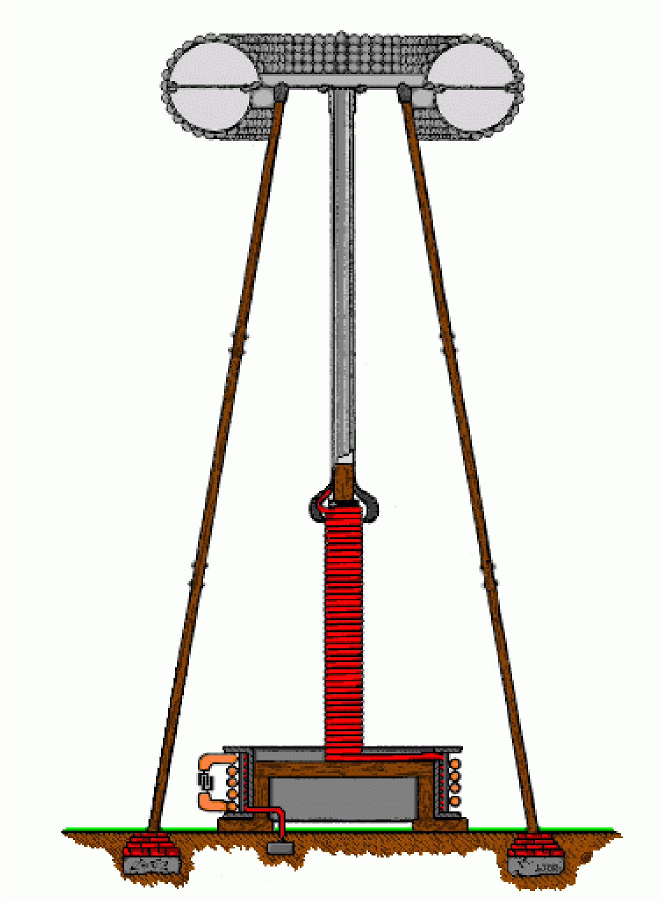


The receiver of a smart card has a coil connected to a chip which provides capacitance to give resonance as well as regulators to provided a suitable voltage

The secondary receiver coils are similar designs to the primary sending coils. Running the secondary at the same resonant frequency as the primary ensures that the secondary has a low impedance at the transmitter's frequency and that the energy is optimally absorbed.

To remove energy from the secondary coil, different methods can be used, the AC can be used directly or rectified and a regulator circuit can be used to generate DC voltage.

History



This advanced Tesla coil was designed to implement wireless power by means of the *disturbed charge of ground and air method.*

In 1894 Nikola Tesla used resonant inductive coupling, also known as "electro-dynamic induction" to wirelessly light up phosphorescent and incandescent lamps at the 35 South Fifth Avenue laboratory, and later at the 46 E. Houston Street laboratory in New York City. In 1897 he patented a device called the high-voltage, resonance transformer or "Tesla coil." Transferring electrical energy from the primary coil to the secondary coil by resonant induction, a Tesla coil is capable of producing very high voltages at high frequency. The improved design allowed for the safe production and utilization of high-potential electrical currents, "without serioius liability of the destruction of the apparatus itself and danger to persons approaching or handling it."

In the early 1960s resonant inductive wireless energy transfer was used successfully in implantable medical devices including such devices as pacemakers and artificial hearts. While the early systems used a resonant receiver coil, later systems implemented resonant transmitter coils as well. These medical devices are designed for high efficiency using low power electronics while efficiently accommodating some misalignment and dynamic twisting of the coils. The separation between the coils in implantable applications is commonly less than 20 cm. Today resonant inductive energy transfer is regularly used for providing electric power in many commercially available medical implantable devices.

Wireless electric energy transfer for experimentally powering electric automobiles and buses is a higher power application (>10 kW) of resonant inductive energy transfer. High power levels are required for rapid recharging and high energy transfer efficiency is required both for operational economy and to avoid negative environmental impact of the system. An experimental electrified roadway test track built circa 1990 achieved 80% energy efficiency while recharging the battery of a prototype bus at a specially equipped bus stop. The bus could be outfitted with a retractable receiving coil for greater coil clearance when moving. The gap between the transmit and receive coils was designed to be less than 10 cm when powered. In addition to buses the use of wireless transfer has been investigated for recharging electric automobiles in parking spots and garages as well.

Some of these wireless resonant inductive devices operate at low milliwatt power levels and are battery powered. Others operate at higher kilowatt power levels. Current implantable medical and road electrification device designs achieve more than 75% transfer efficiency at an operating distance between the transmit and receive coils of less than 10 cm.

In 1995, Professor John Boys and Prof Grant Covic, of The University of Auckland in New Zealand, developed systems to transfer large amounts of energy across small air gaps.

In 1998, RFID tags were patented that were powered in this way.

In November 2006, Marin Soljačić and other researchers at the Massachusetts Institute of Technology applied this near field behavior, well known in electromagnetic theory, the wireless power transmission concept based on strongly-coupled resonators. In a theoretical analysis, they demonstrate that, by designing electromagnetic resonators that suffer minimal loss due to radiation and absorption and have a near field with mid-range extent (namely a few times the resonator size), mid-range efficient wireless energy-transfer is possible. The reason is that, if two such resonant circuits tuned to the same frequency are within a fraction of a wavelength, their near fields (consisting of 'evanescent waves') couple by means of evanescent wave coupling (which is related to quantum tunneling). Oscillating waves develop between the inductors, which can allow the energy to transfer from one object to the other within times much shorter than all loss times, which were designed to be long, and thus with the maximum possible energy-transfer efficiency. Since the resonant wavelength is much larger than the resonators, the field can circumvent extraneous objects in the vicinity and thus this mid-range energy-transfer scheme does not require line-of-sight. By utilizing in particular the magnetic field to achieve the coupling, this method can be safe, since magnetic fields interact weakly with living organisms.

Comparison with other technologies

Compared to inductive transfer in conventional transformers, except when the coils are well within a diameter of each other, the efficiency is somewhat lower (around 80% at short range) whereas tightly coupled conventional transformers may achieve greater efficiency (around 90-95%) and for this reason it cannot be used where high energy transfer is required at greater distances.

However, compared to the costs associated with batteries, particularly non-rechargeable batteries, the costs of the batteries are hundreds of times higher. In situations where a source of power is available nearby, it can be a cheaper solution. In addition, whereas batteries need periodic maintenance and replacement, resonant energy transfer could be used instead. Batteries additionally generate pollution during their construction and their disposal which largely would be avoided.

Regulations and safety

Unlike mains-wired equipment, no direct electrical connection is needed and hence equipment can be sealed to minimize the possibility of electric shock.

Because the coupling is achieved using predominantly magnetic fields; the technology may be relatively safe. Safety standards and guidelines do exist in most countries for electromagnetic field exposures (e.g.) Whether the system can meet the guidelines or the less stringent legal requirements depends on the delivered power and range from the transmitter.

Deployed systems already generate magnetic fields, for example induction cookers and contactless smart card readers.

Uses

- Contactless smart card
- High voltage (one million volt) sources for X-ray production
- Tesla coils

Inductive coupling

In electrical engineering, two conductors are referred to as **mutual-inductively coupled** or **magnetically coupled** when they are configured such that change in current flow through one wire induces a voltage across the ends of the other wire through electromagnetic induction. The amount of inductive coupling between two conductors is measured by their mutual inductance.

The coupling between two wires can be increased by winding them into coils and placing them close together on a common axis, so the magnetic field of one coil passes through the other coil. The two coils may be physically contained in a single unit, as in the primary and secondary sides of a transformer, or may be separated. Coupling may be intentional or unintentional.

Unintentional coupling is called cross-talk, and is a form of electromagnetic interference. Inductive coupling favors low frequency energy sources. High frequency energy sources generally use capacitive coupling.

An inductively coupled transponder comprises an electronic data carrying device, usually a single microchip, and a large coil that functions as an antenna. Inductively coupled transponders are almost always operated passively.

Uses

Devices that use inductive coupling include:

- Transformers
- Electric motors and generators
- Induction loop communication systems
- Metal detectors
- Graphics tablet
- Radio Frequency Identification
- Electronic article surveillance tags to prevent theft (most types).
- Inductive Modems
- Resonant energy transfer
- Inductive charging products charge batteries using inductive coupling, such as eCoupled; Torches, Cochlear Implants and many electric toothbrushes.
- Induction cookers and induction heating systems

Low frequency induction

Low frequency induction is an unwanted form of inductive coupling, which can occur when a metallic pipeline is installed parallel to a high-voltage power line. The pipeline, which is a conductor, and is insulated from the earth by its protective coating, can develop voltages which are hazardous to personnel operating valves or otherwise contacting the pipeline.

Chapter- 4

World Wireless System

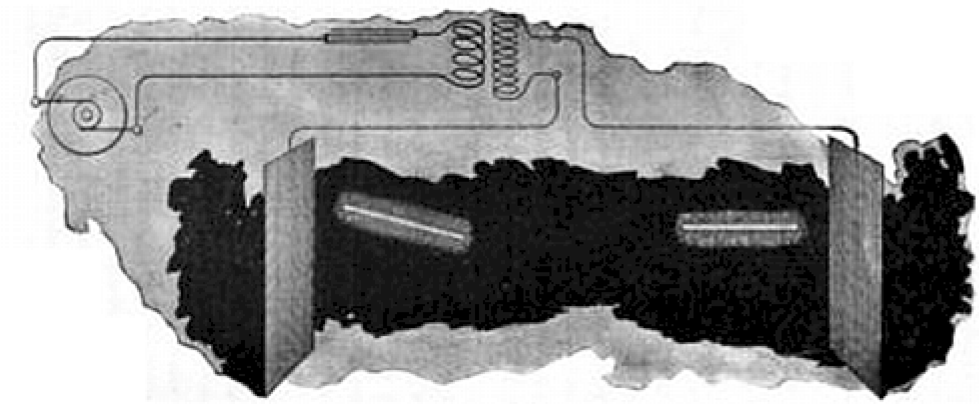
The transmission of electrical energy

In 1891 and 1892, Tesla had used an oscillatory transformer that bears his name in demonstration lectures delivered before meetings of the American Institute of Electrical Engineers (AIEE) in New York City" and the Institute of Electrical Engineers (IEE) in London. Of two striking results that Tesla demonstrated, one was that the wireless transmission of electrical energy was possible. A later presentation, titled "On Light and Other High Frequency Phenomena" (Philadelphia/St. Louis; Franklin Institute in 1893), was a key event in the invention of radio and could also be said to have begun the development of Wardenclyffe.

One-wire transmission

In the early presentations, the first experiment to be demonstrated was the operation of light and motive devices connected by a single wire to only one terminal of a high frequency induction coil, presented during the 1891 New York City lecture at Columbia University. While a single terminal incandescent lamp connected to one of an induction coil's secondary terminals does not form a closed circuit "in the ordinary acceptance of the term", the circuit is closed in the sense that a return path is established back to the secondary by what Tesla called "electrostatic induction" (or 'displacement currents'). This is due to the lamp's filament or refractory button capacitance relative to the coil's free terminal and environment; the free terminal also has capacitance relative to the lamp and environment. At high frequencies, the displacement current through these capacitances is sufficient to light the lamp.

Wireless transmission



The **Tesla effect**. A "World Wireless" system for "the transmission of electrical energy" that depends upon Earth's electrical conductivity and electrical coupling through the upper atmosphere was proposed by Tesla.

The second result demonstrated how energy could be made to go through space without any connecting wires. This was the first step towards a practical wireless system. The wireless energy transmission effect involved the creation of an electric field between two metal plates, each being connected to one terminal of an induction coil's secondary winding. Once again, a light-producing device (in this case a gas discharge tube) was used as a means of detecting the presence of the transmitted energy. "The most striking result obtained" involved the lighting of two partially evacuated tubes in an alternating electrostatic field while held in the hand of the experimenter. In Tesla's words,

... I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets as illustrated in Fig. 29 / 125, each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous.

Here Tesla describes two different types of wireless transmitter, both employing a high-tension induction coil. One had a sheet of metal suspended from the ceiling and connected to one of the induction coil's terminals, with the other terminal being connected to ground. The other type of transmitter had two sheets of metal suspended from the ceiling, each being connected to one of the coil's high-voltage terminals.

Theory of wireless transmission

While working to develop an explanation for the two observed effects mentioned above, Tesla recognized that electrical energy can be projected outward into space and detected by a receiving instrument in the general vicinity of the source without the need for any interconnecting wires. He went on to develop two theories related to these observations, which are:

1. By using two Tesla coil transmitter-receivers positioned at distant points on the Earth's surface, it is possible to induce a flow of electrical current between them.
2. By incorporating a portion of the Earth as part of a powerful dual-elevated-terminal Tesla coil transmitter an electrical disturbance can be impressed upon the Earth and detected "*at great distance, or even all over the surface of the globe*."

Tesla also made the assumption that the Earth is a charged body floating in space.

A point of great importance would be first to know what is the capacity of the Earth? and what charge does it contain if electrified? Though we have no positive evidence of a charged body existing in space without other oppositely electrified bodies being near, there is a fair probability that the Earth is such a body, for by whatever process it was separated from other bodies—and this is the accepted view of its origin—it must have retained a charge, as occurs in all processes of mechanical separation.

Tesla was familiar with demonstrations that involved the charging of Leyden jar capacitors and isolated metal spheres with electrostatic influence machines (in modern terms, high-voltage (kV), low-current (μA) electrostatic generators). By bringing these elements into close proximity with each other, and also by making direct contact followed by their separation, the charge can be manipulated. He surely had this in mind in the creation of his mental image, not being able to know that the model of Earth's origin was inaccurate. The presently accepted model of planetary origin is one of accretion and collision.

If it be a charged body insulated in space its capacity should be extremely small, less than one-thousandth of a farad.

We now know that the Earth is a charged body, made so by processes—at least in part—related to the interaction between the continuous stream of charged particles called the solar wind that flows outward from the center of our solar system and Earth's magnetosphere. And we also know that Tesla's capacitance estimate was correct: Earth's self-capacitance is about 710 microfarads.

But the upper strata of the air are conducting, and so, perhaps, is the medium in free space beyond the atmosphere, and these may contain an opposite charge. Then the capacity might be incomparably greater.

We now also know that Earth's upper atmospheric strata are conducting, or can be made so.

In any case it is of the greatest importance to get an idea of what quantity of electricity the Earth contains.

An additional condition of which we are now aware is that the Earth possesses a naturally existing negative charge with respect to the conducting region of the atmosphere beginning at an elevation of about 50 km. The potential difference between the Earth and this region is on the order of 400,000 volts. Near the Earth's surface there is a ubiquitous downward directed E-field of about 100 V/m. Tesla referred to this charge as the “electric niveau” or electric level.

It is difficult to say whether we shall ever acquire this necessary knowledge, but there is hope that we may, and that is, by means of electrical resonance. If ever we can ascertain at what period the Earth's charge, when disturbed, oscillates with respect to an oppositely electrified system or known circuit, we shall know a fact possibly of the greatest importance to the welfare of the human race. I propose to seek for the period by means of an electrical oscillator, or a source of alternating electric currents...

Some maintain the 200 kW wireless facility would have functioned by the production and propagation of electromagnetic radiation also known as the transverse electromagnetic (TEM) radio wave, but this is not the case.

I am not producing radiation in my system; I am suppressing electromagnetic waves. But, on the other hand, my apparatus can be used effectively with electromagnetic waves. The apparatus has nothing to do with this new method except that it is the only means to practice it. So that in my system, you should free yourself of the idea that there is radiation, that energy is radiated. It is not radiated; it is conserved.

By Tesla's own account, his earth resonance system works by the creation of powerful disturbances in Earth's natural electric charge. The Wardenclyffe facility had a dual purpose. In addition to point-to-point telecommunications and broadcasting it was also intended to demonstrate the transmission of electrical power on a reduced scale. He stated,

It is intended to give practical demonstrations of these principles with the plant illustrated. As soon as completed, it will be possible for a business man in New York to dictate instructions, and have them instantly appear in type at his office in London or elsewhere. He will be able to call up, from his desk, and talk to any telephone subscriber on the globe, without any change whatever in the existing equipment. An inexpensive instrument, not bigger than a watch, will enable its bearer to hear anywhere, on sea or land, music or song, the speech of a political leader, the address of an eminent man of science, or the sermon of an eloquent clergyman, delivered in some other place, however distant. In the same manner any picture, character, drawing, or print can be transferred from one to another place. Millions of such instruments can be operated from but one plant of this kind. More important than all of this, however, will be the transmission of power, without wires, which will be shown on a scale large enough to carry conviction.

Wardenclyffe was the first of many installations to be constructed near major population centers around the world. If Tesla's plans had moved forward without interruption the Long Island prototype would have been followed by a second plant built in the British Isles, perhaps on the west coast of Scotland near Glasgow. Each of these facilities would have included a large magnifying transmitter of a design loosely based upon the apparatus which Tesla assembled at the Colorado Springs Experimental Station in 1899.

> "... The plant in Colorado was merely designed in the same sense as a naval constructor designs first a small model to ascertain all the quantities before he embarks on the construction of a big vessel. I had already planned most of the details of the commercial plant, subsequently put up at Long Island, except that at that time the location was not settled upon. The Colorado plant I have used in determining the construction of the various parts, and the experiments which were carried on there were for the practical purpose of enabling me to design the transmitters and receivers which I was to employ in the large commercial plant subsequently erected..."

Using a global array of these magnifying transmitters, it was Tesla's plan to establish what he called the "World Wireless System," providing multi-channel global broadcasting, an array of secure wireless telecommunications services, and a long range aid to navigation, including means for the precise synchronization of clocks. In a more highly developed state he envisioned the 'World System' would expand to include the wireless industrial transmission of electric power.

At the time the power grid was quite limited in terms of who it reached and the Wardenclyffe prototype represented a way in which to significantly reduce the cost of "electrifying" the countryside. Tesla called his wireless technique the "*disturbed charge of ground and air method*".

There is evidence that Wardenclyffe would have used extremely low frequency signals combined with higher frequency signals. In practice, the transmitter electrically influences both the Earth and the space above it. He made a point of describing the process as being essentially the same as transmitting electricity by conduction through a wire.

Tesla clearly specified the Earth as being one of the conducting media involved in ground and air system technology. The other specified medium is the atmosphere above 5 miles (8.0 km) elevation. While not an ohmic conductor, in this region of the troposphere and upwards, the density or pressure is sufficiently reduced to so that, according to Tesla's theory, the atmosphere's insulating properties can be easily impaired, allowing an electric current to flow. His theory further states that the conducting region is developed through the process of atmospheric ionization, in which the effected portions thereof are changed to plasma. The presence of the magnetic fields developed by each plant's helical resonator suggests that an embedded magnetic field and flux linkage is also involved. Flux linkage with Earth's natural magnetic field is also a possibility, especially in the case of an earth resonance transmission system.

The atmosphere below 5 miles (8.0 km) is also viewed as a propagating medium for a portion of the above-ground circuit, and, being an insulating medium, electrostatic induction would be involved rather than true electrical conduction. Tesla felt that with a sufficiently high electrical potential on the elevated terminal the practical limitation imposed upon its height could be overcome. He anticipated that a highly energetic transmitter, as was intended at Wardenclyffe, would charge the elevated terminal to the point where the atmosphere around and above the facility would break down and become ionized, leading to a flow of true conduction currents between the two terminals by a path up to and through the troposphere, and back down to the other facility. The ionization of the atmosphere directly above the elevated terminals would be facilitated by the use of an ionizing beam of ultraviolet radiation to form what might be called a high-voltage plasma transmission line.

In various writings, Tesla explained that the Earth itself behaves as a resonant LC circuit when it is electrically excited at certain frequencies. At Wardenclyffe he operated at frequencies ranging from 1,000 Hz to 100 kHz. Tesla found the frequency range up to 30 – 35 kHz "to be most economical." Excitation of earth resonance at a harmonic of the 11.78 Hz fundamental frequency suggests energy transmission by means of a TM_{00} spherical conductor "single-wire" surface wave transmission line mode. A Schumann resonance mode (the fundamental frequency being about 7.5 to 7.9 Hz) is probably not involved. The entire Earth can be electrically resonated with a single earth-resonance transmitter, so an earth-resonance based system would require, at a minimum, that only one World Wireless System transmitter be constructed. Alternatively, two distantly spaced transmiter-receiver facilities could be constructed. Such a system would not be so dependent upon the excitation of an earth-resonance mode. In either case a surface wave, similar to the Zenneck wave would be utilized. Artificially induced earth currents would be utilized. According to Tesla, the planet's large cross-sectional area provides a low resistance path for the flow of earth currents. The greatest losses are apt to occur at the points where the transmitting / receiving plants and dedicated receiving stations are connected with the ground. This is why Tesla stated,

You see the underground work is one of the most expensive parts of the tower. In this system that I have invented it is necessary for the machine to get a grip of the Earth, otherwise it cannot shake the Earth. It has to have a grip on the Earth so that the whole of this globe can quiver, and to do that it is necessary to carry out a very expensive construction.

To close the circuit a second path is established between the two transmitter-receiver plants' elevated high-voltage terminals through the rarefied atmospheric strata above five miles (8 km). The connection is made by some combination of electrostatic induction and electrical conduction through plasma. While a number of his wireless patents, including "Apparatus for transmitting electrical energy," U.S. Patent No. 1,119,732, December 1, 1914, describe a system which uses the plasma-conduction scheme, his "Art of transmitting electrical energy through the natural mediums," U.S. Patent No. 787,412, April 18, 1905 and some of his Wardenclyffe design notes from 1901 show the overall plan also involves electrostatically induce oscillations in the potential associated with Earth's self-capacitance. The two tower earth-resonance transmitter is especially designed for this purpose. Tesla wrote,

The specific plan of producing the stationary waves, here-in described, might be departed from. For example, the circuit which impresses the powerful oscillations upon the earth might be connected to the latter at two points.

Tesla believed that a fully developed system with large high-power stations based upon the smaller Wardenclyffe prototype would permit wireless transmission and reception across large distances with negligible losses.

In the course of this work, I mastered the technique of high potentials sufficiently for enabling me to construct and operate, in 1899, a wireless transmitter developing up to twenty million volts. Some time before I contemplated the possibility of transmitting such high tension currents over a narrow beam of radiant energy ionizing the air and rendering it, in measure, conductive. After preliminary laboratory experiments, I made tests on a large scale with the transmitter referred to and a beam of ultra-violet rays of great energy in an attempt to conduct the current to the high rarefied strata of the air and thus create an auroral such as might be utilized for illumination, especially of oceans at night. I found that there was some virtue in the principal but the results did not justify the hope of important practical applications. . . .

In spite of ridicule, many of Tesla's ideas have been demonstrated to be essentially correct. For example he correctly predicted the existence of the ionosphere and electrical resonance of the Earth-atmosphere system. Resonance of the earth-ionosphere cavity with a fundamental frequency in the vicinity of 7.3 Hz was demonstrated in the 1950s as the Schumann resonance. The latter phenomenon was named after Schumann, for although Tesla had detected a resonance of the Earth-atmosphere system, he was not taken seriously in his time. Furthermore, Tesla appears to have excited a different terrestrial resonance mode with a fundamental frequency of 11.78 Hz.

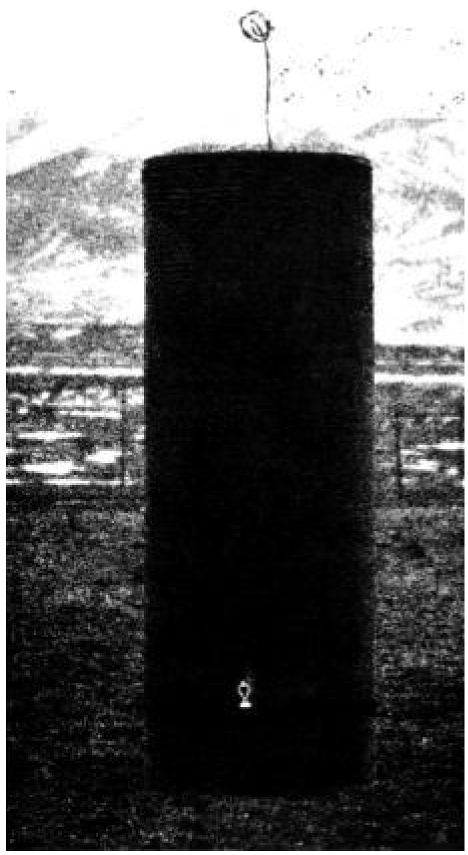
Electrical transmission and reception

Tesla's early experiments involved the propagation of ordinary radio waves, that is to say Hertzian waves, electromagnetic waves propagated through space without artificial guide.

In 1919 Nikola Tesla wrote,

The popular impression is that my wireless work was begun in 1893, but as a matter of fact I spent the two preceding years in investigations, employing forms of apparatus, some of which were almost like those of today. It was clear to me from the very start that the successful consummation could only be brought about by a number of radical improvements. Suitable high frequency generators and electrical oscillators had first to be produced. The energy of these had to be transformed in effective transmitters and collected at a distance in proper receivers. Such a system would be manifestly circumscribed in its usefulness if all extraneous interference were not prevented and exclusiveness secured. In time, however, I recognized that devices of this kind, to be most effective and efficient, should be designed with due regard to the physical properties of this planet and the electrical conditions obtaining on the same.

One of the requirements of the World Wireless system is the construction of resonant receivers. The grounded helical resonator of a Tesla Coil and an elevated terminal can be used in receive mode. Tesla himself repeatedly demonstrated the wireless transmission of electrical energy from a Tesla coil transmitter to a Tesla coil receiver. These concepts and methods are part of his wireless transmission system (US1119732 — Apparatus for Transmitting Electrical Energy — 1902 January 18). Tesla made a proposal that there would be many more than thirty transmission-reception stations worldwide.



Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a distant transmitter; Light is glowing near the bottom.

In the principle form of Tesla system receiver, a Tesla coil receiving transformer acts as a step-down transformer with high current output. The parameters of a Tesla Coil transmitter are identically applicable to it being a receiver (*e.g.*., an antenna circuit), due to reciprocity.

[Impedance, generally though, is not applied in an obvious way; for electrical impedance, the impedance at the load (*e.g.*., where the power is consumed) is most critical and, for a Tesla Coil receiver, this is at the point of utilization (such as at an induction motor) rather than at the receiving node. Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. Commonly, impedance is adjusted at the load with a tuner or a matching networks composed of inductors and capacitors.]

In another form of receiving circuit the two input terminals are connected to a device designed to reverse polarity at predetermined intervals of time and charge a capacitor. This form of Tesla system receiver has means for commutating the current impulses in the charging circuit so as to render them suitable for charging an energy storage device, a device for closing the receiving-circuit, and means for causing the receiver to be operated by the accumulated energy.

Tesla receivers operated correctly act as a step-down transformer with high current output. There are, to date, no commercial power generation entities or businesses that have utilized this technology to full effect. The power levels achieved by Tesla Coil receivers have, thus far, been a fraction of the output power of the transmitters.

While Tesla Coils can be used for wireless energy transmission and reception, much of the public and media attention is directed away from such applications since big electrical discharges are fascinating to most people.

Researchers experimenting with Tesla's wireless energy transmission system design have made observations that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials, which are presently considered to be *nonphysical*.

The intention of the Tesla world wireless energy transmission system is to combine electrical power transmission along with broadcasting and point-to-point wireless telecommunications, and allow for the elimination of many existing high-tension power transmission lines, facilitating the interconnection of electrical generation plants on a global scale.

One of Tesla's patents suggests he may have misinterpreted 25–70 km nodal structures associated with cloud-ground lightning observations made during the 1899 Colorado Springs experiments in terms of circumglobally propagating standing waves instead of a local interference phenomenon of direct and reflected waves.

Regarding the recent notion of power transmission through the earth-ionosphere cavity, a consideration of the earth-ionosphere or concentric spherical shell waveguide propagation parameters as they are known today shows that wireless power transmission by ***direct*** excitation of a Schumann cavity resonance mode is not realizable. "The conceptual difficulty with this model is that, at the very low frequencies that Tesla said that he employed (1-50 kHz), earth-ionosphere waveguide excitation, now well understood, would seem to be impossible with the either the Colorado Springs or the Long Island apparatus (at least with the apparatus that is visible in the photographs of these facilities)."

On the other hand, Tesla's concept of a global wireless electrical power transmission grid and telecommunications network based upon energy transmission by means of a spherical conductor transmission line with an upper three-space model return circuit, while perhaps not practical for power transmission, is feasible, defying no law of physics. Global wireless transmission by means of a spherical conductor “single-wire” surface wave transmission line and a propagating TM_{00} mode may also be possible, a feasibility study using a sufficiently powerful and properly tuned Tesla coil earth-resonance transmitter being called for.

Common misconceptions

Propagation mode

It was once thought the 200 kW Wardenclyffe prototype World Wireless station would have functioned by the production and propagation of electromagnetic radiation also known as the transverse electromagnetic (TEM) radio wave, but this is not the case. The World Wireless System actually works by the creation of powerful disturbances in Earth's natural electric charge and TM_{00} mode propagation over a spherical single conductor transmission line.

I am not producing radiation in my system; I am suppressing electromagnetic waves. But, on the other hand, my apparatus can be used effectively with electromagnetic waves. The apparatus has nothing to do with this new method except that it is the only means to practice it. So that in my system, you should free yourself of the idea that there is radiation, that energy is radiated. It is not radiated; it is conserved.

World System functionality

It is believed by some that World Wireless System technology is intended only for wireless power transmission. The prototype Wardenclyffe installation and the second facility planned in Scotland had a dual purpose. Their primary function was worldwide broadcasting and trans-Atlantic point-to-point wireless telecommunications. The prototype system was also intended for proof-of-concept wireless power transmission demonstrations, although on a greatly reduced scale.

It is intended to give practical demonstrations of these principles with the plant illustrated. As soon as completed, it will be possible for a business man in New York to dictate instructions, and have them instantly appear in type at his office in London or elsewhere. He will be able to call up, from his desk, and talk to any telephone subscriber on the globe, without any change whatever in the existing equipment. An inexpensive instrument, not bigger than a watch, will enable its bearer to hear anywhere, on sea or land, music or song, the speech of a political leader, the address of an eminent man of science, or the sermon of an eloquent clergyman, delivered in some other place, however distant. In the same manner any picture, character, drawing, or print can be transferred from one to another place. Millions of such instruments can be operated from but one plant of this kind. More important than all of this, however, will be the transmission of power, without wires, which will be shown on a scale large enough to carry conviction.

Schuman Cavity resonance hypothesis

It has been proposed the World Wireless System involve energy transfer by means of a concentric spherical shell waveguide composed of Earth's surface and the ionosphere. This is known as the Schumann Cavity. Natural lightning excites Schumann resonances that are observed at the lowest few resonance frequencies (about 8 Hertz and multiples of that). Their measured Q's of order 5 to 10 suggest that the electrical disturbances produced by lightning make a few circuits of the Earth before damping out, and create a fairly definite terrestrial standing wave of a few cycles duration.

The concept of transferring power with small losses in this manner will not work because the standing wave would occur in the Earth-ionosphere cavity, which is too lossy, that is to say, the cavity Q too small to enable a standing wave of sufficient amplitude to be generated. This limitation is independent of the power of the transmitter. In order for the transmitter to feed power to the receiver as efficiently as it would in a closed low-loss circuit the power transferred to the receiver should be able to transfer power of the same order of magnitude reciprocally to the transmitter. This is a necessary condition for the transmitter to “feel” the load connected to the receiver and to supply power to it via the standing wave.

This would require an Earth-ionosphere cavity Q of order ~10^6 or 10^7 at the lowest Schumann resonance frequencies. Measurements based on the spectrum of natural electrical radio noise yield a Q of only about 5 to 10. Cavity Q is defined here as the ratio of the electric field energy stored in the Earth-ionosphere cavity per cycle of the oscillation to the average power input to the cavity from the transmitter. The situation only gets worse at higher frequencies because of increasing energy losses in the earth and ionosphere, as is the case in radio transmission.

Furthermore, it has been pointed out that wireless energy transmission using the concentric spherical shell model, as discussed above, is not consistent with the Tesla type transmitter.

The conceptual difficulty with this model is that, at the very low frequencies that Tesla said that he employed (1-50 kHz), earth-ionosphere waveguide excitation, now well understood, would seem to be impossible with the either the Colorado Springs or the Long Island apparatus (at least with the apparatus that is visible in the photographs of these facilities).

The maximum recommended operating frequencies of 25 kHz as specified by Tesla is far above the highest easily observable Schumann resonance mode (this is the 9th overtone) that exists at approximately 66.4 Hz. Tesla's selection of 25 kHz is wholly inconsistent with the operation of a system that is based upon the direct excitation of a Schumann resonance mode.

Ionospheric conduction

It is believed by some the atmospheric path used in the two-conductor method, i.e., the "second path," is the ionosphere, the uppermost strata of Earth's atmosphere starting at approximately 30 miles (48 km) in daytime and approximately 55 miles (89 km) at night. The atmospheric strata through which energy can be transmitted has a barometric pressure of 75 mm, equivilent to an elevation of about 15 miles (24 km). World Wireless System apparatus allows this elevation to be reduced down to approximately 4.5 miles (7.2 km).

A Variant Receiver

A variant was suggested by Tesla for exploiting the vertical voltage gradient in the Earth's atmosphere.

A variant was suggested that could utilize the phantom loop effect to form a circuit to induct energy from the Earth's magnetic field and other radiant energy sources (including, but not limited to, electrostatics).

A Tesla Coil can receive electromagnetic impulses from atmospheric electricity and radiant energy, besides normal wireless transmissions.

The charging-circuit can be adapted to be energized by the action of various other disturbances and effects at a distance. Arbitrary and intermittent oscillations that are propagated via conduction to the receiving resonator will charge the receiver's capacitor and utilize the potential energy to greater effect.

Various radiations can be used to charge and discharge conductors, with the radiations considered electromagnetic vibrations of various wavelengths and ionizing potential.

Radiant energy throws off with great velocity minute particles which are strongly electrified and other rays falling on the insulated-conductor connected to a condenser (i.e., a capacitor) can cause the condenser to indefinitely charge electrically.

The helical resonator can be "shock excited" due to radiant energy disturbances not only at the fundamental wave at one-quarter wave-length but also is excited at its harmonics.

The output power from these devices, attained from Hertzian methods of charging, is low, but alternative charging means are available.

Hertzian methods can be used to excite a the receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the receiver, but are again at a disadvantages for utilization.

The receiver utilizes the effects or disturbances to charge a storage device with energy from an external source (natural or man-made) and controls the charging of said device by the actions of the effects or disturbances (during succeeding intervals of time determined by means of such effects and disturbances corresponding in succession and duration of the effects and disturbances). The stored energy can also be used to operate the receiving device. The accumulated energy can, for example, operate a transformer by discharging through a primary circuit at predetermined times which, from the secondary currents, operate the receiving device.

With regard to Tesla's statements on the harnessing of natural phenomena to obtain electric power, he stated:

Ere many generations pass, our machinery will be driven by a power obtainable at any point of the universe. — "Experiments with Alternate Currents of High Potential and High Frequency" (February 1892)

Chapter- 5

Microwave Power Transmission and Space-based Solar Power

Microwave power transmission (**MPT**) is the use of microwaves to transmit power through outer space or the atmosphere without the need for wires. It is a sub-type of the more general wireless energy transfer methods.

History

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. In 1964, William C. Brown demonstrated a miniature helicopter equipped with a combination antenna and rectifier device called a rectenna. The rectenna converted microwave power into electricity, allowing the helicopter to fly. In principle, the rectenna is capable of very high conversion efficiencies - over 90% in optimal circumstances.

Most proposed MPT systems now usually include a phased array microwave transmitter. While these have lower efficiency levels they have the advantage of being electrically steered using no moving parts, and are easier to scale to the necessary levels that a practical MPT system requires.

Using microwave power transmission to deliver electricity to communities without having to build cable-based infrastructure is being studied at Grand Bassin on Reunion Island in the Indian Ocean.

Common safety concerns

The common reaction to microwave transmission is one of concern, as microwaves are generally perceived by the public as dangerous forms of radiation - stemming from the fact that they are used in microwave ovens. While high power microwaves can be painful and dangerous as in the United States Military's Active Denial System, MPT systems are generally proposed to have only low intensity at the rectenna.

Though this would be extremely safe as the power levels would be about equal to the leakage from a microwave oven, and only slightly more than a cell phone, the relatively diffuse microwave beam necessitates a large rectenna area for a significant amount of energy to be transmitted.

Research has involved exposing multiple generations of animals to microwave radiation of this or higher intensity, and no health issues have been found.

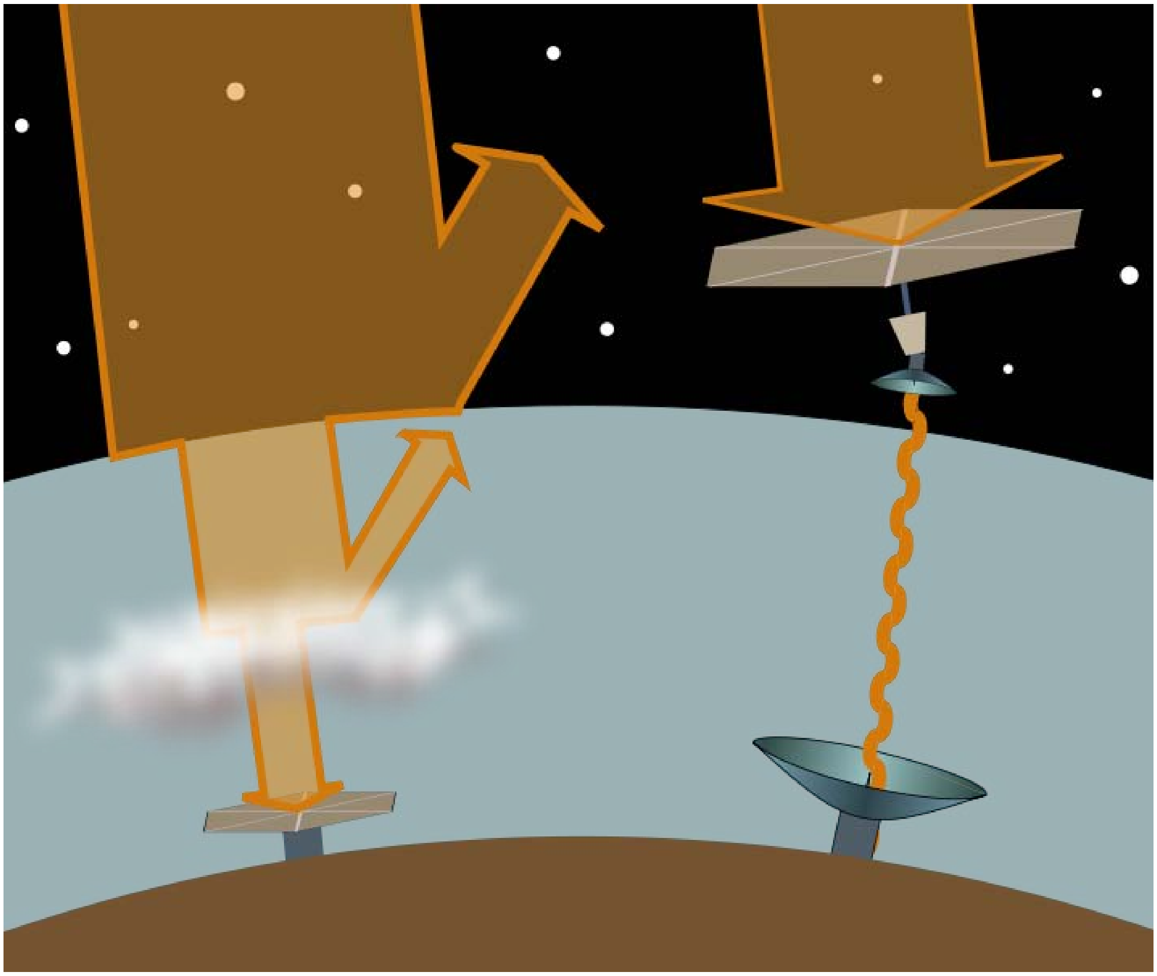
Proposed uses

MPT is the most commonly proposed method for transferring energy to the surface of the Earth from solar power satellites or other in-orbit power sources. MPT is occasionally proposed for the power supply in [beam-powered propulsion] for orbital lift space ships. Even though lasers are more commonly proposed, their low efficiency in light generation and reception has led some designers to opt for microwave based systems.

Current status

Wireless Power Transmission (using microwaves) is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. In 2008 a long range transmission experiment successfully transmitted 20 watts 92 miles from a mountain on Maui to the main island of Hawaii.

Space-based solar power



On the left: Part of the solar energy is lost on its way through the atmosphere by the effects of reflection and absorption.
On the right: Space-based solar power systems convert sunlight to microwaves outside the atmosphere, avoiding these losses, and the downtime due to Earth's rotation, experienced by surface installations.

Space-based solar power (**SBSP**), or historically **space solar power** (**SSP**) is a system for the collection of solar power in space, for use on Earth. SBSP differs from the usual method of solar power collection in that the solar panels used to collect the energy would reside on a satellite in orbit, often referred to as a **solar power satellite** (SPS), rather than on Earth's surface. In space, collection of the Sun's energy is unaffected by the various obstructions which reduce efficiency or capacities of Earth surface solar power collection.

The World Radiation Centre's 1985 standard extraterrestrial level for mean solar irradiance at one astronomical unit from the Sun is 1367 W/m^2. The integrated total terrestrial solar irradiance is 950 W/m^2. Extraterrestrial solar irradiance is thus 144% of the maximum terrestrial irradiance, and has a different radiation profile, including wavelengths blocked by the atmosphere. A major interest in SBSP stems from the length of time the solar collection panels can be exposed to a consistently high amount of solar radiation. For most of the year, a satellite-based solar panel can collect power 24 hours per day, whereas a terrestrial station can collect for at most 12 hours per day, unless at the poles, but then only for 6 months of the year, if weather permits, and only during peak hours—irradiance under the best of conditions is quite reduced near sunset and sunrise.

Collection of solar energy in space for use on Earth introduces two new problems and can alleviate an existing one. First, installation of the collection satellites, and second transmitting energy from them to the surface for use. The first requires upgrading and extension of existing solar panel technologies. Since wires extending from Earth's surface to an orbiting satellite are neither practical nor currently possible, many SBSP designs have proposed the use of microwave beams for wireless power transmission. The collecting satellite would convert solar energy into electrical energy, powering a microwave emitter oriented toward a collector on the Earth's surface. Dynamic solar thermal power systems on satellites are also being investigated. Since the beam can be steered, it can be directed as needed to accommodate periods of high power use in particular locations (e.g., during the hottest part of the day in summer, or cold spells in winter). As well, one of the current problems of electricity use is long distance transmission from generating sites to usage sites. Because at least one type of receiving antenna, the rectenna, is relatively inexpensive, it may be possible to reduce the need for electricity transmission lines by sensible siting of receiving antennas, potentially reducing costs and grid interconnect failures, such as the blackouts of 1965 and 2003.

Some problems normally associated with terrestrial solar power collection would be entirely avoided by such a design, e.g., dependence on weather conditions, contamination or corrosion, damage by wildlife or plant encroachment, etc. Other problems will likely be encountered, such as more rapid radiation damage or micrometeoroid impacts.

Timeline

- **1968**: Dr. Peter Glaser introduced the idea of a large solar power satellite system with square miles of solar collectors in high geosynchronous orbit (GEO is an orbit 36,000 km above the equator), for collection and conversion of sun's energy into an electromagnetic microwave beam to transmit usable energy to large receiving antennas (rectennas) on Earth for distribution.

- **1973**: Dr. Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a large (on the close order of one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

- **1970s**: United States Department of Energy and NASA examined the Solar Power Satellite (SPS) concept extensively, publishing the design and feasibility studies.

- **1994**: The United States Air Force conducted the Advanced Photovoltaic Experiment using a satellite launched into low Earth orbit by a Pegasus rocket.

- **1995–1997**: NASA conducted a “Fresh Look” study of space solar power (SSP) concepts and technologies.

- **1998**: Space Solar Power Concept Definition Study (CDS) identified credible commercially viable SSP concepts, identifying technical and programmatic risks.

- **1998**: Japan's space agency starts a program for developing a Space Solar Power System (SSPS), which continues to the present day.

- **1999**: NASA's Space Solar Power Exploratory Research and Technology program (SERT see section below) program begun.

- **2000**: John Mankins of NASA testified in the U.S. House of Representatives, saying "Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities. A technology roadmap has been developed that lays out potential paths for achieving all needed advances — albeit over several decades.

- **2001**: PowerSat Corporation founded by William Maness.

- **2001**: Dr. Neville Marzwell of NASA stated, "We now have the technology to convert the sun's energy at the rate of 42 to 56 percent... We have made tremendous progress. ...If you can concentrate the sun's rays through the use of large mirrors or lenses you get more for your money because most of the cost is in the PV arrays... There is a risk element but you can reduce it... You can put these small receivers in the desert or in the mountains away from populated areas. ...We believe that in 15 to 25 years we can lower that cost to 7 to 10 cents per kilowatt hour. ...We offer an advantage. You don't need cables, pipes, gas or copper wires. We can send it to you like a cell phone call—where you want it and when you want it, in real time."

- **2001**: NASDA (Japan's national space agency) announced plans to perform additional research and prototyping by launching an experimental satellite with 10 kilowatts and 1 megawatt of power.

- **2007**: The US Pentagon's National Security Space Office (NSSO) issued a report on October 10, 2007 stating they intend to collect solar energy from space for use on Earth to help the United States' ongoing relationship with the Middle East and the battle for oil. The International Space Station may be the first test ground for this new idea, even though it is in a low-earth orbit.

- **2007**: In May 2007 a workshop was held in the USA at the Massachusetts Institute of Technology (MIT) to review the current state of the market and technology.

- **2009**: A new company from the US, Space Energy, Inc., announced plans to provide commercial space-based solar power. They say they have developed a "rock-solid business platform" and should be able to provide space-based solar power within a decade.

- **2009**: American company Pacific Gas and Electric (PG&E) announced it is seeking regulatory approval for an agreement with Solaren to buy 200 MW of solar power, starting in 2016, which Solaren has plans to provide via SBSP. PG&E spokesman Jonathan Marshall stated that "We've been very careful not to bear risk in this."

- **2009**: PowerSat Corporation filed a patent application concerning ganging multiple power satellites to form a single coherent microwave beam, and a mechanism to use the solar array to power ion thrusters to lift a power satellite from low Earth orbit to geostationary orbit.

- **2009**: Jaxa, the Japan Aerospace Exploration Agency announced plans to orbit solar power satellites that will transmit energy back to earth via microwaves. They hope to have the first prototype orbiting by 2030.

- **2010**: Europe's largest space company EADS Astrium plans to put a solar-collecting demo satellite in space.

- **2010**: Prof. Andrea Massa and Prof. Giorgio Franceschetti will organize a Special Session on the "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" at the 2010 Institute of Electrical and Electronics Engineers International Symposium on Antennas and Propagation.

History

The SBSP concept, originally known as *Satellite Solar Power System* ("SSPS") was first described in November 1968. In 1973 Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a very large (up to one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

Glaser then worked at Arthur D. Little, Inc., as a vice-president. NASA signed a contract with ADL to lead four other companies in a broader study in 1974. They found that, while the concept had several major problems—chiefly the expense of putting the required materials in orbit and the lack of experience on projects of this scale in space, it showed enough promise to merit further investigation and research.

Between 1978 and 1981, the Congress authorized the Department of Energy and NASA to jointly investigate the concept. They organized the Satellite Power System Concept Development and Evaluation Program. The study remains the most extensive performed to date. Several reports were published investigating the engineering feasibility of such an engineering project. They include:

- Resource Requirements (Critical Materials, Energy, and Land)
- Financial/Management Scenarios
- Public Acceptance
- State and Local Regulations as Applied to Satellite Power System Microwave Receiving Antenna Facilities
- Student Participation
- Potential of Laser for SBSP Power Transmission
- International Agreements
- Centralization/Decentralization
- Mapping of Exclusion Areas For Rectenna Sites
- Economic and Demographic Issues Related to Deployment
- Some Questions and Answers
- Meteorological Effects on Laser Beam Propagation and Direct Solar Pumped Lasers
- Public Outreach Experiment
- Power Transmission and Reception Technical Summary and Assessment
- Space Transportation

The project was not continued with the change in Administrations after the 1980 US Federal elections.

The Office of Technology Assessment concluded

Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment. In addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture.

More recently, the SBSP concept has again become interesting, due to increased energy demand, increased energy costs, and emission implications, starting in 1997 with the NASA "Fresh Look". In assessing "What has changed" since the DOE study, this study asserts that

Another important change has occurred at the US national policy level. US National Space Policy now calls for NASA to make significant investments in technology (not a particular vehicle) to drive the costs of ETO *[Earth to Orbit]* transportation down dramatically. This is, of course, an absolute requirement of space solar power.

One might take the NASA "Fresh Look" study as encouraging because the main difficulty identified is driving down Earth to Orbit costs. However, Dr. Pete Worden claimed that space-based solar is about five orders of magnitude more expensive than solar power from the Arizona desert. A major factor in this five orders of magnitude is the cost of transporting materials to orbit. Dr. Worden referred to possible solutions as speculative solutions that would not be available for decades at the best, leaving space-based solar power with no business case for the foreseeable future.

SERT

In 1999 NASA's Space Solar Power Exploratory Research and Technology program (SERT) was initiated for the following purpose:

- Perform design studies of selected flight demonstration concepts;
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the U.S. (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical Space Solar Power (SSP) elements.

It was to develop a solar power satellite (SPS) concept for a future gigawatt space power systems to provide electrical power by converting the Sun’s energy and beaming it to the Earth's surface. It was also to provide a developmental path to solutions for current space power architectures. Subject to further study, it proposed an inflatable photovoltaic gossamer structure with concentrator lenses or solar heat engines to convert sunlight into electricity. The program looked at both systems in sun-synchronous orbit and geosynchronous orbit.

Some of SERT's conclusions include the following:

- The increasing global energy demand is likely to continue for many decades resulting in new power plants of all sizes being built.
- The environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic.
- Renewable energy is a compelling approach, both philosophically and in engineering terms.
- Many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.
- Based on their Concept Definition Study, space solar power concepts may be ready to reenter the discussion.
- Solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin.
- Space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches.

- The economic viability of space solar power systems depends on many factors and the successful development of various new technologies (not least of which is the availability of much lower cost access to space than has been available), however, the same can be said of many other advanced power technologies options.
- Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

Advantages

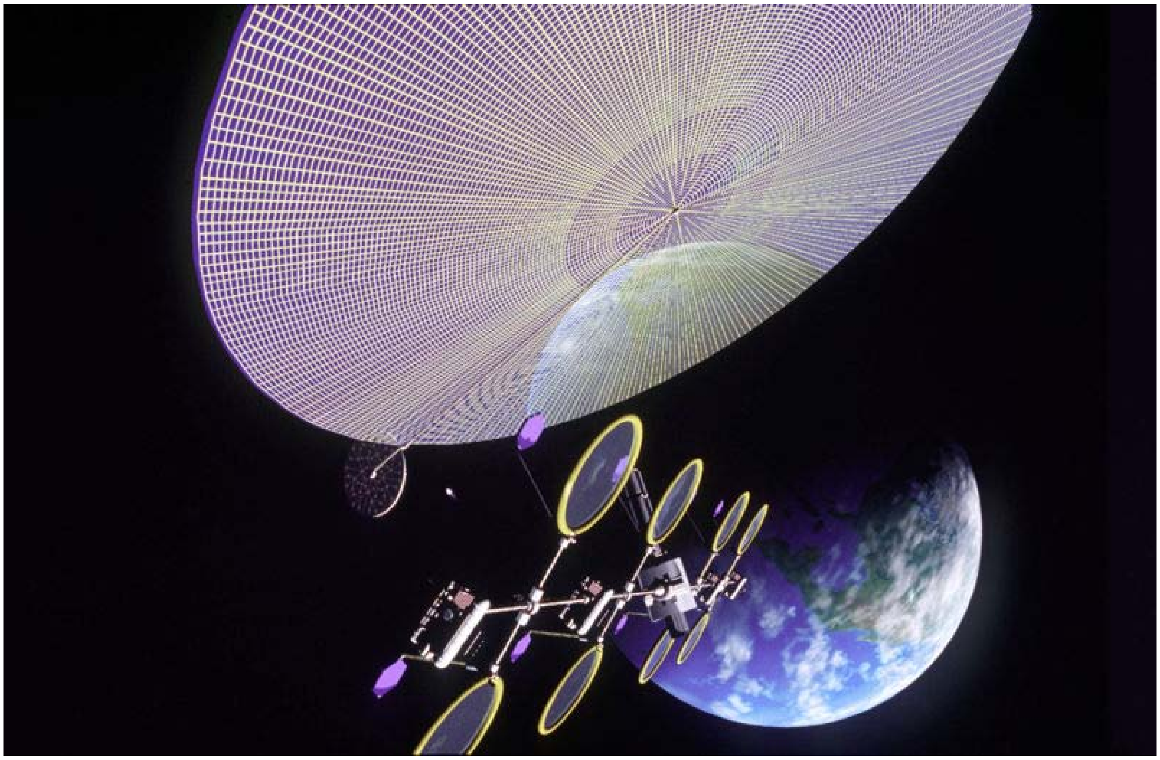
The SBSP concept is attractive because space has several major advantages over the Earth's surface for the collection of solar power. There is no air in space, so the collecting surfaces would receive much more intense sunlight, unaffected by weather. In geostationary orbit, an SPS would be illuminated over 99% of the time; such an SPS would be in Earth's shadow on only a few days at the spring and fall equinoxes; and even then for a maximum of 75 minutes late at night when power demands are at their lowest. This characteristic of SBSP avoids the expense of storage facilities (dams, oil storage tanks, coal dumps) necessary in many Earth-based power generation systems. Additionally, SBSP would have fewer or none of the ecological (or political) consequences of fossil fuel systems.

SBSP would also be applicable on a global scale. Nuclear power raises questions of proliferation and waste disposal, which pose problems everywhere, but especially in undeveloped areas which are less capable of coping with them. SBSP poses no such known potential threat.

This technology can be of value to relief efforts in disaster areas. SBSP could step in at short notice to provide as much power as is necessary both for the relief effort and to provide continuity of energy until ground based transfer methods are restored.

There is a significant military advantage to SBSP in that it would provide the option to have almost instantaneous sustained power nearly anywhere on the globe. It has been estimated that the average price of fuel for the US Army exceeds $5 per gallon. During Operation Iraqi Freedom, there is an estimate that fuel costs in some areas approached $20 per gallon. This is undoubtedly due to the cost of physically moving large quantities of fuel, and the massive security costs in protecting these convoys in a war zone. The estimated costs given above do not include the high cost in the lives of American servicemen and women who are killed or injured during attacks on supply convoys. With a mobile SBSP receiving station, the Army could quickly be provided with megawatts of clean, sustained energy. If a conflict forced a rapid change in the geographic location of Army personnel, the power from SBSP could simply be redirected by altering the position of the SBSP satellites. If SBSP became an established source of power, it could also provide a military benefit in that the supply would inherently be much more secure than traditional energy delivery methods, chances of an energy scarcity based conflict could be much reduced.

Design



Space-based solar power essentially consists of three parts:

1. a means of collecting solar power in space, for example via solar cells or a heat engine
2. a means of transmitting power to earth, for example via microwave or laser
3. a means of receiving power on earth, for example via a microwave antenna (rectenna)

The space-based portion will be in a freefall, vacuum environment and will not need to support itself against gravity other than relatively weak tidal stresses. It needs no protection from terrestrial wind or weather, but will have to cope with space-based hazards such as micrometeors and solar storms.

Solar energy conversion (solar photons to DC current)

Two basic methods of converting sunlight to electricity have been studied: photovoltaic (PV) conversion, and solar dynamic (SD) conversion.

Most analyses of solar power satellites have focused on photovoltaic conversion (commonly known as "solar cells"). Photovoltaic conversion uses semiconductor cells (*e.g.*, silicon or gallium arsenide) to directly convert photons into electrical power via a quantum mechanical mechanism. Photovoltaic cells are not perfect in practice, as material purity and processing issues during production affect performance; each has been progressively improved for some decades. Some new, thin-film approaches are less efficient (about 20% vs 41% for best in class in each case as of late 2009), but are much less expensive and generally lighter.

In an SPS implementation, photovoltaic cells will likely be rather different from the glass-pane protected solar cell panels familiar to many in current terrestrial use, since they will be optimized for weight, and will be designed to be tolerant of the space radiation environment (some thin film silicon solar panels are highly insensitive to ionising radiation), but will not need to be encapsulated against corrosion from environmental exposure or biological deterioration. They do not require the structural support required for terrestrial use, where the considerable gravity and wind loading imposes structural requirements on terrestrial implementations.

Wireless power transmission to the Earth

Wireless power transmission was proposed early on as a means to transfer energy from collection to the Earth's surface. The power could be transmitted as either microwave or laser radiation at a variety of frequencies depending on system design. Whichever choice is made, the transmitting radiation would have to be non-ionizing to avoid potential disturbances either ecologically or biologically. This established an upper limit for the frequency used, as energy per photon (and consequently the ability to cause ionization) increases with frequency. Ionization of biological materials doesn't begin until ultraviolet or higher frequencies, so most radio frequencies would be feasible.

Microwave power transmission

William C. Brown demonstrated in 1964, during Walter Cronkite's CBS News program, a microwave-powered model helicopter that received all the power it needed for flight from a microwave beam. Between 1969 and 1975, Bill Brown was technical director of a JPL Raytheon program that beamed 30 kW of power over a distance of 1 mile at 84% efficiency.

Microwave power transmission of tens of kilowatts has been well proven by existing tests at Goldstone in California (1975) and Grand Bassin on Reunion Island (1997).

More recently, microwave power transmission has been demonstrated, in conjunction with solar energy capture, between a mountain top in Maui and the main island of Hawaii (92 miles away), by a team under John C. Mankins. Technological challenges in terms of array layout, single radiation element design, and overall efficiency, as well as the associated theoretical limits are presently a subject of research, as it is demonstrated by the upcoming Special Session on "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" to be held in the 2010 IEEE Symposium on Antennas and Propagation.

Laser power beaming experiments

A large-scale demonstration of power beaming is a necessary step to the development of solar power satellites. Laser power beaming was envisioned by some at NASA as a stepping stone to further industrialization of space.

In the 1980s researchers at NASA worked on the potential use of lasers for space-to-space power beaming, focusing primarily on the development of a solar-powered laser. In 1989 it was suggested that power could also be usefully beamed by laser from Earth to space. In 1991 the SELENE project (SpacE Laser ENErgy) was begun, which included the study of laser power beaming for supplying power to a lunar base.

In 1988 the use of an Earth-based laser to power an electric thruster for space propulsion was proposed by Grant Logan, with technical details worked out in 1989. He proposed using diamond solar cells operating at six hundred degrees to convert ultraviolet laser light, a technology that has yet to be demonstrated even in the laboratory. His ideas were adapted to be more practical.

The SELENE program was a two-year research effort, but the cost of taking the concept to operational status was too high, and the official project was ended in 1993, before reaching a space-based demonstration.

Spacecraft sizing

The size of a solar power satellite would be dominated by two factors: the size of the collecting apparatus (e.g. panels and mirrors), and the size of the transmitting antenna. The distance from Earth to geostationary orbit (22,300 miles, 35,700 km), the chosen wavelength of the microwaves, and certain laws of physics (specifically the Rayleigh Criterion or diffraction limit) will all be factors.

It has been suggested that, for best efficiency, the satellite antenna should be circular and about 1 kilometer in diameter or larger; the ground antenna (rectenna) should be elliptical, 10 km wide, and a length that makes the rectenna appear circular from GEO (Geostationary Orbit). (Typically, 14 km at some North American latitudes.) Smaller antennas would result in increased losses to diffraction/sidelobes. For the desired (23 mW/cm^2) microwave intensity these antennas could transfer between 5 and 10 gigawatts of power.

According to some research, to collect and convert the target volume of power, the satellite would require between 50 and 100 square kilometers of collector area (if readily available ~14% efficient monocrystalline silicon solar cells were deployed). State of the art multi-junction solar cells with a maximum efficiency of 43% could reduce the necessary collector area by two thirds. In any case, an SPS's structure will necessarily be large (perhaps kilometers across), making it larger than most man-made structures on Earth, and building structures of such size in orbit has never been attempted.

Location

GEO

The main advantage of locating a space power station in geostationary orbit is that the antenna geometry stays constant, and so keeping the antennas lined up is simpler. Another advantage is that nearly continuous power transmission is immediately available as soon as the first space power station is placed in orbit; other space-based power stations have much longer start-up times before they are producing nearly continuous power.

LEO/MEO instead of GEO

A collection of LEO (Low Earth Orbit) space power stations has been proposed as a precursor to GEO (Geostationary Orbit) space-based solar power. There would be both advantages (shorter energy transmission path, lower cost) and disadvantages (frequent changes in antenna geometries, increased debris collisions, more power stations needed to receive power continuously). It might be possible to deploy LEO systems sooner than GEO because the antenna development would take less time, but it may take longer to prepare and launch the number of required satellites.

Moon

People such as David Criswell suggest that the moon is the optimum location for solar power stations, and promote **lunar solar power**.

The main advantages of locating the solar power collector on the moon is that most of its mass could be constructed out of locally available lunar materials, using in-situ resource utilization, significantly reducing the amount of mass and therefore the launch costs required compared to other space-based solar power stations.

Earth-based infrastructure

The Earth-based receiver antenna (or rectenna) is a critical part of the original SPS concept. It would probably consist of many short dipole antennas, connected via diodes. Microwaves broadcast from the SPS will be received in the dipoles with about 85% efficiency. With a conventional microwave antenna, the reception efficiency is still better, but the cost and complexity is also considerably greater, almost certainly prohibitively so. Rectennas would be multiple kilometers across. Crops and farm animals may be raised underneath a rectenna, as the thin wires used for support and for the dipoles will only slightly reduce sunlight, or non arable land could be used, so such a rectenna would not be as expensive in terms of land use as might be supposed.

Dealing with launch costs

One problem for the SBSP concept is the cost of space launches and the amount of material that would need to be launched.

Reusable launch systems are predicted to provide lower launch costs to low Earth orbit (LEO).

Much of the material launched need not be delivered to its eventual orbit immediately, which raises the possibility that high efficiency (but slower) engines could move SPS material from LEO to GEO at an acceptable cost. Examples include ion thrusters or nuclear propulsion.

Power beaming from geostationary orbit by microwaves carries the difficulty that the required 'optical aperture' sizes are very large. For example, the 1978 NASA SPS study required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although they have increased atmospheric absorption and even potential beam blockage by rain or water droplets. Because of the thinned array curse, it is not possible to make a narrower beam by combining the beams of several smaller satellites. The large size of the transmitting and receiving antennas means that the minimum practical power level for an SPS will necessarily be high; small SPS systems will be possible, but uneconomic.

To give an idea of the scale of the problem, assuming a solar panel mass of 20 kg per kilowatt (without considering the mass of the supporting structure, antenna, or any significant mass reduction of any focusing mirrors) a 4 GW power station would weigh about 80,000 metric tons, all of which would, in current circumstances, be launched from the Earth. Very lightweight designs could likely achieve 1 kg/kW,, meaning 4,000 metric tons for the solar panels for the same 4 GW capacity station. This would be the equivalent of between 40 and 150 heavy-lift launch vehicle (HLLV) launches to send the material to low earth orbit, where it would likely be converted into subassembly solar arrays, which then could use high-efficiency ion-engine style rockets to (slowly) reach GEO (Geostationary orbit). With an estimated serial launch cost for shuttle-based HLLVs of $500 million to $800 million, and launch costs for alternative HLLVs at $78 million, total launch costs would range between $11 billion (low cost HLLV, low weight panels) and $320 billion ('expensive' HLLV, heavier panels). For comparison, the direct cost of a new coal or nuclear power plant ranges from $1 billion to $1.5 billion dollars per GW (not including the full cost to the environment from CO2 emissions or storage of spent nuclear fuel, respectively); another example is the Apollo missions to the Moon cost a grand total of $24 billion (1970's dollars), taking inflation into account, would cost $140 billion today, more expensive than the construction of the International Space Station.

Building from space

Gerard O'Neill, noting the problem of high launch costs in the early 1970s, proposed building the SPS's in orbit with materials from the Moon. Launch costs from the Moon are potentially much lower than from Earth, due to the lower gravity. This 1970s proposal assumed the then-advertised future launch costing of NASA's space shuttle. This approach would require substantial up front capital investment to establish mass drivers on the Moon.

Nevertheless, on 30 April 1979, the Final Report ("Lunar Resources Utilization for Space Construction") by General Dynamics' Convair Division, under NASA contract NAS9-15560, concluded that use of lunar resources would be cheaper than Earth-based materials for a system of as few as thirty Solar Power Satellites of 10GW capacity each.

In 1980, when it became obvious NASA's launch cost estimates for the space shuttle were grossly optimistic, O'Neill et al. published another route to manufacturing using lunar materials with much lower startup costs. This 1980s SPS concept relied less on human presence in space and more on partially self-replicating systems on the lunar surface under remote control of workers stationed on Earth. This proposal suffers from the current lack of such automated systems. The design and construction of these automated systems and their use to produce a mass driver launching system on the moon from lunar materials is expected to take more than twenty years. The partially self replicating systems would include locally produced power generation, perhaps solar cells or heat engine produced electrical power.

Asteroid mining has also been seriously considered. A NASA design study evaluated a 10,000 ton mining vehicle (to be assembled in orbit) that would return a 500,000 ton asteroid fragment to geostationary orbit. Only about 3,000 tons of the mining ship would be traditional aerospace-grade payload. The rest would be reaction mass for the mass-driver engine, which could be arranged to be the spent rocket stages used to launch the payload. Assuming that 100% of the returned asteroid was useful, and that the asteroid miner itself couldn't be reused, that represents nearly a 95% reduction in launch costs. However, the true merits of such a method would depend on a thorough mineral survey of the candidate asteroids; thus far, we have only estimates of their composition.

Having a relatively cheap per pound source of raw materials from space would lessen the concern for low mass designs and result in a different sort of SPS being built. The low cost per pound of lunar materials in O'neill's vision would be supported by using lunar material to manufacture more facilities in orbit than just solar power satellites.

Non-conventional launch methods

SBSP costs might be reduced if a means of putting the materials into orbit were developed that did not rely on rockets. Some possible technologies include ground launch systems such as mass drivers or Lofstrom loops, which would launch using electrical power, or the geosynchronous orbit space elevator. However, these require technology that is yet to be developed. John Hunter of Quicklaunch is working on commercialising the 'Hydrogen Gun', a new form of mass driver which proposes to deliver unmanned payloads to orbit for around 5% of regular launch costs (or $500 per pound; US$1,000 *per* kilogram) and perform 5 launches per day.

Advanced techniques for launching from the moon may reduce the cost of building a solar power satellite from lunar materials. Some proposed techniques include the lunar mass driver and the lunar space elevator, first described by Jerome Pearson. It would require establishing silicon mining and solar cell manufacturing facilities on the Moon.

Counter arguments

Safety

The use of microwave transmission of power has been the most controversial issue in considering any SPS design.

At the Earth's surface, a suggested microwave beam would have a maximum intensity at its center, of 23 mW/cm^2 (less than 1/4 the solar irradiation constant), and an intensity of less than 1 mW/cm^2 outside of the rectenna fenceline (the receiver's perimeter). These compare with current United States Occupational Safety and Health Act (OSHA) workplace exposure limits for microwaves, which are 10 mW/cm^2, - the limit itself being expressed in voluntary terms and ruled unenforceable for Federal OSHA enforcement purposes. A beam of this intensity is therefore at its center, of a similar magnitude to current safe workplace levels, even for long term or indefinite exposure. Outside the receiver, it is far less than the OSHA long-term levels Over 95% of the beam energy will fall on the rectenna. The remaining microwave energy will be absorbed and dispersed well within standards currently imposed upon microwave emissions around the world. It is important for system efficiency that as much of the microwave radiation as possible be focused on the rectenna. Outside of the rectenna, microwave intensities rapidly decrease, so nearby towns or other human activity should be completely unaffected.

Exposure to the beam is able to be minimized in other ways. On the ground, physical access is controllable (e.g., via fencing), and typical aircraft flying through the beam provide passengers with a protective metal shell (i.e., a Faraday Cage), which will intercept the microwaves. Other aircraft (balloons, ultralight, etc.) can avoid exposure by observing airflight control spaces, as is currently done for military and other controlled airspace.

The microwave beam intensity at ground level in the center of the beam would be designed and physically built into the system; simply, the transmitter would be too far away and too small to be able to increase the intensity to unsafe levels, even in principle.

In addition, a design constraint is that the microwave beam must not be so intense as to injure wildlife, particularly birds. Experiments with deliberate microwave irradiation at reasonable levels have failed to show negative effects even over multiple generations.

Some have suggested locating rectennas offshore, but this presents serious problems, including corrosion, mechanical stresses, and biological contamination.

A commonly proposed approach to ensuring fail-safe beam targeting is to use a retrodirective phased array antenna/rectenna. A "pilot" microwave beam emitted from the center of the rectenna on the ground establishes a phase front at the transmitting antenna. There, circuits in each of the antenna's subarrays compare the pilot beam's phase front with an internal clock phase to control the phase of the outgoing signal. This forces the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity; if the pilot beam is lost for any reason (if the transmitting antenna is turned away from the rectenna, for example) the phase control value fails and the microwave power beam is automatically defocused. Such a system would be physically incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

The long-term effects of beaming power through the ionosphere in the form of microwaves has yet to be studied, but nothing has been suggested which might lead to any significant effect.

Atmospheric damage due to launches

When hot rocket exhaust reacts with atmospheric nitrogen, it can form nitrogen compounds. In particular these nitrogen compounds are problematic when they form in the stratosphere, as they can damage the ozone layer. However, the environmental effect of rocket launches is negligible compared to higher volume polluters, such as airplanes and automobiles.

Chapter- 6

Inductive Charging

Magne Charge wall, handheld, and floor mount

Inductive charging uses the electromagnetic field to transfer energy between two objects. A charging station sends energy through inductive coupling to an electrical device, which stores the energy in the batteries. Because there is a small gap between the two coils, inductive charging is one kind of short-distance wireless energy transfer.

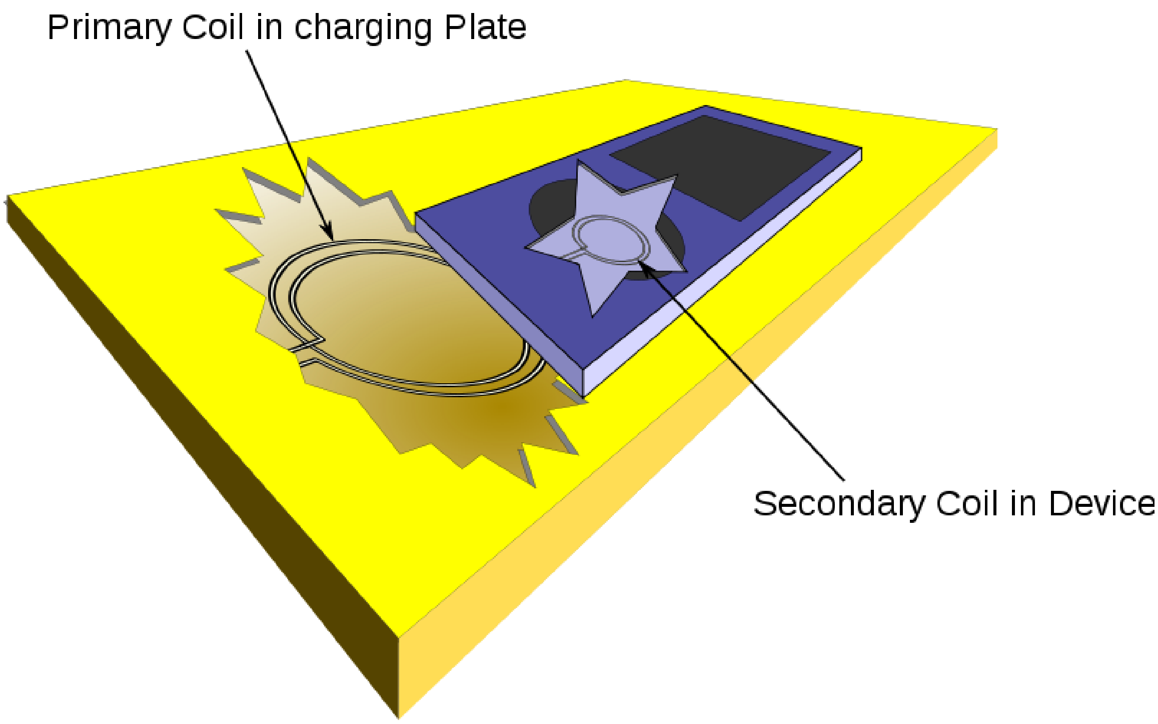
The other kind of charging, direct wired contact (also known as conductive charging or direct coupling) requires direct electrical contact between the batteries and the charger. Conductive charging is achieved by connecting a device to a power source with plug-in wires, such as a docking station, or by moving batteries from a device to charger.

Induction chargers typically use an induction coil to create an alternating electromagnetic field from within a charging base station, and a second induction coil in the portable device takes power from the electromagnetic field and converts it back into electrical current to charge the battery. The two induction coils in proximity combine to form an electrical transformer.

Greater distances can be achieved when the inductive charging system uses resonant inductive coupling.

Advantages

Inductive charging carries a far lower risk of electrical shock, when compared with conductive charging, because there are no exposed conductors. The ability to fully enclose the charging connection also makes the approach attractive where water impermeability is required; for instance, inductive charging is used for implanted medical devices that require periodic or even constant external power, and for electric hygiene devices, such as toothbrushes and shavers, that are frequently used near or even in water. Inductive charging makes charging mobile devices and electric vehicles more convenient; rather than having to connect a power cable, the unit can be placed on or close to a charge plate.



Inductive Charging. The primary coil in the charger induces a current in the secondary coil in the device being charged.

Disadvantages

One disadvantage of inductive charging is its lower efficiency and increased resistive heating in comparison to direct contact. Implementations using lower frequencies or older drive technologies charge more slowly and generate heat for most portable electronics; the technology is nonetheless commonly used in some electric toothbrushes and wet/dry electric shavers, partly for the advantage that the battery contacts can be completely sealed to prevent exposure to water. Inductive charging also requires drive electronics and coils that increase manufacturing complexity and cost.

Newer approaches diminish the transfer losses with ultra thin coils, higher frequencies and optimized drive electronics, thus providing chargers and receivers that are compact, more efficient and can be integrated into mobile devices or batteries with minimal change. These technologies provide charging time that are the same as wired approaches and are finding their way into mobile devices rapidly. The Magne Charge system employed high-frequency induction to deliver high power at an efficiency of 86% (6.6 kW power delivery from a 7.68 kW power draw).

Examples

- Transcutaneous energy transfer (TET) systems in artificial hearts and other surgically implanted devices.

- Inductive charging is used in Oral-B rechargeable toothbrushes by the Braun (company) since the early 1990s.

- Hughes Electronics developed the Magne Charge interface for General Motors. The General Motors EV1 electric car was charged by inserting an inductive charging paddle into a receptacle on the vehicle. General Motors and Toyota agreed on this interface and it was also used in the Chevrolet S-10 EV and Toyota RAV4 EV vehicles.

- In 2006, researchers at the Massachusetts Institute of Technology reported that they had discovered an efficient way to transfer power between coils separated by a few meters. The team, led by Marin Soljačić, theorized that they could extend the distance between the coils by adding resonance to the equation. The MIT wireless power project, called WiTricity, uses a curved coil and capacitive plates.

- April 28, 2009: An Energizer inductive charging station for the Wii remote is reported on IGN.

- At CES in January 2009, Palm, Inc. announced their new Pre smartphone would be available with an optional inductive charger accessory, the "Touchstone". The charger came with a required special backplate that became standard on the subsequent Pre Plus model announced at CES 2010.

- In August 2009 A consortium of interested companies called the Wireless Power Consortium announced they were nearing completion for a new industry standard for low-power Inductive charging

Electric vehicles

As mentioned above, Magne Charge inductive charging was employed by several of electric vehicles around 1998, but was discontinued after the California Air Resources Board selected the SAE J1772-2001, or "Avcon", conductive charging interface for electric vehicles in California in June 2001.

In 2009, Evatran, a subsidiary of MTC Transformers, formally began development of Plugless Power, an inductive charging system they claim is the world's first hands-free, plugless, proximity charging system for Electric Vehicles. With the participation of the local municipality and several businesses, field trials were begun in March, 2010, on the system scheduled to be available in fourth quarter 2010.

Researchers at the Korea Advanced Institute of Science and Technology (KAIST) have developed an electric transport system (called Online Electric Vehicle, OLEV) where the vehicles get their power needs from cables underneath the surface of the road via non-contact magnetic charging, (where a power source is placed underneath the road surface and power is wirelessly picked up on the vehicle itself. As a possible solution to traffic congestion and to improve overall efficiency by minimizing air resistance and so reduce energy consumption, the test vehicles followed the power track in a convoy formation. In July 2009 the researchers successfully supplied up to 60% power to a bus over a gap of 12 cm.

In one inductive charging system, one winding is attached to the underside of the car, and the other stays on the floor of the garage.

The major advantage of the inductive approach for vehicle charging is that there is no possibility of electric shock as there are no exposed conductors, although interlocks, special connectors and RCDs (ground fault detectors) can make conductive coupling nearly as safe. An inductive charging proponent from Toyota contended in 1998 that overall cost differences were minimal, while a conductive charging proponent from Ford contended that conductive charging was more cost efficient.

In 2010 onwards, car makers are signaling their interest in wireless charging as another piece of the digital cockpit. A group was launched in May 2010 by the Consumer Electronics Association to set a baseline for interoperability for chargers. In one sign of the road ahead a General Motors executive is chairing the standards effort group. Toyota and Ford managers said they also are interested in the technology and the standards effort.

Chapter- 7

Electromagnetic Radiation

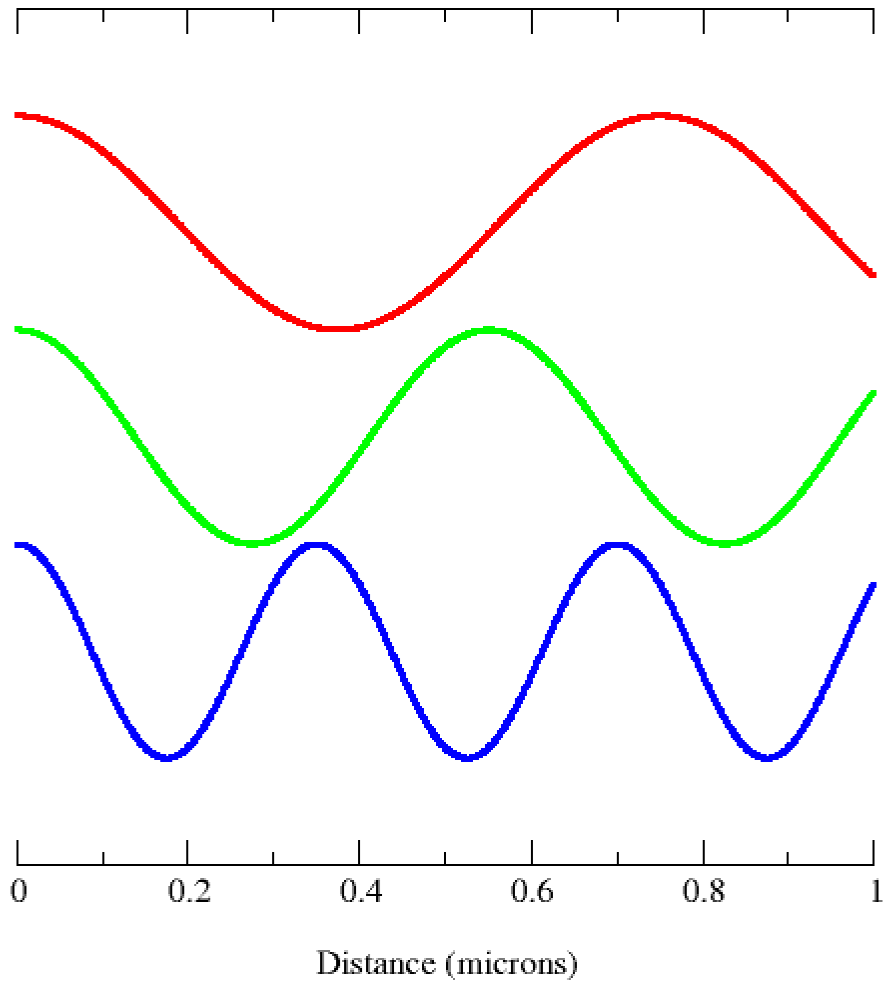
Electromagnetic radiation (often abbreviated **E-M radiation** or **EMR**) is a form of energy exhibiting wave like behavior as it travels through space. EMR has both electric and magnetic field components, which oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation.

Electromagnetic radiation is classified according to the frequency of its wave. In order of increasing frequency and decreasing wavelength, these are radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. The eyes of various organisms sense a small and somewhat variable window of frequencies called the visible spectrum. The photon is the quantum of the electromagnetic interaction and the basic "unit" of light and all other forms of electromagnetic radiation and is also the force carrier for the electromagnetic force.

EM radiation carries energy and momentum that may be imparted to matter with which it interacts.

Physics

Theory



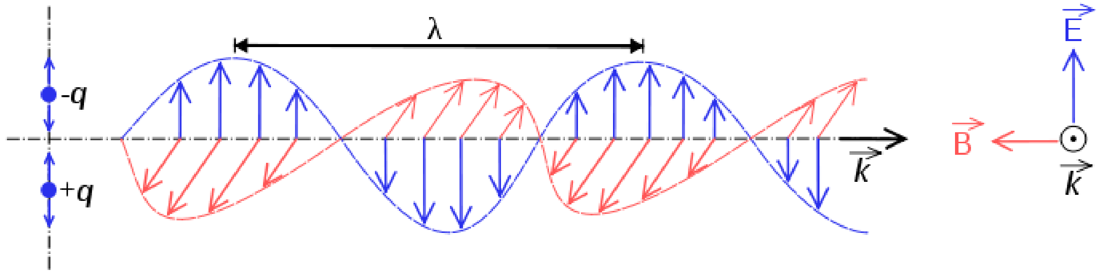
Shows three electromagnetic modes (blue, green and red) with a distance scale in micrometres along the x-axis.

James Clerk Maxwell first formally-postulated **Electromagnetic waves**. These were subsequently confirmed by Heinrich Hertz. Maxwell derived a wave form of the electric and magnetic equations, thus uncovering the wave-like nature of electric and magnetic fields, and their symmetry. Because the speed of EM waves predicted by the wave equation coincided with the measured speed of light, Maxwell concluded that light itself is an EM wave.

According to Maxwell's equations, a time-varying electric field generates a time-varying magnetic field and *vice versa*. Therefore, as an oscillating electric field generates an oscillating magnetic field, the magnetic field in turn generates an oscillating electric field, and so on. These oscillating fields together form a propagating electromagnetic wave.

A quantum theory of the interaction between electromagnetic radiation and matter such as electrons is described by the theory of quantum electrodynamics.

Properties



Electromagnetic waves can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. This diagram shows a plane linearly polarized wave propagating from right to left. The electric field is in a vertical plane and the magnetic field in a horizontal plane.

The physics of electromagnetic radiation is electrodynamics. Electromagnetism is the physical phenomenon associated with the theory of electrodynamics. Electric and magnetic fields obey the properties of superposition. Thus, a field due to any particular particle or time-varying electric or magnetic field contributes to the fields present in the same space due to other causes. Further, as they are vector fields, all magnetic and electric field vectors add together according to vector addition. For example, in optics two or more coherent lightwaves may interact and by constructive or destructive interference yield a resultant irradiance deviating from the sum of the component irradiances of the individual lightwaves.

Since light is an oscillation it is not affected by travelling through static electric or magnetic fields in a linear medium such as a vacuum. However in nonlinear media, such as some crystals, interactions can occur between light and static electric and magnetic fields — these interactions include the Faraday effect and the Kerr effect.

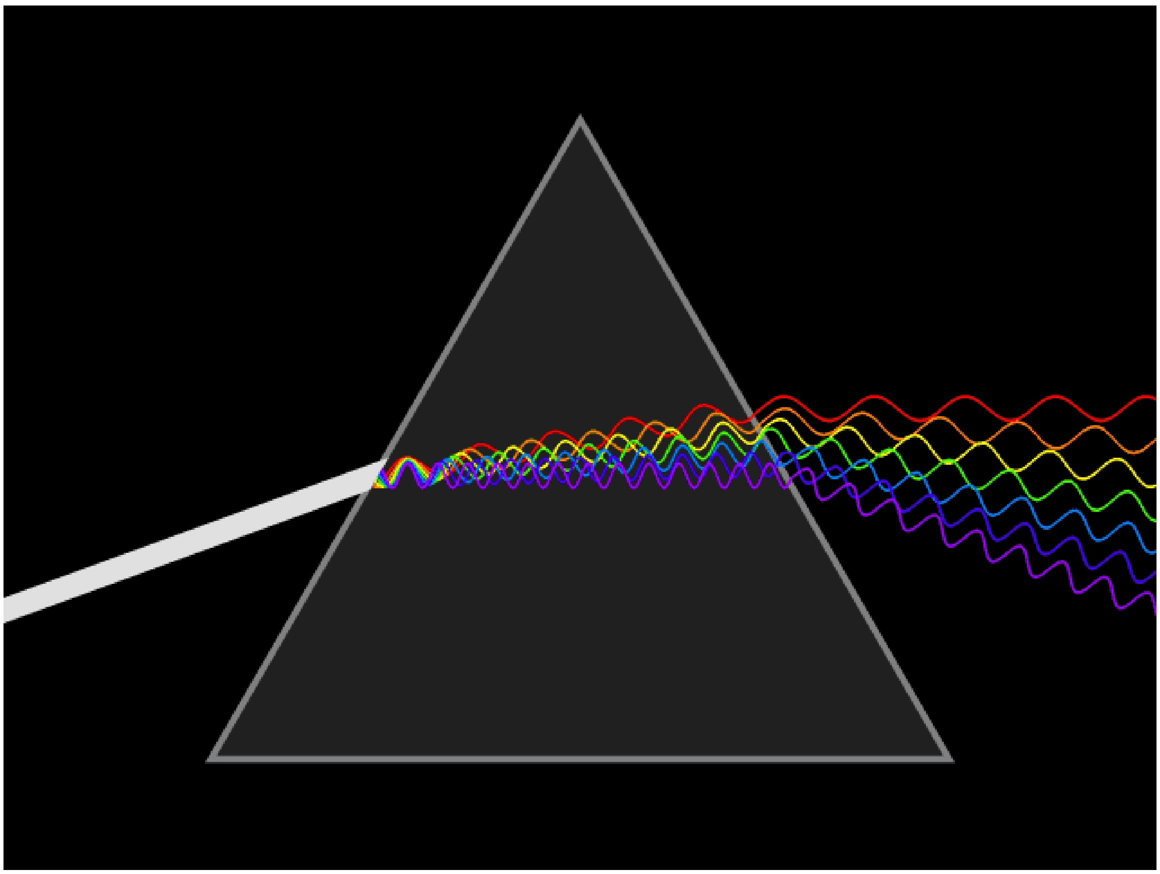
In refraction, a wave crossing from one medium to another of different density alters its speed and direction upon entering the new medium. The ratio of the refractive indices of the media determines the degree of refraction, and is summarized by Snell's law. Light disperses into a visible spectrum as light is shone through a prism because of the wavelength dependent refractive index of the prism material (Dispersion).

EM radiation exhibits both wave properties and particle properties at the same time. Both wave and particle characteristics have been confirmed in a large number of experiments. Wave characteristics are more apparent when EM radiation is measured over relatively large timescales and over large distances while particle characteristics are more evident when measuring small timescales and distances. For example, when electromagnetic radiation is absorbed by matter, particle-like properties will be more obvious when the average number of photons in the cube of the relevant wavelength is much smaller than 1.

Upon absorption of light, it is not too difficult to experimentally observe non-uniform deposition of energy. Strictly speaking, however, this alone is not evidence of "particulate" behavior of light, rather it reflects the quantum nature of *matter*.

There are experiments in which the wave and particle natures of electromagnetic waves appear in the same experiment, such as the self-interference of a single photon. *True* single-photon experiments (in a quantum optical sense) can be done today in undergraduate-level labs. When a single photon is sent through an interferometer, it passes through both paths, interfering with itself, as waves do, yet is detected by a photomultiplier or other sensitive detector only once.

Wave model



White light being separated into its components

Electromagnetic radiation is a transverse wave meaning that the oscillations of the waves are perpendicular to the direction of energy transfer and travel. An important aspect of the nature of light is frequency. The frequency of a wave is its rate of oscillation and is measured in hertz, the SI unit of frequency, where one hertz is equal to one oscillation per second. Light usually has a spectrum of frequencies which sum together to form the resultant wave. Different frequencies undergo different angles of refraction.

A wave consists of successive troughs and crests, and the distance between two adjacent crests or troughs is called the wavelength. Waves of the electromagnetic spectrum vary in size, from very long radio waves the size of buildings to very short gamma rays smaller than atom nuclei. Frequency is inversely proportional to wavelength, according to the equation:

$$v = f\lambda$$

where v is the speed of the wave (c in a vacuum, or less in other media), f is the frequency and λ is the wavelength. As waves cross boundaries between different media, their speeds change but their frequencies remain constant.

Interference is the superposition of two or more waves resulting in a new wave pattern. If the fields have components in the same direction, they constructively interfere, while opposite directions cause destructive interference.

The energy in electromagnetic waves is sometimes called radiant energy.

Particle model

Because energy of an EM interaction is quantized, in the particle model of EM radiation, emissions and absorptions are discrete packets of energy, or quanta, called photons. Because photons are emitted and absorbed by charged particles, they act as transporters of energy, and are associated with waves with frequency proportional to the energy carried. The energy per photon can be related to the frequency via the Planck–Einstein equation:

$$E = hf$$

where E is the energy, h is Planck's constant, and f is frequency. The energy is commonly expressed in the unit of electronvolt (eV). This photon-energy expression is a particular case of the energy levels of the more general *electromagnetic oscillator*, whose average energy, which is used to obtain Planck's radiation law, can be shown to differ sharply from that predicted by the equipartition principle at low temperature, thereby establishes a failure of equipartition due to quantum effects at low temperature.

As a photon is absorbed by an atom, it excites the atom, elevating an electron to a higher energy level. If the energy is great enough, so that the electron jumps to a high enough energy level, it may escape the positive pull of the nucleus and be liberated from the atom in a process called photoionisation. Conversely, an electron that descends to a lower energy level in an atom emits a photon of light equal to the energy difference. Since the energy levels of electrons in atoms are discrete, each element emits and absorbs its own characteristic frequencies.

Together, these effects explain the emission and absorption spectra of light. The dark bands in the absorption spectrum are due to the atoms in the intervening medium absorbing different frequencies of the light. The composition of the medium through which the light travels determines the nature of the absorption spectrum. For instance, dark bands in the light emitted by a distant star are due to the atoms in the star's atmosphere. These bands correspond to the allowed energy levels in the atoms. A similar phenomenon occurs for emission. As the electrons descend to lower energy levels, a spectrum is emitted that represents the jumps between the energy levels of the electrons. This is manifested in the emission spectrum of nebulae. Today, scientists use this phenomenon to observe what elements a certain star is composed of. It is also used in the determination of the distance of a star, using the red shift.

Speed of propagation

Any electric charge which accelerates, or any changing magnetic field, produces electromagnetic radiation. Electromagnetic information about the charge travels at the speed of light. Accurate treatment thus incorporates a concept known as retarded time (as opposed to advanced time, which is not physically possible in light of causality), which adds to the expressions for the electrodynamic electric field and magnetic field. These extra terms are responsible for electromagnetic radiation. When any wire (or other conducting object such as an antenna) conducts alternating current, electromagnetic radiation is propagated at the same frequency as the electric current. At the quantum level, electromagnetic radiation is produced when the wavepacket of a charged particle oscillates or otherwise accelerates. Charged particles in a stationary state do not move, but a superposition of such states may result in oscillation, which is responsible for the phenomenon of radiative transition between quantum states of a charged particle.

Depending on the circumstances, electromagnetic radiation may behave as a wave or as particles. As a wave, it is characterized by a velocity (the speed of light), wavelength, and frequency. When considered as particles, they are known as photons, and each has an energy related to the frequency of the wave given by Planck's relation $E = h\nu$, where E is the energy of the photon, $h = 6.626 \times 10^{-34}$ J·s is Planck's constant, and ν is the frequency of the wave.

One rule is always obeyed regardless of the circumstances: EM radiation in a vacuum always travels at the speed of light, *relative to the observer*, regardless of the observer's velocity. (This observation led to Albert Einstein's development of the theory of special relativity.)

In a medium (other than vacuum), velocity factor or refractive index are considered, depending on frequency and application. Both of these are ratios of the speed in a medium to speed in a vacuum.

Thermal radiation and electromagnetic radiation as a form of heat

The basic structure of matter involves charged particles bound together in many different ways. When electromagnetic radiation is incident on matter, it causes the charged particles to oscillate and gain energy. The ultimate fate of this energy depends on the situation. It could be immediately re-radiated and appear as scattered, reflected, or transmitted radiation. It may also get dissipated into other microscopic motions within the matter, coming to thermal equilibrium and manifesting itself as thermal energy in the material. With a few exceptions such as fluorescence, harmonic generation, photochemical reactions and the photovoltaic effect, absorbed electromagnetic radiation simply deposits its energy by heating the material. This happens both for infrared and non-infrared radiation. Intense radio waves can thermally burn living tissue and can cook food. In addition to infrared lasers, sufficiently intense visible and ultraviolet lasers can also easily set paper afire. Ionizing electromagnetic radiation can create high-speed electrons in a material and break chemical bonds, but after these electrons collide many times with other atoms in the material eventually most of the energy gets downgraded to thermal energy, this whole process happening in a tiny fraction of a second. That infrared radiation is a form of heat and other electromagnetic radiation is not, is a widespread misconception in physics. *Any* electromagnetic radiation can heat a material when it is absorbed.

The inverse or time-reversed process of absorption is responsible for thermal radiation. Much of the thermal energy in matter consists of random motion of charged particles, and this energy can be radiated away from the matter. The resulting radiation may subsequently be absorbed by another piece of matter, with the deposited energy heating the material. Radiation is an important mechanism of heat transfer.

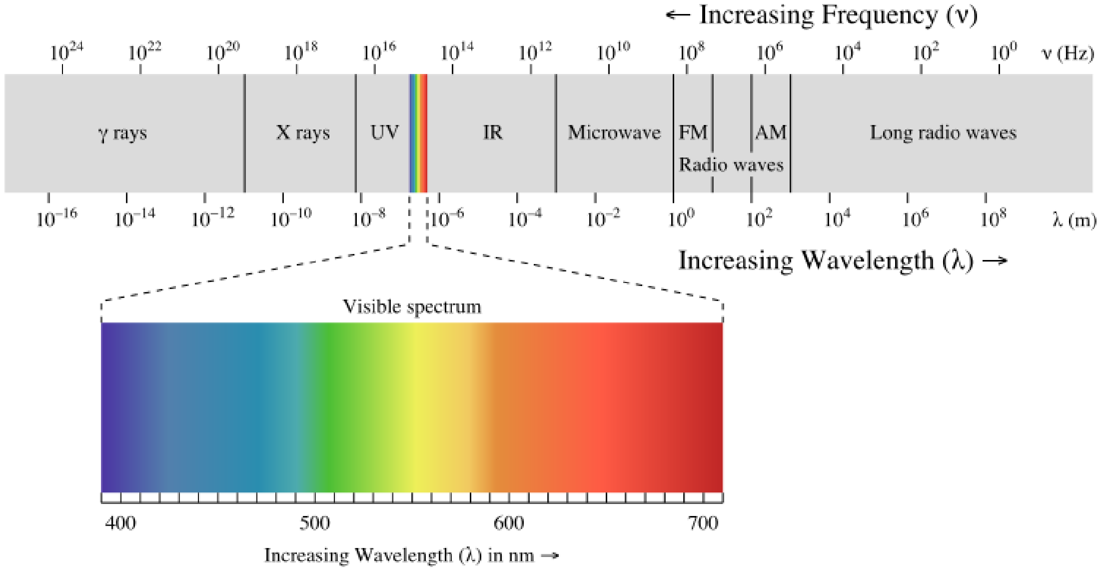
The electromagnetic radiation in an opaque cavity at thermal equilibrium is effectively a form of thermal energy, having maximum radiation entropy. The thermodynamic potentials of electromagnetic radiation can be well-defined as for matter. Thermal radiation in a cavity has energy density of

$$\frac{U}{V} = \frac{8\pi^5(kT)^4}{15(hc)^3},$$

Differentiating the above with respect to temperature, we may say that the electromagnetic radiation field has an effective volumetric heat capacity given by

$$\frac{32\pi^5 k^4 T^3}{15(hc)^3},$$

Electromagnetic spectrum



Electromagnetic spectrum with light highlighted

CLASS	FREQUENCY	WAVELENGTH	ENERGY
Y	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
	3 EHz	100 pm	12.4 keV
SX	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 μm	1.24 eV
MIR	30 THz	10 μm	124 meV
FIR	3 THz	100 μm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 μeV
UHF	3 GHz	1 dm	12.4 μeV
VHF	300 MHz	1 m	1.24 μeV
HF	30 MHz	10 m	124 neV
MF	3 MHz	100 m	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF/ULF	3 kHz	100 km	12.4 peV
SLF	300 Hz	1 Mm	1.24 peV
ELF	30 Hz	10 Mm	124 feV
	3 Hz	100 Mm	12.4 feV

Legend:
γ = Gamma rays
HX = Hard X-rays
SX = Soft X-Rays
EUV = Extreme ultraviolet
NUV = Near ultraviolet
Visible light
NIR = Near infrared
MIR = Moderate infrared
FIR = Far infrared

Radio waves:
EHF = Extremely high frequency (Microwaves)
SHF = Super high frequency (Microwaves)
UHF = Ultrahigh frequency
VHF = Very high frequency
HF = High frequency
MF = Medium frequency
LF = Low frequency
VLF = Very low frequency
VF = Voice frequency
ULF = Ultra low frequency
SLF = Super low frequency
ELF = Extremely low frequency

Generally, EM radiation (the designation 'radiation' excludes static electric and magnetic and near fields) is classified by wavelength into radio, microwave, infrared, the visible region we perceive as light, ultraviolet, X-rays and gamma rays. Arbitrary electromagnetic waves can always be expressed by Fourier analysis in terms of sinusoidal monochromatic waves which can be classified into these regions of the spectrum.

The behavior of EM radiation depends on its wavelength. Higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths. When EM radiation interacts with single atoms and molecules, its behavior depends on the amount of energy per quantum it carries. Spectroscopy can detect a much wider region of the EM spectrum than the visible range of 400 nm to 700 nm. A common laboratory spectroscope can detect wavelengths from 2 nm to 2500 nm. Detailed information about the physical properties of objects, gases, or even stars can be obtained from this type of device. It is widely used in astrophysics. For example, hydrogen atoms emit radio waves of wavelength 21.12 cm.

Soundwaves are not electromagnetic radiation. At the lower end of the electromagnetic spectrum, about 20 Hz to about 20 kHz, are frequencies that might be considered in the audio range. However, electromagnetic waves cannot be directly perceived by human ears. Sound waves are the oscillating compression of molecules. To be heard, electromagnetic radiation must be converted to air pressure waves, or if the ear is submerged, water pressure waves.

Light

EM radiation with a wavelength between approximately 400 nm and 700 nm is directly detected by the human eye and perceived as visible light. Other wavelengths, especially nearby infrared (longer than 700 nm) and ultraviolet (shorter than 400 nm) are also sometimes referred to as light, especially when visibility to humans is not relevant.

If radiation having a frequency in the visible region of the EM spectrum reflects off of an object, say, a bowl of fruit, and then strikes our eyes, this results in our visual perception of the scene. Our brain's visual system processes the multitude of reflected frequencies into different shades and hues, and through this not-entirely-understood psychophysical phenomenon, most people perceive a bowl of fruit.

At most wavelengths, however, the information carried by electromagnetic radiation is not directly detected by human senses. Natural sources produce EM radiation across the spectrum, and our technology can also manipulate a broad range of wavelengths. Optical fiber transmits light which, although not suitable for direct viewing, can carry data that can be translated into sound or an image. To be meaningful both transmitter and receiver must use some agreed-upon encoding system - especially so if the transmission is digital as opposed to the analog nature of the waves.

Radio waves

Radio waves can be made to carry information by varying a combination of the amplitude, frequency and phase of the wave within a frequency band.

When EM radiation impinges upon a conductor, it couples to the conductor, travels along it, and induces an electric current on the surface of that conductor by exciting the electrons of the conducting material. This effect (the skin effect) is used in antennas. EM radiation may also cause certain molecules to absorb energy and thus to heat up; this is exploited in microwave ovens. Radio waves are *not* ionizing radiation, as the energy per photon is too small.

Derivation

Electromagnetic waves as a general phenomenon were predicted by the classical laws of electricity and magnetism, known as Maxwell's equations. If you inspect Maxwell's equations without sources (charges or currents) then you will find that, along with the possibility of nothing happening, the theory will also admit nontrivial solutions of changing electric and magnetic fields. Beginning with Maxwell's equations in free space:

$$\nabla \cdot \mathbf{E} = 0 \qquad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (2)$$
$$\nabla \cdot \mathbf{B} = 0 \qquad (3)$$
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \qquad (4)$$

where
∇ is a vector differential operator.

One solution,

$$\mathbf{E} = \mathbf{B} = \mathbf{0},$$

is trivial.

To see the more interesting one, we utilize vector identities, which work for any vector, as follows:

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla (\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

To see how we can use this, take the curl of equation (2):

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla \times \left(-\frac{\partial \mathbf{B}}{\partial t} \right) \qquad (5)$$

Evaluating the left hand side:

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla (\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = -\nabla^2 \mathbf{E} \qquad (6)$$

where we simplified the above by using equation (1).

Evaluate the right hand side:

$$\nabla \times \left(-\frac{\partial \mathbf{B}}{\partial t} \right) = -\frac{\partial}{\partial t} (\nabla \times \mathbf{B}) = -\mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (7)$$

Equations (6) and (7) are equal, so this results in a vector-valued differential equation for the electric field, namely

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

Applying a similar pattern results in similar differential equation for the magnetic field:

$$\nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2}.$$

These differential equations are equivalent to the wave equation:

$$\nabla^2 f = \frac{1}{{c_0}^2} \frac{\partial^2 f}{\partial t^2}$$

where
c_0 is the speed of the wave in free space and
f describes a displacement

Or more simply:

$$\Box f = 0$$

where $\Box$ is d'Alembertian:

$$\Box = \nabla^2 - \frac{1}{{c_0}^2}\frac{\partial^2}{\partial t^2} = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{{c_0}^2}\frac{\partial^2}{\partial t^2}$$

Notice that in the case of the electric and magnetic fields, the speed is:

$$c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

Which, as it turns out, is the speed of light in vacuum. Maxwell's equations have unified the vacuum permittivity ε_0, the vacuum permeability μ_0, and the speed of light itself, c_0. Before this derivation it was not known that there was such a strong relationship between light and electricity and magnetism.

But these are only two equations and we started with four, so there is still more information pertaining to these waves hidden within Maxwell's equations. Let's consider a generic vector wave for the electric field.

$$\mathbf{E} = \mathbf{E}_0 f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right)$$

Here $\mathbf{E}_0$ is the constant amplitude, f is any second differentiable function, $\hat{\mathbf{k}}$ is a unit vector in the direction of propagation, and $\mathbf{x}$ is a position vector. We observe that $f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right)$ is a generic solution to the wave equation. In other words

$$\nabla^2 f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = \frac{1}{{c_0}^2}\frac{\partial^2}{\partial t^2} f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right),$$

for a generic wave traveling in the $\hat{\mathbf{k}}$direction.

This form will satisfy the wave equation, but will it satisfy all of Maxwell's equations, and with what corresponding magnetic field?

$$\nabla \cdot \mathbf{E} = \hat{\mathbf{k}} \cdot \mathbf{E}_0 f'\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = 0$$
$$\mathbf{E} \cdot \hat{\mathbf{k}} = 0$$

The first of Maxwell's equations implies that electric field is orthogonal to the direction the wave propagates.

$$\nabla \times \mathbf{E} = \hat{\mathbf{k}} \times \mathbf{E}_0 f'\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\mathbf{B} = \frac{1}{c_0}\hat{\mathbf{k}} \times \mathbf{E}$$

The second of Maxwell's equations yields the magnetic field. The remaining equations will be satisfied by this choice of $\mathbf{E}, \mathbf{B}$.

Not only are the electric and magnetic field waves traveling at the speed of light, but they have a special restricted orientation and proportional magnitudes, $E_0 = c_0 B_0$, which can be seen immediately from the Poynting vector. The electric field, magnetic field, and direction of wave propagation are all orthogonal, and the wave propagates in the same direction as $\mathbf{E} \times \mathbf{B}$.

From the viewpoint of an electromagnetic wave traveling forward, the electric field might be oscillating up and down, while the magnetic field oscillates right and left; but this picture can be rotated with the electric field oscillating right and left and the magnetic field oscillating down and up. This is a different solution that is traveling in the same direction. This arbitrariness in the orientation with respect to propagation direction is known as polarization. On a quantum level, it is described as photon polarization.

More general forms of the second order wave equations given above are available, allowing for both non-vacuum propagation media and sources. A great many competing derivations exist, all with varying levels of approximation and intended applications. One very general example is a form of the electric field equation, which was factorized into a pair of explicitly directional wave equations, and then efficiently reduced into a single uni-directional wave equation by means of a simple slow-evolution approximation.

Chapter- 8

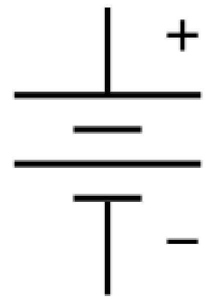
Battery

Various cells and batteries (top-left to bottom-right): two AA, one D, one handheld ham radio battery, two 9-volt (PP3), two AAA, one C, one camcorder battery, one cordless phone battery.

An electrical **battery** is one or more electrochemical cells that convert stored chemical energy into electrical energy. Since the invention of the first battery (or "voltaic pile") in 1800 by Alessandro Volta, batteries have become a common power source for many household and industrial applications. According to a 2005 estimate, the worldwide battery industry generates US$48 billion in sales each year, with 6% annual growth.

There are two types of batteries: primary batteries (disposable batteries), which are designed to be used once and discarded, and secondary batteries (rechargeable batteries), which are designed to be recharged and used multiple times. Miniature cells are used to power devices such as hearing aids and wristwatches; larger batteries provide standby power for telephone exchanges or computer data centers.

History



The symbol for a battery in a circuit diagram. It originated as a schematic drawing of the earliest type of battery, a voltaic pile.

Strictly, a battery is a collection of multiple electrochemical cells, but in popular usage *battery* often refers to a single cell. The first electrochemical cell was developed by the Italian physicist Alessandro Volta in 1792, and in 1800 he invented the first battery—for him, a "pile" of cells.

The usage of "battery" to describe electrical devices dates to Benjamin Franklin, who in 1748 described multiple Leyden jars (early electrical capacitors) by analogy to a battery of cannons. Thus Franklin's usage to describe multiple Leyden jars predated Volta's use of multiple galvanic cells. It is speculated, but not established, that several ancient artifacts consisting of copper sheets and iron bars, and known as Baghdad batteries may have been galvanic cells.

Volta's work was stimulated by the Italian anatomist and physiologist Luigi Galvani, who in 1780 noticed that dissected frog's legs would twitch when struck by a spark from a Leyden jar, an external source of electricity. In 1786 he noticed that twitching would occur during lightning storms. After many years Galvani learned how to produce twitching without using any external source of electricity. In 1791 he published a report on "animal electricity." He created an electric circuit consisting of the frog's leg (FL) and two different metals A and B, each metal touching the frog's leg and each other, thus producing the circuit A-FL-B-A-FL-B...etc. In modern terms, the frog's leg served as both the electrolyte and the sensor, and the metals served as electrodes. He noticed that even though the frog was dead, its legs would twitch when he touched them with the metals.

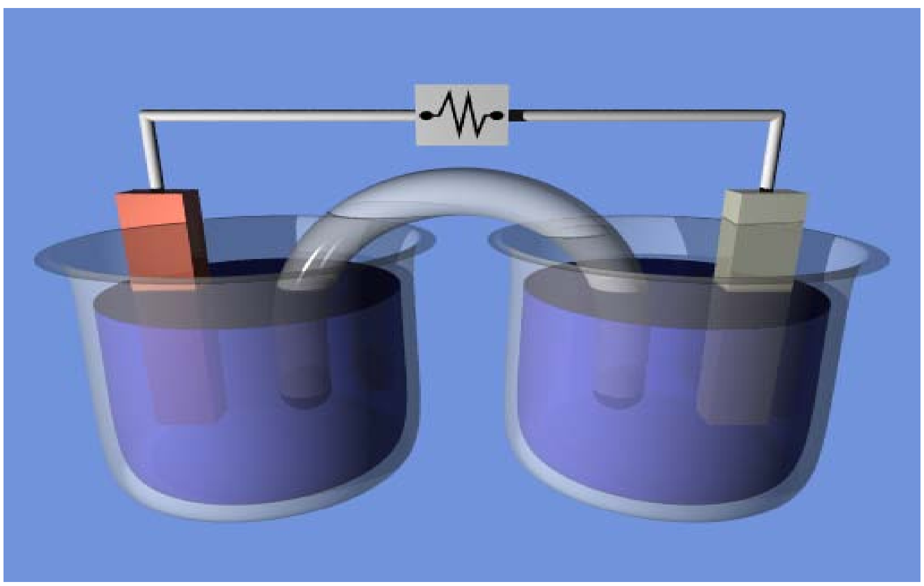
Within a year, Volta realized the frog's moist tissues could be replaced by cardboard soaked in salt water, and the frog's muscular response could be replaced by another form of electrical detection. He already had studied the electrostatic phenomenon of capacitance, which required measurements of electric charge and of electrical potential ("tension"). Building on this experience, Volta was able to detect electric current through his system, also called a Galvanic cell. The terminal voltage of a cell that is not discharging is called its electromotive force (emf), and has the same unit as electrical potential, named (voltage) and measured in volts, in honor of Volta. In 1800, Volta invented the battery by placing many voltaic cells in series, literally piling them one above the other. This voltaic pile gave a greatly enhanced net emf for the combination, with a voltage of about 50 volts for a 32-cell pile. In many parts of Europe batteries continue to be called piles.

Volta did not appreciate that the voltage was due to chemical reactions. He thought that his cells were an inexhaustible source of energy, and that the associated chemical effects at the electrodes (e.g. corrosion) were a mere nuisance, rather than an unavoidable consequence of their operation, as Michael Faraday showed in 1834. According to Faraday, cations (positively charged ions) are attracted to the cathode, and anions (negatively charged ions) are attracted to the anode.

Although early batteries were of great value for experimental purposes, in practice their voltages fluctuated and they could not provide a large current for a sustained period. Later, starting with the Daniell cell in 1836, batteries provided more reliable currents and were adopted by industry for use in stationary devices, particularly in telegraph networks where they were the only practical source of electricity, since electrical distribution networks did not exist at the time. These wet cells used liquid electrolytes, which were prone to leakage and spillage if not handled correctly. Many used glass jars to hold their components, which made them fragile. These characteristics made wet cells unsuitable for portable appliances. Near the end of the nineteenth century, the invention of dry cell batteries, which replaced the liquid electrolyte with a paste, made portable electrical devices practical.

Since then, batteries have gained popularity as they became portable and useful for a variety of purposes.

Principle of operation



A voltaic cell for demonstration purposes. In this example the two half-cells are linked by a salt bridge separator that permits the transfer of ions, but not water molecules.

A battery is a device that converts chemical energy directly to electrical energy. It consists of a number of voltaic cells; each voltaic cell consists of two half cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the electrode to which anions (negatively charged ions) migrate, i.e., the anode or negative electrode; the other half-cell includes electrolyte and the electrode to which cations (positively charged ions) migrate, i.e., the cathode or positive electrode. In the redox reaction that powers the battery, reduction (addition of electrons) occurs to cations at the cathode, while oxidation (removal of electrons) occurs to anions at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Some cells use two half-cells with different electrolytes. A separator between half cells allows ions to flow, but prevents mixing of the electrolytes.

Each half cell has an electromotive force (or emf), determined by its ability to drive electric current from the interior to the exterior of the cell. The net emf of the cell is the difference between the emfs of its half-cells, as first recognized by Volta. Therefore, if the electrodes have emfs $\mathcal{E}_1$and $\mathcal{E}_2$, then the net emf is $\mathcal{E}_2 - \mathcal{E}_1$; in other words, the net emf is the difference between the reduction potentials of the half-reactions.

The electrical driving force or ΔV_{bat}across the terminals of a cell is known as the *terminal voltage (difference)* and is measured in volts. The terminal voltage of a cell that is neither charging nor discharging is called the open-circuit voltage and equals the emf of the cell. Because of internal resistance, the terminal voltage of a cell that is discharging is smaller in magnitude than the open-circuit voltage and the terminal voltage of a cell that is charging exceeds the open-circuit voltage. An ideal cell has negligible internal resistance, so it would maintain a constant terminal voltage of $\mathcal{E}$until exhausted, then dropping to zero. If such a cell maintained 1.5 volts and stored a charge of one coulomb then on complete discharge it would perform 1.5 joule of work. In actual cells, the internal resistance increases under discharge, and the open circuit voltage also decreases under discharge. If the voltage and resistance are plotted against time, the resulting graphs typically are a curve; the shape of the curve varies according to the chemistry and internal arrangement employed.

As stated above, the voltage developed across a cell's terminals depends on the energy release of the chemical reactions of its electrodes and electrolyte. Alkaline and carbon-zinc cells have different chemistries but approximately the same emf of 1.5 volts; likewise NiCd and NiMH cells have different chemistries, but approximately the same emf of 1.2 volts. On the other hand the high electrochemical potential changes in the reactions of lithium compounds give lithium cells emfs of 3 volts or more.

Categories and types of batteries

From top to bottom: SR41/AG3, SR44/AG13 (button cells), a 9-volt *PP3 battery*, an *AAA cell*, an *AA cell*, a *C cell*, a *D Cell*, and a large *3R12*. The ruler's unit is in centimeters.

Batteries are classified into two broad categories, each type with advantages and disadvantages.

- *Primary* batteries irreversibly (within limits of practicality) transform chemical energy to electrical energy. When the initial supply of reactants is exhausted, energy cannot be readily restored to the battery by electrical means.
- *Secondary* batteries can be recharged; that is, they can have their chemical reactions reversed by supplying electrical energy to the cell, restoring their original composition.

Historically, some types of primary batteries used, for example, for telegraph circuits, were restored to operation by replacing the components of the battery consumed by the chemical reaction. Secondary batteries are not indefinitely rechargeable due to dissipation of the active materials, loss of electrolyte and internal corrosion.

Primary batteries

Primary batteries can produce current immediately on assembly. Disposable batteries are intended to be used once and discarded. These are most commonly used in portable devices that have low current drain, are only used intermittently, or are used well away from an alternative power source, such as in alarm and communication circuits where other electric power is only intermittently available. Disposable primary cells cannot be reliably recharged, since the chemical reactions are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against attempting to recharge primary cells.

Common types of disposable batteries include zinc-carbon batteries and alkaline batteries. Generally, these have higher energy densities than rechargeable batteries, but disposable batteries do not fare well under high-drain applications with loads under 75 ohms (75 Ω).

Secondary batteries

Secondary batteries must be charged before use; they are usually assembled with active materials in the discharged state. Rechargeable batteries or *secondary cells* can be recharged by applying electric current, which reverses the chemical reactions that occur during its use. Devices to supply the appropriate current are called chargers or rechargers.

The oldest form of rechargeable battery is the lead-acid battery. This battery is notable in that it contains a liquid in an unsealed container, requiring that the battery be kept upright and the area be well ventilated to ensure safe dispersal of the hydrogen gas produced by these batteries during overcharging. The lead-acid battery is also very heavy for the amount of electrical energy it can supply. Despite this, its low manufacturing cost and its high surge current levels make its use common where a large capacity (over approximately 10Ah) is required or where the weight and ease of handling are not concerns.

A common form of the lead-acid battery is the modern car battery, which can generally deliver a peak current of 450 amperes. An improved type of liquid electrolyte battery is the sealed valve regulated lead acid (VRLA) battery, popular in the automotive industry as a replacement for the lead-acid wet cell. The VRLA battery uses an immobilized sulfuric acid electrolyte, reducing the chance of leakage and extending shelf life. VRLA batteries have the electrolyte immobilized, usually by one of two means:

- *Gel batteries* (or "gel cell") contain a semi-solid electrolyte to prevent spillage.

- *Absorbed Glass Mat* (AGM) batteries absorb the electrolyte in a special fiberglass matting.

Other portable rechargeable batteries include several "dry cell" types, which are sealed units and are therefore useful in appliances such as mobile phones and laptop computers. Cells of this type (in order of increasing power density and cost) include nickel-cadmium (NiCd), nickel-zinc (NiZn), nickel metal hydride (NiMH) and lithium-ion (Li-ion) cells. By far, Li-ion has the highest share of the dry cell rechargeable market. Meanwhile, NiMH has replaced NiCd in most applications due to its higher capacity, but NiCd remains in use in power tools, two-way radios, and medical equipment. NiZn is a new technology that is not yet well established commercially.

Recent developments include batteries with embedded functionality such as USBCELL, with a built-in charger and USB connector within the AA format, enabling the battery to be charged by plugging into a USB port without a charger, and low self-discharge (LSD) mix chemistries such as Hybrio, ReCyko, and Eneloop, where cells are precharged prior to shipping.

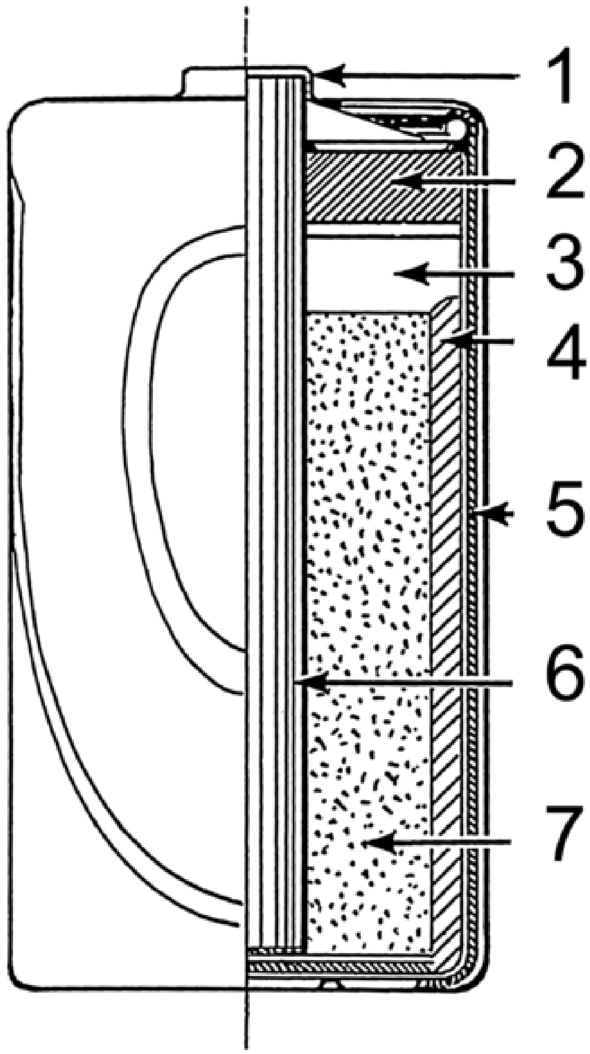
Battery cell types

There are many general types of electrochemical cells, according to chemical processes applied and design chosen. The variation includes galvanic cells, electrolytic cells, fuel cells, flow cells and voltaic piles.

Wet cell

A *wet cell* battery has a liquid electrolyte. Other names are *flooded cell* since the liquid covers all internal parts, or *vented cell* since gases produced during operation can escape to the air. Wet cells were a precursor to dry cells and are commonly used as a learning tool for electrochemistry. It is often built with common laboratory supplies, like beakers, for demonstrations of how electrochemical cells work. A particular type of wet cell known as a concentration cell is important in understanding corrosion. Wet cells may be primary cells (non-rechargeable) or secondary cells (rechargeable). Originally all practical primary batteries such as the Daniell cell were built as open-topped glass jar wet cells. Other primary wet cells are the Leclanche cell, Grove cell, Bunsen cell, Chromic acid cell, Clark cell and Weston cell. The Leclanche cell chemistry was adapted to the first dry cells. Wet cells are still used in automobile batteries and in industry for standby power for switchgear, telecommunication or large uninterruptible power supplies, but in many places batteries with gel cells have been used instead. These applications commonly use lead-acid or nickel-cadmium cells.

Dry cell



Line art drawing of a dry cell:
1. brass cap, 2. plastic seal, 3. expansion space, 4. porous cardboard, 5. zinc can, 6. carbon rod, 7. chemical mixture.

A *dry cell* has the electrolyte immobilized as a paste, with only enough moisture in the paste to allow current to flow. As opposed to a wet cell, the battery can be operated in any random position, and will not spill its electrolyte if inverted.

While a dry cell's electrolyte is not truly completely free of moisture and must contain some moisture to function, it has the advantage of containing no sloshing liquid that might leak or drip out when inverted or handled roughly, making it highly suitable for small portable electric devices. By comparison, the first wet cells were typically fragile glass containers with lead rods hanging from the open top, and needed careful handling to avoid spillage. An inverted wet cell would leak, while a dry cell would not. Lead-acid batteries would not achieve the safety and portability of the dry cell until the development of the gel battery.

A common dry cell battery is the zinc-carbon battery, using a cell sometimes called the dry Leclanché cell, with a nominal voltage of 1.5 volts, the same nominal voltage as the alkaline battery (since both use the same zinc-manganese dioxide combination).

The makeup of a standard dry cell is a zinc anode (negative pole), usually in the form of a cylindrical pot, with a carbon cathode (positive pole) in the form of a central rod. The electrolyte is ammonium chloride in the form of a paste next to the zinc anode. The remaining space between the electrolyte and carbon cathode is taken up by a second paste consisting of ammonium chloride and manganese dioxide, the latter acting as a depolariser. In some more modern types of so called 'high power' batteries, the ammonium chloride has been replaced by zinc chloride.

Molten salt

A molten salt battery is a primary or secondary battery that uses a molten salt as its electrolyte. Their energy density and power density makes them potentially useful for electric vehicles, but they must be carefully insulated to retain heat.

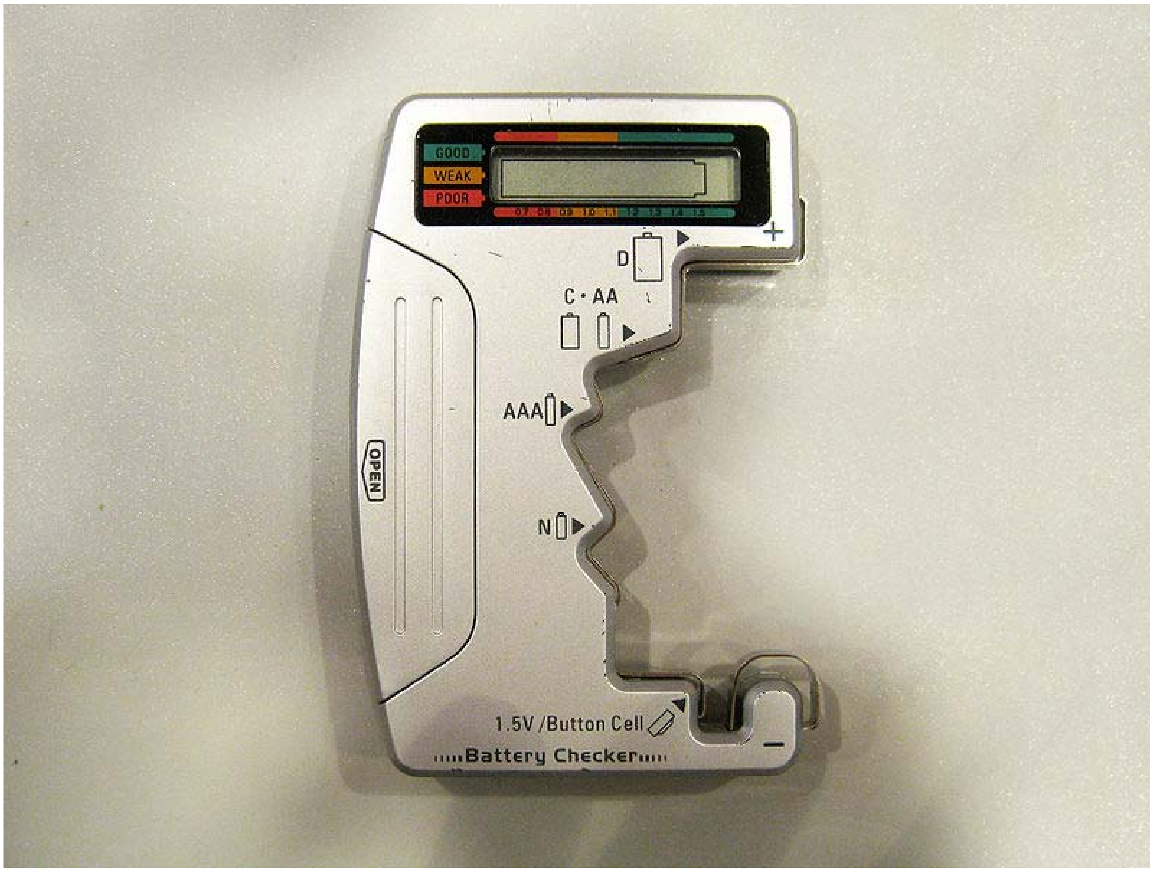
Reserve

A reserve battery can be stored for a long period of time and is activated when its internal parts (usually electrolyte) are assembled. For example, a battery for an electronic fuze might be activated by the impact of firing a gun, breaking a capsule of electrolyte to activate the battery and power the fuze's circuits. Reserve batteries are usually designed for a short service life (seconds or minutes) after long storage (years). A water-activated battery for oceanographic instruments or military applications becomes activated on immersion in water.

Battery cell performance

A battery's characteristics may vary over load cycle, charge cycle and over lifetime due to many factors including internal chemistry, current drain and temperature.

Battery capacity and discharging



A device to check battery voltage

The more electrolyte and electrode material there is in the cell, the greater the capacity of the cell. Thus a small cell has less capacity than a larger cell, given the same chemistry (e.g. alkaline cells), though they develop the same open-circuit voltage.

Because of the chemical reactions within the cells, the capacity of a battery depends on the discharge conditions such as the magnitude of the current (which may vary with time), the allowable terminal voltage of the battery, temperature and other factors. The available capacity of a battery depends upon the rate at which it is discharged. If a battery is discharged at a relatively high rate, the available capacity will be lower than expected.

The battery capacity that battery manufacturers print on a battery is usually the product of 20 hours multiplied by the maximum constant current that a new battery can supply for 20 hours at 68 F° (20 C°), down to a predetermined terminal voltage per cell. A battery rated at 100 A·h will deliver 5 A over a 20 hour period at room temperature. However, if it is instead discharged at 50 A, it will have a lower apparent capacity.

The relationship between current, discharge time, and capacity for a lead acid battery is approximated (over a certain range of current values) by Peukert's law:

$$t = \frac{Q_P}{I^k}$$

where

Q_P is the capacity when discharged at a rate of 1 amp.
I is the current drawn from battery (A).
t is the amount of time (in hours) that a battery can sustain.
k is a constant around 1.3.

For low values of I internal self-discharge must be included.

In practical batteries, internal energy losses, and limited rate of diffusion of ions through the electrolyte, cause the efficiency of a battery to vary at different discharge rates. When discharging at low rate, the battery's energy is delivered more efficiently than at higher discharge rates, but if the rate is too low, it will self-discharge during the long time of operation, again lowering its efficiency.

Installing batteries with different A·h ratings will not affect the operation of a device rated for a specific voltage unless the load limits of the battery are exceeded. High-drain loads like digital cameras can result in lower actual energy, most notably for alkaline batteries. For example, a battery rated at 2000 mA·h would not sustain a current of 1 A for the full two hours, if it had been rated at a 10-hour or 20-hour discharge.

Fastest charging, largest, and lightest batteries

Lithium iron phosphate ($LiFePO_4$) batteries are the fastest charging and discharging, next to supercapacitors. The world's largest battery is in Fairbanks, Alaska, composed of Ni-Cd cells. Sodium-sulfur batteries are being used to store wind power. Lithium-sulfur batteries have been used on the longest and highest solar powered flight. The speed of recharging for lithium-ion batteries may be increased by manipulation.

Battery lifetime

Life of primary batteries

Even if never taken out of the original package, disposable (or "primary") batteries can lose 8 to 20 percent of their original charge every year at a temperature of about 20°–30°C. This is known as the "self discharge" rate and is due to non-current-producing "side" chemical reactions, which occur within the cell even if no load is applied to it. The rate of the side reactions is reduced if the batteries are stored at low temperature, although some batteries can be damaged by freezing. High or low temperatures may reduce battery performance. This will affect the initial voltage of the battery. For an AA alkaline battery this initial voltage is approximately normally distributed around 1.6 volts.

Discharging performance of all batteries drops at low temperature.

Lifespan of rechargeable batteries

Rechargeable batteries

Rechargeable batteries self-discharge more rapidly than disposable alkaline batteries, especially nickel-based batteries; a freshly charged NiCd loses 10% of its charge in the first 24 hours, and thereafter discharges at a rate of about 10% a month. However, modern lithium designs have reduced the self-discharge rate to a relatively low level (but still poorer than for primary batteries). Most nickel-based batteries are partially discharged when purchased, and must be charged before first use.

Although rechargeable batteries have their energy content restored by charging, some deterioration occurs on each charge/discharge cycle. Low-capacity nickel metal hydride (NiMH) batteries (1700-2000 mA·h) can be charged for about 1000 cycles, whereas high capacity NiMH batteries (above 2500 mA·h) can be charged for about 500 cycles. Nickel cadmium (NiCd) batteries tend to be rated for 1,000 cycles before their internal resistance permanently increases beyond usable values. Normally a fast charge, rather than a slow overnight charge, will shorten battery lifespan. However, if the overnight charger is not "smart" and cannot detect when the battery is fully charged, then overcharging is likely, which also damages the battery. Degradation usually occurs because electrolyte migrates away from the electrodes or because active material falls off the electrodes. NiCd batteries suffer the drawback that they should be fully discharged before recharge. Without full discharge, crystals may build up on the electrodes, thus decreasing the active surface area and increasing internal resistance. This decreases battery capacity and causes the "memory effect". These electrode crystals can also penetrate the electrolyte separator, thereby causing shorts. NiMH, although similar in chemistry, does not suffer from memory effect to quite this extent. When a battery reaches the end of its lifetime, it will not suddenly lose all of its capacity; rather, its capacity will gradually decrease.

Automotive lead-acid rechargeable batteries have a much harder life. Because of vibration, shock, heat, cold, and sulfation of their lead plates, few automotive batteries last beyond six years of regular use. Automotive starting batteries have many thin plates to provide as much current as possible in a reasonably small package. In general, the thicker the plates, the longer the life of the battery. Typically they are only drained a small amount before recharge. Care should be taken to avoid deep discharging a starting battery, since each charge and discharge cycle causes active material to be shed from the plates.

"Deep-cycle" lead-acid batteries such as those used in electric golf carts have much thicker plates to aid their longevity. The main benefit of the lead-acid battery is its low cost; the main drawbacks are its large size and weight for a given capacity and voltage. Lead-acid batteries should never be discharged to below 20% of their full capacity, because internal resistance will cause heat and damage when they are recharged. Deep-cycle lead-acid systems often use a low-charge warning light or a low-charge power cut-off switch to prevent the type of damage that will shorten the battery's life.

Extending battery life

Battery life can be extended by storing the batteries at a low temperature, as in a refrigerator or freezer, which slows the chemical reactions in the battery. Such storage can extend the life of alkaline batteries by about 5%, while the charge of rechargeable batteries can be extended from a few days up to several months. To reach their maximum voltage, batteries must be returned to room temperature; discharging an alkaline battery at 250 mAh at 0°C is only half as efficient as it is at 20°C. As a result, alkaline battery manufacturers like Duracell do not recommend refrigerating or freezing batteries.

Prolonging life in multiple cells through cell balancing

Analog front ends that balance cells and eliminate mismatches of cells in series or parallel combination significantly improve battery efficiency and increase the overall pack capacity. As the number of cells and load currents increase, the potential for mismatch also increases. There are two kinds of mismatch in the pack: state-of-charge (SOC) and capacity/energy (C/E) mismatch. Though the SOC mismatch is more common, each problem limits the pack capacity (mAh) to the capacity of the weakest cell.

Cell balancing principle

Battery pack cells are balanced when all the cells in the battery pack meet two conditions:

1. If all cells have the same capacity, then they are balanced when they have the same State of Charge (SOC.) In this case, the Open Circuit Voltage (OCV) is a good measure of the SOC. If, in an out of balance pack, all cells can be differentially charged to full capacity (balanced), then they will subsequently cycle normally without any additional adjustments. This is mostly a one shot fix.
2. If the cells have different capacities, they are also considered balanced when the SOC is the same. But, since SOC is a relative measure, the absolute amount of capacity for each cell is different. To keep the cells with different capacities at the same SOC, cell balancing must provide differential amounts of current to cells in the series string during both charge and discharge on every cycle.

Cell balancing electronics

Cell balancing is defined as the application of differential currents to individual cells (or combinations of cells) in a series string. Normally, of course, cells in a series string receive identical currents. A battery pack requires additional components and circuitry to achieve cell balancing. However, the use of a fully integrated analog front end for cell balancing reduces the required external components to just balancing resistors.

It is important to recognize that the cell mismatch results more from limitations in process control and inspection than from variations inherent in the Lithium Ion chemistry. The use of a fully integrated analog front end for cell balancing can improve the performance of series connected Li-ion Cells by addressing both SOC and C/E issues. SOC mismatch can be remedied by balancing the cell during an initial conditioning period and subsequently only during the charge phase. C/E mismatch remedies are more difficult to implement and harder to measure and require balancing during both charge and discharge periods.

This type of solution eliminates the quantity of external components, as for discrete capacitors, diodes and most other resistors to achieve balance.

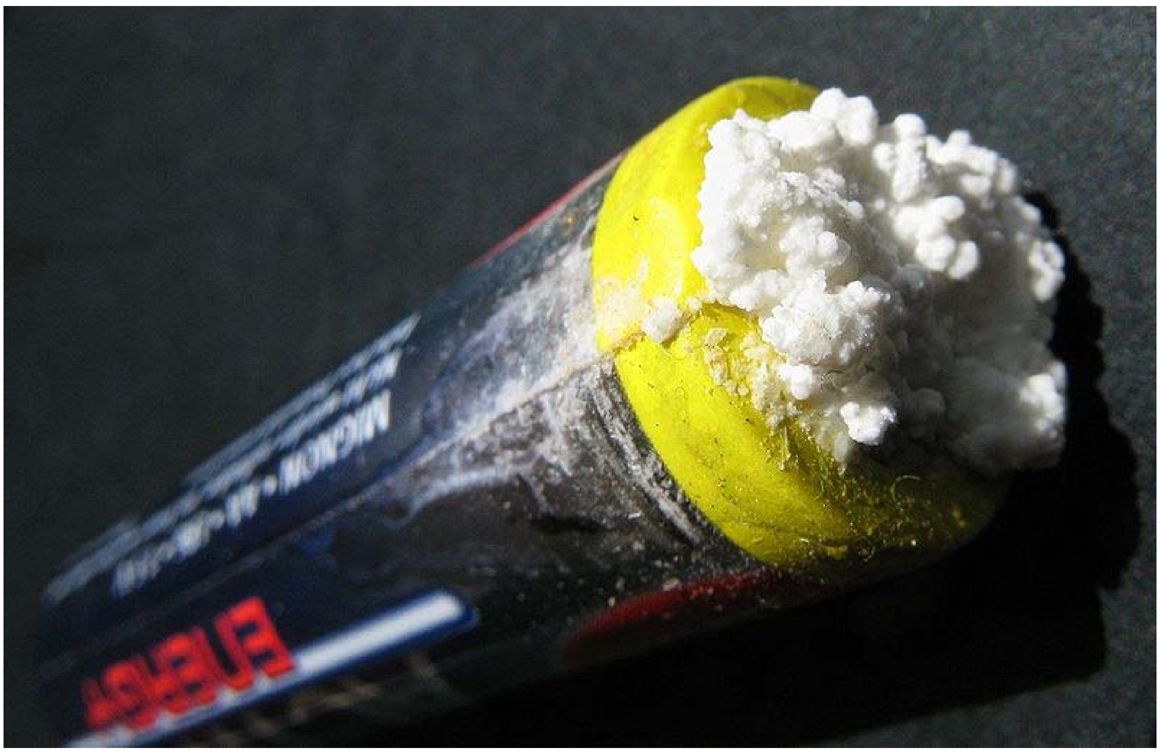
Hazards

Explosion

A battery explosion is caused by the misuse or malfunction of a battery, such as attempting to recharge a primary (non-rechargeable) battery, or short circuiting a battery. With car batteries, explosions are most likely to occur when a short circuit generates very large currents. In addition, car batteries liberate hydrogen when they are overcharged (because of electrolysis of the water in the electrolyte). Normally the amount of overcharging is very small, as is the amount of explosive gas developed, and the gas dissipates quickly. However, when "jumping" a car battery, the high current can cause the rapid release of large volumes of hydrogen, which can be ignited by a nearby spark (for example, when removing the jumper cables).

When a battery is recharged at an excessive rate, an explosive gas mixture of hydrogen and oxygen may be produced faster than it can escape from within the walls of the battery, leading to pressure build-up and the possibility of the battery case bursting. In extreme cases, the battery acid may spray violently from the casing of the battery and cause injury. Overcharging—that is, attempting to charge a battery beyond its electrical capacity—can also lead to a battery explosion, leakage, or irreversible damage to the battery. It may also cause damage to the charger or device in which the overcharged battery is later used. Additionally, disposing of a battery in fire may cause an explosion as steam builds up within the sealed case of the battery.

Leakage



Leaked alkaline battery

Many battery chemicals are corrosive, poisonous, or both. If leakage occurs, either spontaneously or through accident, the chemicals released may be dangerous.

For example, disposable batteries often use a zinc "can" as both a reactant and as the container to hold the other reagents. If this kind of battery is run all the way down, or if it is recharged after running down too far, the reagents can emerge through the cardboard and plastic that form the remainder of the container. The active chemical leakage can then damage the equipment that the batteries were inserted into. For this reason, many electronic device manufacturers recommend removing the batteries from devices that will not be used for extended periods of time.

Environmental concerns

The widespread use of batteries has created many environmental concerns, such as toxic metal pollution. Battery manufacture consumes resources and often involves hazardous chemicals. Used batteries also contribute to electronic waste. Some areas now have battery recycling services available to recover some of the materials from used batteries. Batteries may be harmful or fatal if swallowed. Recycling or proper disposal prevents dangerous elements (such as lead, mercury, and cadmium) found in some types of batteries from entering the environment. In the United States, Americans purchase nearly three billion batteries annually, and about 179,000 tons of those end up in landfills across the country.

In the United States, the Mercury-Containing and Rechargeable Battery Management Act of 1996 banned the sale of mercury-containing batteries, enacted uniform labeling requirements for rechargeable batteries, and required that rechargeable batteries be easily removable. California, and New York City prohibit the disposal of rechargeable batteries in solid waste, and along with Maine require recycling of cell phones. The rechargeable battery industry has nationwide recycling programs in the United States and Canada, with dropoff points at local retailers.

The Battery Directive of the European Union has similar requirements, in addition to requiring increased recycling of batteries, and promoting research on improved battery recycling methods.

Ingestion

Small button/disk batteries can be swallowed by young children. While in the digestive tract the battery's electrical discharge can burn the tissues and can be serious enough to lead to death. Disk batteries do not usually cause problems unless they become lodged in the gastrointestinal (GI) tract. The most common place disk batteries become lodged, resulting in clinical sequelae, is the esophagus. Batteries that successfully traverse the esophagus are unlikely to lodge at any other location. The likelihood that a disk battery will lodge in the esophagus is a function of the patient's age and the size of the battery. Disk batteries of 16 mm have become lodged in the esophagi of 2 children younger than 1 year. Older children do not have problems with batteries smaller than 21–23 mm. For comparison, a dime is 18 mm, a nickel is 21 mm, and a quarter is 24 mm. Liquefaction necrosis may occur because sodium hydroxide is generated by the current produced by the battery (usually at the anode). Perforation has occurred as rapidly as 6 hours after ingestion.

Battery chemistry

Primary battery chemistries

Chemistry	Nominal Cell Voltage	Specific Energy [MJ/kg]	Elaboration
Zinc–carbon	1.5	0.13	Inexpensive.
Zinc–chloride	1.5		Also known as "heavy duty", inexpensive.
Alkaline (zinc–manganese dioxide)	1.5	0.4-0.59	Moderate energy density. Good for high and low drain uses.
Oxy nickel hydroxide (zinc–manganese dioxide/oxy nickel hydroxide)	1.7		Moderate energy density. Good for high drain uses
Lithium (lithium–copper oxide) Li–CuO	1.7		No longer manufactured. Replaced by silver oxide (IEC-type "SR") batteries.
Lithium (lithium–iron disulfide) $LiFeS_2$	1.5		Expensive. Used in 'plus' or 'extra' batteries.
Lithium (lithium–manganese dioxide) $LiMnO_2$	3.0	0.83-1.01	Expensive. Only used in high-drain devices or for long shelf life due to very low rate of self discharge. 'Lithium' alone usually refers to this type of chemistry.
Mercury oxide	1.35		High drain and constant voltage. Banned in most countries because of health concerns.
Zinc–air	1.35–1.65	1.59	Mostly used in hearing aids.
Silver-oxide (silver–zinc)	1.55	0.47	Very expensive. Only used commercially in 'button' cells.

Rechargeable battery chemistries

Chemistry	Cell Voltage	Specific Energy [MJ/kg]	Comments
NiCd	1.2	0.14	Inexpensive. High/low drain, moderate energy density. Can withstand very high discharge rates with virtually no loss of capacity. Moderate rate of self discharge. Reputed to suffer from memory effect (which is alleged to cause early failure). Environmental hazard due to Cadmium - use now virtually prohibited in Europe.
Lead acid	2.1	0.14	Moderately expensive. Moderate energy density. Moderate rate of self discharge. Higher discharge rates result in considerable loss of capacity. Does not suffer from memory effect. Environmental hazard due to Lead. Common use - Automobile batteries
NiMH	1.2	0.36	Inexpensive. Performs better than alkaline batteries in higher drain devices. Traditional chemistry has high energy density, but also a high rate of self-discharge. Newer chemistry has low self-discharge rate, but also a ~25% lower energy density. Very heavy. Used in some cars.
NiZn	1.6	0.36	Moderately inexpensive. High drain device suitable. Low self-discharge rate. Voltage closer to alkaline primary cells than other secondary cells. No toxic components. Newly introduced to the market (2009). Has not yet established a track record. Limited size availability.
Lithium ion	3.6	0.46	Very expensive. Very high energy density. Not usually available in "common" battery sizes. Very common in laptop computers, moderate to high-end digital cameras and camcorders, and cellphones. Very low rate of self discharge. Volatile: Chance of explosion if short circuited, allowed

to overheat, or not manufactured with rigorous quality standards.

Homemade cells

Almost any liquid or moist object that has enough ions to be electrically conductive can serve as the electrolyte for a cell. As a novelty or science demonstration, it is possible to insert two electrodes made of different metals into a lemon, potato, etc. and generate small amounts of electricity. "Two-potato clocks" are also widely available in hobby and toy stores; they consist of a pair of cells, each consisting of a potato (lemon, et cetera) with two electrodes inserted into it, wired in series to form a battery with enough voltage to power a digital clock. Homemade cells of this kind are of no real practical use, because they produce far less current—and cost far more per unit of energy generated—than commercial cells, due to the need for frequent replacement of the fruit or vegetable. In addition, one can make a voltaic pile from two coins (such as a nickel and a penny) and a piece of paper towel dipped in salt water. Such a pile would make very little voltage itself, but when many of them are stacked together in series, they can replace normal batteries for a short amount of time.

Sony has developed a biological battery that generates electricity from sugar in a way that is similar to the processes observed in living organisms. The battery generates electricity through the use of enzymes that break down carbohydrates, which are essentially sugar. A similarly designed sugar drink powers a phone using enzymes to generate electricity from carbohydrates that covers the phone's electrical needs. It only needs a pack of sugary drink and it generates water and oxygen while the battery dies out.

Lead acid cells can easily be manufactured at home, but a tedious charge/discharge cycle is needed to 'form' the plates. This is a process whereby lead sulfate forms on the plates, and during charge is converted to lead dioxide (positive plate) and pure lead (negative plate). Repeating this process results in a microscopically rough surface, with far greater surface area being exposed. This increases the current the cell can deliver.

Daniell cells are also easy to make at home. Aluminum-air batteries can also be produced with high purity aluminum. Aluminum foil batteries will produce some electricity, but they are not very efficient, in part because a significant amount of hydrogen gas is produced.