SOAR

STATE-OF-THE-ART REPORT (SOAR)
NOVEMBER 2021

DSIAC-BCO-2021-168

MATERIALS AND APPLICATIONS FOR ELECTROMAGNETIC INTERFERENCE SHIELDING

By Megan Lietha, Richard Piner, and Doyle T. Motes III, P.E.
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MEGAN LIETHA, RICHARD PINER PH.D., AND DOYLE MOTES III, P.E.

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13. ABSTRACT
The wars that the U.S. military will be fighting in the coming years will revolve greatly around the United States' ability to deploy weapon systems with many embedded electronics. One key to enabling these technologies is ensuring that these electronics are protected against electromagnetic interference (EMI) from both natural and artificial sources. This work explores the options available to contain and protect electronics from EMI from a materials development and materials engineering perspective. A background on EMI is provided, along with examples of military applications, discussion of recent research into materials and engineering, markets and weaknesses in the supply chains, and conclusions.

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ABSTRACT

The wars that the U.S. military will be fighting in the coming years will revolve greatly around the United States' ability to deploy weapon systems with many embedded electronics. One key to enabling these technologies is ensuring that these electronics are protected against electromagnetic interference (EMI) from both natural and artificial sources. This work explores the options available to contain and protect electronics from EMI from a materials development and materials engineering perspective. A background on EMI is provided, along with examples of military applications, discussion of recent research into materials and engineering, markets and weaknesses in the supply chains, and conclusions.

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SECTION 01 INTRODUCTION

Electromagnetic (EM) waves, otherwise known as EM radiation, are ubiquitous in the modern world. Every electronic device emits some form of EM radiation, whether it be radios, cell phones, televisions, computers, light bulbs, power lines, or dishwashers. The list of applications is almost endless and growing every day. With so many sources of EM radiation in constant proximity to each other, it is not surprising that unwanted EM signals, called EM interference (EMI), can cause problems for many different devices in each environment. To reduce the unintended effects of EM radiation sources interfering with each other, EMI shielding is used to protect devices. EMI shielding is accomplished with the use of certain materials that either absorb (electrical conductors or semiconductors) or reflect (electrical conductors) the interfering EM waves so as not to allow radiation in or out, depending upon the circumstance (see Figure 1-1, where the transmitted wave has been significantly weakened [or blocked] by the material). Shielding is used in all electronic devices. Even inside electronic devices built with vacuum tubes, metallic shields can be found around some of the tubes to protect them from stray signals from other parts of the circuit and prevent them from radiating their own signals into the surrounding space.

EMI shielding can be accomplished most with the use of metals, such as copper, nickel, steel, tin, Mu-metals, or a combination of these materials. New technologies are requiring new applications

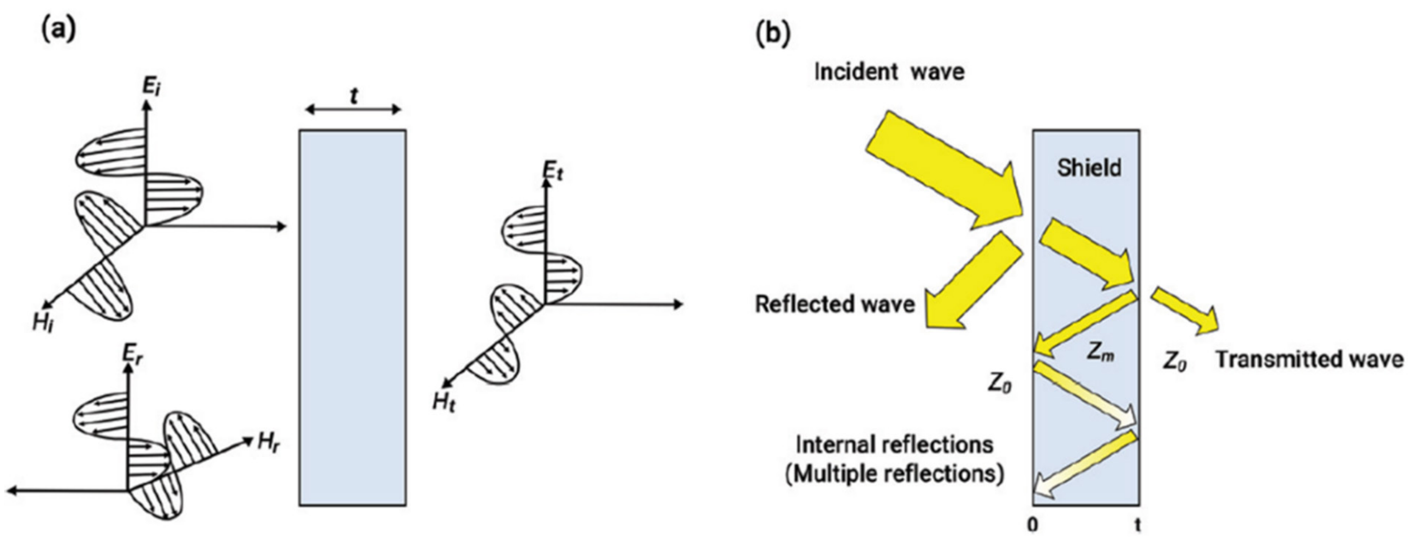

Figure 1-1. (a) A Schematic Illustration of an EM Plane Wave Perpendicular to a Material With a Thickness t and (b) a Schematic Illustration of the Attenuation of an Incident EM Wave by the Shielding Material (Reproduced from Zhang et al. [1]).

or uses for EMI shielding, which is driving research to develop new materials or new implementation methods for existing EMI shielding technology. Some of those new applications include military uses, such as protecting against hostile attack or even subverting radar detection, while other new uses include optically transparent and/or mechanically flexible materials for next-generation technology. Not only are shielding materials necessary to limit interference, but several government regulatory bodies also exist to moderate use of EM radiation frequencies to limit the possibilities of interference across environments and devices. These regulations and guidelines are important to ensuring the operability of all devices, especially those essential to public safety and basic operations, such as power grid stability and other important infrastructure.

This report will cover the basics of EM radiation and interference, the sources of radiation (including telecommunications, military, satellite, and more), standards for the control of interference, materials both current and in development for shielding, and the modern landscape of EMI shielding research and manufacturing. It will give a broad background in current developments in each of these applications and direct the reader toward current references discussing further research and subjects of interest.

1.1 EM RADIATION BASICS

EM radiation is a traveling wave made up of oscillating electric and magnetic fields. A schematic representation of this is shown in Figure 1-1(a), where E represents the electric field and H represents the magnetic field components. The nature of these waves is characterized by their wavelength and frequency:

$$c = f\lambda,$$

where f is the frequency in Hertz, λ is the wavelength in meters, and c is the speed of light in a vacuum in meters/second. The wavelength and frequency determine how these waves interact with matter. The distribution of the different frequencies and wavelengths is the electromagnetic spectrum seen in Figure 1-2. In the radio part of the spectrum (defined as 3 kHz to 300 GHz) in this figure, VLF = very low frequency, LF = low frequency, MF = medium frequency, HF = high frequency, VHF = very high frequency, UHF = ultra-high frequency, SHF = super high frequency, and EHF = extreme high frequency.

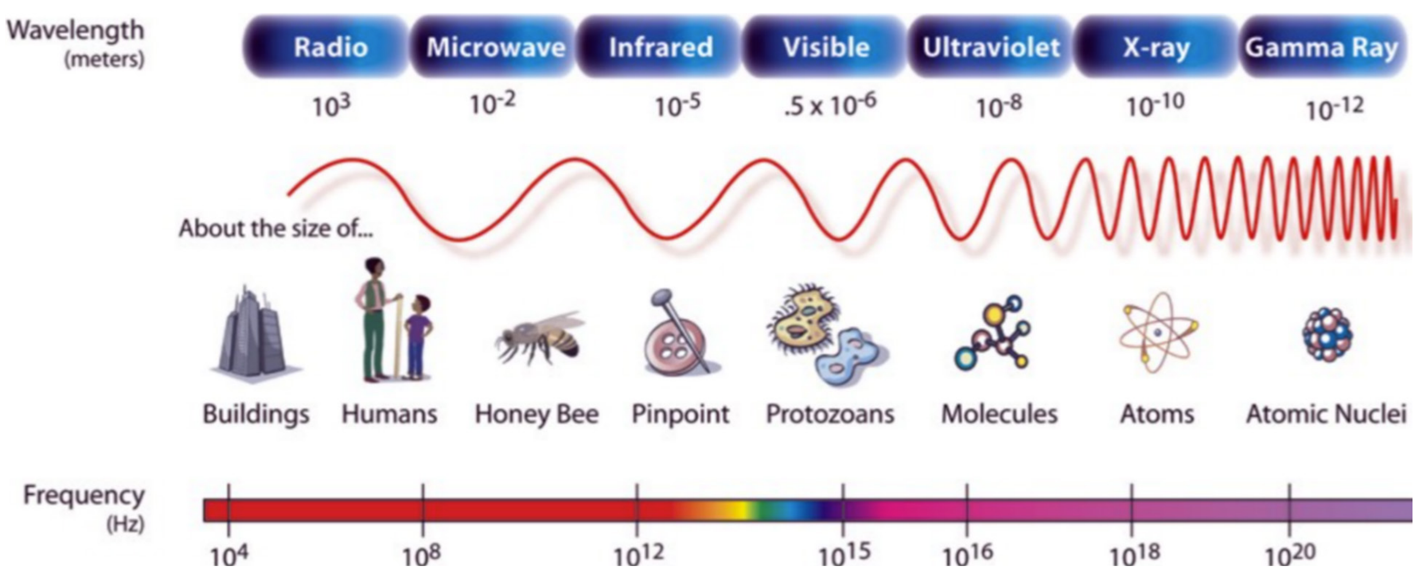

Figure 1-2. Electromagnetic Radiation Spectrum [2].

EMI is not caused by waves interacting with each other; EM waves do not interact. If crossed, two laser beams would pass through each other completely undisturbed. The problem arises when we try to detect them, which requires that the wave(s) interact with matter. For example, a radio needs a metallic antenna to operate, and human eyes need a retina to perceive visible light. EMI is caused when an unwanted wave is picked up by a receiver, instead of or in addition to, the wave of interest. Simply put, EMI is caused by an undesirable interaction between a device and some extraneous source of EM radiation.

Figure 1-1 shows that the magnetic and electric fields compromising an EM wave are coupled. English physicist and chemist Michael Faraday first noticed that an electric current flowing in a wire produced a magnetic field. It was soon discovered that a changing magnetic field would also induce a current in a conductor. This relationship between electric currents and magnetic fields led to the invention of the telegraph. Thereafter, it was discovered that oscillating fields would propagate through space and could be detected at large distances from the source, i.e., the wireless telegraph. Scottish mathematician and scientist James Clerk Maxwell reduced all the physics governing propagation of EM waves to a set of relations shown as Maxwell's Equations. These explicitly make clear the relationship between magnetic and electric fields. The interaction between these waves and matter is far more complex and governed by the laws of quantum electro-dynamics.

EM radiation is emitted by all things. As an example, an incandescent light bulb emits EM radiation at multiple frequencies, the majority of which is infrared (heat) and, to a smaller extent, visible light. The visible light emitted reflects off the objects around us and enters our eyes, which act as a receiver within the frequency range of the visible light spectrum sensitive to human eyes. Furthermore, EM radiation is used in cell phones and radios to transmit and receive signals, providing a means of communication. The circuits and fans inside a computer, as well as many of the other components, each produce some form of EM radiation, whether in the radio frequency or infrared ranges. Common household appliances produce radiation as well, including microwave ovens, toasters, and ovens. Even the human body produces heat in the form of infrared radiation.

There are two broad classifications of EM radiation—natural and man-made. While natural sources of EM radiation, such as lightning, solar flares, or auroras, are potential disruptors, man-made sources of EM interference are the primary concern driving the majority of EM shielding use. More specifically, most EM shielding is primarily concerned with addressing radiation in the radio frequency range of the spectrum, as this is the range used by almost all man-made electronics for communication and is the most common source for interference between electronic devices. It is possible for interference to occur between frequencies of significantly different wavelengths, but it is very rare.

EM waves within the radio spectrum are created both intentionally, such as when transmitting a signal from a cell phone to a cell phone tower, and unintentionally, such as radiated EM noise from a circuit on a computer chip or radiated EM signals from an unshielded power line (also known as leakage). To intentionally generate a signal, a transmitter within a device will emit EM waves of a certain frequency (or over a certain frequency range or band) that will be projected outward from the device. When the EM waves encounter a receiver tuned to the frequency of the transmitter (or within the frequency band), the receiver converts the signal into usable data. These types of transmissions are typically made over either narrow- or broad-band frequency ranges. The limiting factor in data transmission rates depends on the frequency width of the spectrum allocated to the device. For example, radio stations transmitting in the amplitude modulation (AM) band are limited to 5-kHz modulation, meaning they can transmit 5,000 "characters" per second. As the human ear can hear up to about 20 kHz, the sound quality is rather low. The frequency modulation (FM) band is limited to 15-kHz modulation, 3× the data speed compared to the AM band limit. There are limits to the amount of radio spectrum assigned to each station so their signals do not overlap and interfere with each other. The general rule of thumb is the higher the frequency of a communication channel, the larger the bandwidth that can be supported. These signals are considered "narrow bandwidth" (or narrow band). Thus, if their input is well filtered, interference from other sources at nearby frequencies can be minimized. However, devices that have a high bandwidth (or broad band) are much more prone to interference because a highly selective input filter is not possible for such signals; thus, shielding is very important for these applications. The Federal Communications Commission (FCC) does not have a fixed definition of broad band; however, the bandwidth is 1–25 MHz.

To mitigate some of the issues with EM interference from everyday devices, the radio frequency spectrum used for communications is divided into different frequency bands. These bands are used for different applications and defined by government regulations. Table 1-1 lists the most common broadcast applications and the frequencies used with each. For civilian radio stations and television (TV) stations, different networks or stations are given a particular narrow-band frequency range by the FCC that they are allowed to broadcast within. Buffer zones are used between bands to prevent other channels from unintentionally causing interference. Knowing the frequencies a technology emits over is also important since the methods/materials used for EM shielding depend on the emission frequency (or frequency range).

1.2 EM INTERFERENCE

For an electronic device to "interfere" with another electronic device, it must produce an electric field at a frequency sufficiently close to the frequency that the "victim" device is tuned to so that the field modulates the frequency of the signal. The

Table 1-1. Electromagnetic Frequency Ranges for Different Commonplace Applications

Application	Frequency or Range
AM Radio Broadcasts	~530 kHz–1.7 MHz
Broadcast TV	54–88, 174–261, 470–698 MHz
FM Radio Broadcasts	88–108 MHz
Cell Phone Signals	~850, ~900, ~1800, ~1900 MHz
Global Positioning System (GPS)	~1.5 GHz
Satellite Radio	~2.3 GHz
Wireless Computer Networking	2.4 and 5.8 GHz
Satellite TV	12 GHz
5G Bands	**High band:** 24, 28, 37, 39, 47 GHz **Mid band:** 2.5, 3.5, 3.7–4.2 GHz **Low band:** 600, 800, 900 MHz **Unlicensed:** 5.9, 6, >95 GHz
6G Bands (Future)	FCC has granted the 95-GHz–3-THz band for 6G research (will require clear line-of-sight for transmit/receive)

modulation is a result of constructive or destructive interference, which amplifies or reduces the signal's amplitude. Depending on the source of the interference and the strength and duration of the interference, a device may be incapacitated and completely unable to function. For medical devices, air traffic control communication, emergency response equipment, military operation and communication, and, in many other cases, the inability for devices and means of communication to operate properly can have direct and catastrophic effects.

Not all forms of EMI directly affect a particular device. There are cases where currents are induced in either power or signal wiring that is connected to a victim device. For example, electric motors can cause current spikes in power lines. If these lines are powering an electronic instrument, the signals can be conducted into the instrument and generate noise in the measurement. This kind of EMI, conducted EMI, is not transmitted through free space but rather through the wiring. This is a common problem in laboratory environments, and some instruments are run solely on batteries for this reason. To prevent this, there are "power conditioners" to clear up power supplies. In addition, there are ferrite cores that attach to power lines to filter out unwanted signals from the power lines. Filtering and shielding should be considered whenever highly sensitive measurements are undertaken. These sources of EMI are common enough that allowance must be made. However, existing solutions to these issues are readily available (power conditioners, ferrite cores, battery power, etc.) but not addressed in this report.

To protect against radiated EMI, a shield around components, devices, and even buildings must be designed. Shielding serves one of two functions—keep external signals from an enclosed space or keep signals generated inside a space from escaping. A shielding material works by reflecting or absorbing some, or all, of the incident wave. What is left is the transmitted wave (if it has not been completely reflected or absorbed [see Figure 1-1]). Different materials/ material combinations have different shielding properties over different frequencies and frequency ranges. Research and strategies to improve shielding are aimed at increasing the reflectivity or the absorbance, or a combination thereof, for the shielding material.

All EM shielding is created using some sort of barrier—a wall, screen, box, etc. Materials used for EM shielding are typically electrically conducting metals (although some highly conducting plastics or composites can also be used). In a reflector-type EMI shield, metallic conductors are effective because they operate as mirrors, reflecting EMI. These materials are compared with a figure of merit called "shielding effectiveness" (SE). SE is evaluated by the ratio of the received to transmitted power (or power not stopped by the shield), expressed in decibels. While basic geometries for shielding solutions are well defined, most current research concentrates on improving SE via the development of new materials or the use of metamaterials (materials that are a combination of reflectors and absorbers). A recent collection in Jaroszewski et al. [3] includes a large set of review papers that are a rich source of information on the latest developments in EM radiation shielding materials. In addition, the introductory chapters give a thorough background on the physics and mathematics that come into play when evaluating the SE of different materials. Another good primer to the topic is contained in the introduction to "Lightweight Electromagnetic Interference Shielding Materials and Their Mechanisms" [1] on lightweight shielding materials.

For every EM shielding material, the SE value must be known. As a result, there are defined methods on how to measure the SE of different materials/ material systems for certification against regulated standards. The most often used standard to measure the SE of a material is from the American Society for Testing and Materials (ASTM) D4935-10 [4]. This standard is derived from measurements first made at the National Bureau of Standards (now the National Institute of Standards and Technology). Figure 1-3 shows a typical setup for taking shielding measurements (in this case, the SE of a plaster sample [5]).

The specific shielding strategy used in each situation very often depends on the application. For example, if the goal is to shield a room or build-

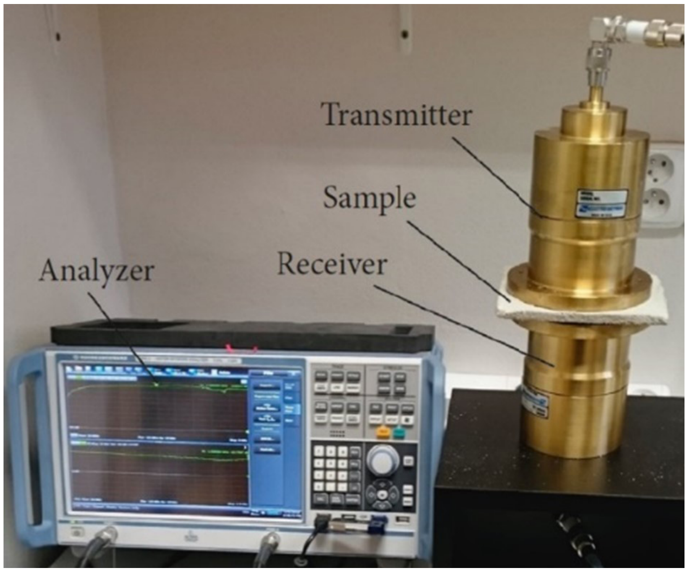

Figure 1-3. Typical Test Setup for Measuring the SE of a Material Sample [5].

ing from external sources of radio emissions, a reflective material may work best. By contrast, if a reflective material is used in an enclosure to block emissions from escaping an electronic circuit, the EM waves will reflect off all surfaces inside the box and interfere with the circuit's operation. In this case, a shield material with a high absorbance, rather than reflectance, is preferred. Additionally, when used around a circuit or a transmitter, an absorbing material will block power at undesired frequencies from escaping while allowing power at the intended signal frequency to transmit freely from the device, usually through a path like a conductor to an external antenna. Absorbers are designed to convert EM waves into heat. There are numerous materials which do this by several loss mechanisms. For example, composite materials containing short carbon fibers absorb EM radiation through inducing currents within the fibers that are then converted to heat via Ohm's Law:

$$Q = I^2R,$$

where I is the current, R is the resistance, and Q is the heat power generated. More details will be discussed later in this report.

At times, a combination of materials to achieve tuned absorbance and reflectance may be desired (to operate over particular ranges of frequencies). Other considerations relative to the application can be cost, weight, or volume required. Cost can be important for building materials, while weight/volume may be most important for mobile applications.

SECTION 02 MILITARY APPLICATIONS OF EMI

EMI is an issue across all forms of electronics-based technology in all domains, including civilian and military. It is well known and documented that portable communication devices onboard airplanes can affect the operation of other aircraft—air travelers are familiar with the preflight message to turn off electronic devices during take-off [6]. EMI affects radio transmissions, and solar radiation is known to interfere with satellite transmissions [7]. A National Aeronautics and Space Administration (NASA) report documenting EMI disturbances in aviation [8] lists various statistics for disturbances reported on flights between 1986 and 1999 and documents effects, such as incorrect navigation data, off-course flight paths, deviations in compass direction/accuracy, and lost communication capabilities. Another report by NASA documenting EMI incidents during the development and operation of air- and spacecraft [9] includes an example of carbon arc lamps interfering with range safety receivers at Kennedy Space Center, an instance where a commercial-off-the-shelf part interfered with the space lab intercom, and a case of an F-16 crashing near a Voice of America radio transmitter because of interference with the aircraft's instruments by the transmitter's errant signals.

While the physics and engineering challenges of EMI shielding are common to both civilian and military applications, the two differ in matters of national security and threats to both information security and physical safety. Transmission of secure information must be protected from snooping/eavesdropping threats, in digital transmissions and in person (such as when briefing the president or a top-level officer about imminent threats or highly sensitive information). In addition, military personnel need to be protected from electromagnetic pulse (EMP) and microwave attacks. As an example of this, it has been speculated that the attacks on U.S. embassy personnel in Cuba in 2017 were the result of a directed microwave energy attack [10]. EM shielding and interference technologies in the military domain continue to be developed to improve protective capabilities and weaponize capabilities for intelligence gathering and physical attacks. Selected examples of these technologies are explored next.

2.1 SENSITIVE COMPARTMENTED INFORMATION FACILITY (SCIF)

A SCIF is any space, whether a fixed or mobile facility, that is secured from outside eavesdropping or theft of sensitive information being discussed or shared by U.S. government officials. Figure 2-1 shows a famous image from the situation room at the White House during Operation Neptune Spear. This picture shows one of several small conference rooms that are part of the situation room; the entire space is a SCIF. It is important to note the computers visible on the table. All the connections into the space must be secured from EM leakage, in or out. The penetrations through the walls are all shielded, the connectors are shielded, and the cables are also shielded. Not only are the electronics shielded, but the room itself is built to specification using designated materials to shield the space from allowing EM radiation to leak out. Publicly available technical requirements for a SCIF are, of course, vague.

Figure 2-1. President Obama and His National Security Team in the White House Situation Room During Operation Neptune Spear [11].

However, some useful documents are available online, including an outline of SCIF requirements as provided by the Office of the National Counterintelligence Executive [12] and a PDF of a presentation on SCIFs given by Richard Cofer at the U.S. Naval Facilities Engineering Command explaining how they are defined, built, managed, and used [13].

2.2 UNDERSEA CABLES

Most data traffic is now carried by fiber-optic cables traversing the globe both underground and undersea. Fiber-optic cables use light created by either lasers or LEDs to transmit data across glass fibers at higher speeds and capacities than other traditional cable technologies. On land, these cables are mostly secured by virtue that significant excavation is required to tap into them, which would attract attention. Also, while the most vulnerable part of the system is the terminals on land, these are housed in SCIF-like buildings and therefore difficult to penetrate. The fiber cables undersea, however, are unguarded, making them a prime target for tampering, as outlined in an article published by *Defense News* [14]. An example of this (although targeting slightly different cables) was performed by the U.S. Navy, National Security Administration (NSA), and Central Intelligence Agency (CIA) as part of Operation Ivy Bells.

Physically tapping into undersea cables is almost impossible (the potential for the use of undersea drones, such as those capable of being deployed from the Russian Belgorod class submarines notwithstanding), as modern repeaters no longer amplify the signal with electronics. Despite this, undersea cable tampering is not a new phenomenon [15]; maintenance, replacement, and upkeep of this infrastructure have been the burden of the commercial sector. This has led to some concern in recent years over the involvement of foreign telecom companies who may be owned or operated by U.S. adversaries tampering with the cables during replacement or maintenance operations [16].

2.3 EMP

EMPs are generated whenever there is a surge of electrical current that produces a pulse of EM radiation (in the form of an electric field with a very high voltage). When the pulse reaches and passes through an electrical conductor, large currents are induced within the conductor. The resulting currents can trip circuit breakers, destroy semiconductor chips, and do other kinds of damage. Any time-varying part of the magnetic field in the EM wave induces currents in conductors. These currents can cause damage to electronics. If the frequency is low, magnetic shielding is most effective. If the frequency is high, a good conductive shield will reflect most of the incoming radiation. This effect can be purposefully induced and used as a weapon. The U.S. Army is working on a small EMP generator that can take down a drone by destroying its electronics (Figure 2-2) [17, 18].

Man-made EMP weapons can deal incredible amounts of damage, with some used as a first-strike weapon to disable power grid infrastructure. The most threatening form of an EMP weapon is a high-altitude EMP (HEMP), which is the detonation of a nuclear warhead very high in the atmosphere. This type of blast would have the ability to knock out communications, power, and most electronic devices for thousands of miles, with the potential to disable satellites. The United States first discovered the effects of HEMPs during nuclear bomb testing programs of the 1960s [19]. This form of attack is believed to be a viable means of first-strike capability for U.S. adversaries in the future. A report by Executive Director Dr. Peter Vincent Pry of the EMP Task Force on National and Homeland Security in June 2020 [20] thoroughly enumerates the risk posed by China associated with this field of attack. A more general report on EMP, which enumerates the critical infrastructure of concern, was posted in 2019 [21].

There are methods to reduce or mitigate surge incidents, such as surge protection on power outlets, ferrite cores on power cords, etc., but these are measures taken on a small scale. In most current system designs, EMP threats are not considered. EMPs are considered one of many issues that could threaten critical infrastructure if not adequately addressed.

In addition to the U.S. Army developing non-nuclear EMP weapons (more commonly called radio frequency weapons), the United States Air Force (USAF) has developed and deployed CHAMP, a

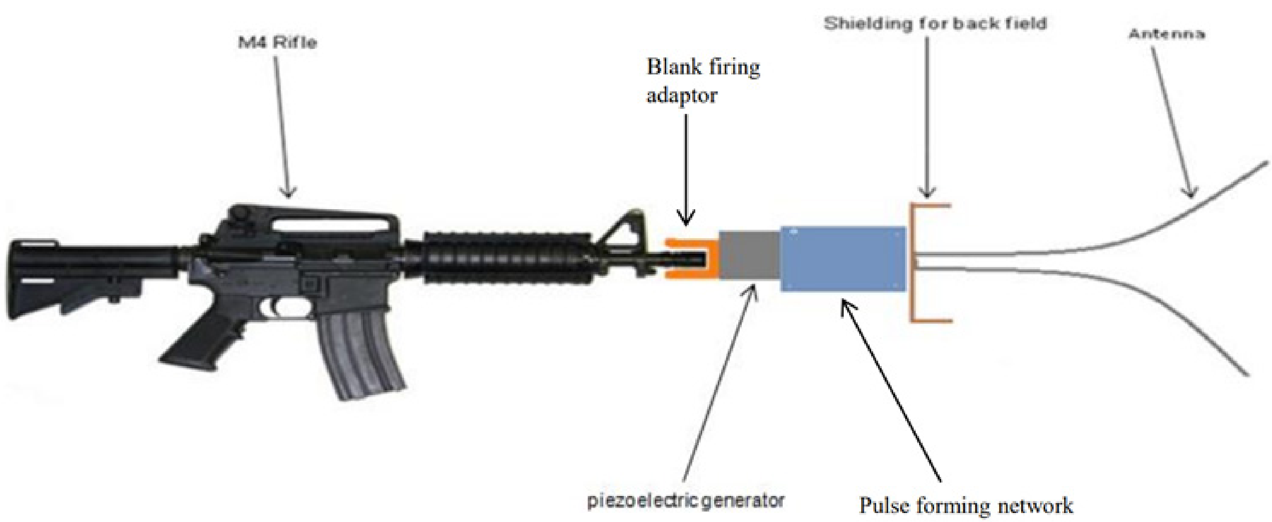

Figure 2-2. Schematic of the M4 Rifle Blank-Firing Attachment With the Piezoelectric Generator Attached [17].

drone or cruise missile armed with an EMP generator to attack command, control, communication, and intelligence (C3I) and power grids. Reportedly, the USAF has deployed CHAMP in Japan to preempt a nuclear missile attack by North Korea by "frying" North Korean missiles and C3I and blacking out power grids.

2.4 STEALTH

Stealth systems share overlap in terms of technological applications to EM shielding. As previously noted, EM shielding works by either reflecting EM waves or absorbing them. In the case of stealth applications, the intention is to shield a craft from radar detection, which is the reflection of EM radiation from the aircraft in question back to the receiver. To accomplish this, the radar beam should be reflected in a direction away from the source or absorbed so it minimizes the amount of energy reflected to the receiver (an example of this is shown in Figure 2-3 for the B-2 Bomber).

Figure 2-3. The B-2 Bomber With Radar Absorbing Coating and Characteristic Radar Minimizing Geometry *(Source: https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104482/b-2-spirit/).*

There are numerous research efforts in materials science to improve the SE of shielding, and many of these can also be useful in stealth coating (as noted in a recent paper by Rao et al. [22]). Most stealth coatings include ferromagnetic materials, but nanomaterials are being used to create lighter, thinner, more durable materials [23]. In that vein, the global stealth coating market is "forecast[ed] to exceed USD $834 million by 2026," according to Kiran Pulidindi [24].

2.5 SATELLITE PROTECTION

There are several unique problems associated with EM shielding that particularly affect satellites (and spacecraft, depicted pictorially in Figure 2-4). The first is cosmic radiation. Cosmic rays are high-energy particles and photons, which are "ionizing radiation." They are produced by the sun, extrasolar, and extragalactic sources and can damage the typical semiconductor chips in use today on most satellites. To defend against cosmic rays, spacecraft designs usually place the most radiation-sensitive parts at the center of mass of the satellite, as the only defense from the high-energy photons is the density of the materials surrounding them. In addition to shielding, the electronic components themselves are radiation hardened.

The second threat comes from the sun in the form of "magnetic storms." These are caused by bursts of particles and EM radiation resulting from solar flares. When these bursts are strong, we can see the effects near Earth's magnetic poles—the Aurora Borealis. These solar flares can also cause damage to satellites and other craft orbiting higher in or above the atmosphere. Traditional EM shielding methods can prevent damage to electronics from solar EM radiation. However, these materials can be bulky, and getting mass into space is very expensive. Because of the need for the lightest possible materials for spaceflight, research into lightweight materials for shielding applications is very important for this field (see Chapter 15 in Jaroszewski et al. [3] and Turer and Aydin [25]).

The third main threat comes from the Van Allen radiation belts—bands of charged particles trapped in the Earth's magnetic field. Here, electrons (up to about 10 MeV) and protons (up to hundreds of MeV) trapped in the geomagnetic field [26] can wreak havoc on electronics. The particle flux in the regions farther from the Earth can vary

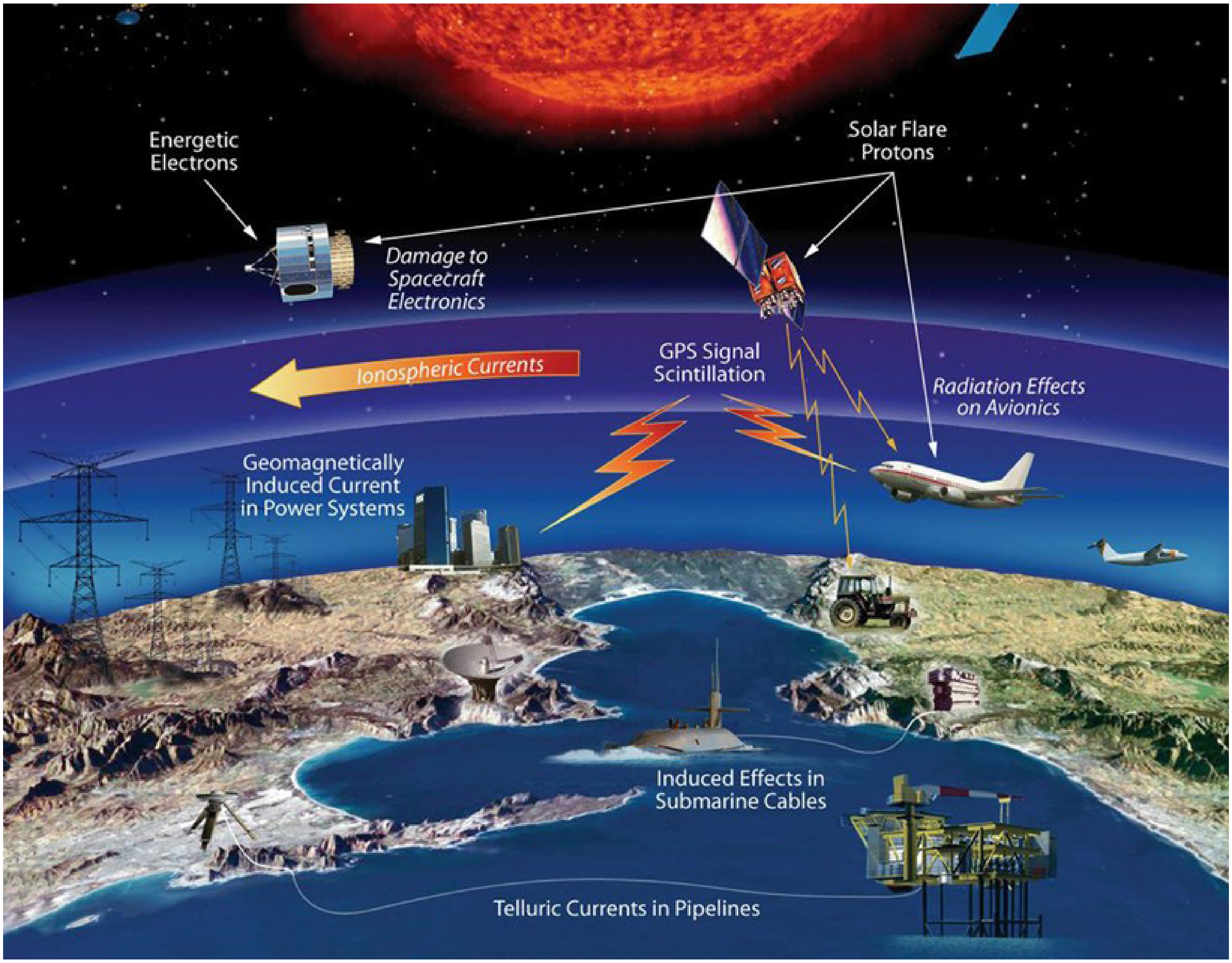

Figure 2-4. Artist's Rendition of the Effects of Solar Radiation on Space and Ground Systems From NASA [27].

wildly, depending on the actual conditions of the sun and the magnetosphere [28].

The fourth tread relates back to HEMPs. A HEMP travels downward through the atmosphere toward the Earth and does not propagate outward through outer space so as not to threaten orbiting satellites directly. But it can damage or destroy ground stations vital to satellite operations. However, detonation of a nuclear weapon at a high altitude for HEMP attack creates other collateral effects that can damage and destroy orbiting satellites, including X-rays, gamma rays, and "pumping" the Van Allen Belts. During the 1962 Starfish Prime high-altitude nuclear test over Johnston Island that generated a HEMP field reaching as far as Hawaii [19], several satellites were damaged by these collateral effects. Gamma rays striking satellites can generate a phenomenon called System-Generated EMP (SGEMP) that can destroy satellite electronics. Military satellites are supposed to be designed to harden against SGEMP and other effects using materials and electronics resistant to SGEMP and other similar phenomenon. But the advent of "Super-EMP" nuclear weapons in the inventories of Russia, China, and North Korea raises questions about the adequacy of protection for U.S. military satellites. "Super EMP" weapons, in addition to generating enhanced HEMP, also emit enhanced gamma rays.

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SECTION 03 SOURCES OF EMI AND THEIR DEFENSES

There are several different naturally occurring (both extraterrestrial- and terrestrial-based) and human-based sources (intentional and unintentional) of EMI. EMI can take the forms of continuous and transient wave sources. Identifying these sources is an important consideration in EM shielding design. Sources of interference can range from nearby transmitting devices like cell phones to solar flares produced by the sun. Without an understanding of the potential sources of interference, it is nearly impossible to design an effective shield.

While shielding is one of the primary forms of defense against unwanted interference, there are additional measures that can be taken to protect against it. One of these is regulation, which includes standards, procedures, policies, and regulations by national and international organizations. By regulating the design and use of EMI-producing devices, agencies can limit and prevent possible interference for civilian and military operations. Additionally, the maintenance and upkeep of the defense infrastructure is another form of defense and helps to protect national security in the event of an EMI-related attack. These defense methods, coupled with shielding against the sources, provide the basis for managing EMI.

3.1 SOURCES

Only certain forms of radiation have an impact on any given device or system. Identifying the sources of EMI is a useful exercise when designing an electronic device. When identifying sources, there are a few broad categories that almost all sources of radiation can be grouped. These categories include natural, unintentional, and intentional radiation. In "Common Sources of Interference" by A. Milne [29], EMI is discussed from the perspective of wireless microphone design. The engineer should know what kind of environment the device will be used in and the nature of EM radiation that the device will need to be shielded against. In this report, the sources have been broken down more broadly, using extraterrestrial and terrestrial sources as the categories, as security considerations for EMI include satellites and infrastructure. Therefore, the scope of possible radiation sources is wider than for the microphone example.

3.1.1 Extraterrestrial EMI Sources

Extraterrestrial sources of EM radiation are either solar (local to within our solar system) or cosmic (outside our solar system). The primary source of solar EM radiation is the sun. Other planets, notably, the gas giant planets Jupiter and Saturn, do produce radiation—both particle and EM. However, this is only a concern for space missions (governed by NASA) to those planets, as their effects do not reach Earth. The sun produces EM radiation in multiple forms and over a broad spectrum, from low-frequency radio emission to X-ray and gamma ray radiation. The sun can not only interfere with radio communication but produces light and even causes cancer because of prolonged exposure to ultraviolet radiation. One way the sun radiates EM is in a steady stream of high-energy charged particles known as solar winds. Solar winds are produced by the upper layer of the sun's atmosphere (the corona) and cause auroras and geomagnetic storms [30]. These winds are believed to cause comet's tails [31]. A more serious solar source is solar flares, which occur when the sun's magnetic field traps the energy of very hot plasma above the chromospheres in the corona [32]. Solar flares can cause damage in two ways. First, when the magnetic field of the sun is disrupted, causing a solar flare, EM waves can be propagated through space and eventually impact Earth. These waves present a radiation hazard and can cause geomagnetic storms. Second, charged particles and X-rays can be released by a solar flare. When this charged energy reaches Earth's ionosphere, the interaction between the flux and Earth's magnetic field can generate a broad spectrum of EM radiation, interfering with radio and satellite communications and causing other EMI problems.

Cosmic sources of EM radiation are relatively weak and do not often cause direct problems to Earth. There are two terms to distinguish here—cosmic radiation and cosmic rays. Cosmic radiation is inclusive and includes radio waves, high-energy photons (gamma rays), and charged particles (cosmic rays) [33]. The term "cosmic rays" is exclusive to charged particles and includes electrons, protons, alpha particles, and charged nuclei of heavier elements. The greater challenge in the extrasolar environment is from cosmic rays [34]. On the surface of Earth, most cosmic rays are filtered out or deflected by the Earth's magnetic field and blocked by the atmosphere. However, spacecraft (including satellites) and high-altitude aircraft can be affected by both cosmic and solar radiation. "Electrostatic discharge (ESD), single-event effects (SEEs), and cumulative radiation damage are the major concerns" [35]. All three of these can cause malfunctions of, damage to, and degradation of crucial electronics on a satellite or spacecraft (Figure 3-1). The amounts of cosmic radiation are constant, except for cosmic ray bursts, which typically last a few seconds. Spacecraft and high-altitude aircraft design consider the cosmic ray background to improve protection of both electronics and, when applicable, human health [36, 37].

3.1.2 Terrestrial EMI Sources

Compared to the relatively few sources of extraterrestrial radiation, there are almost countless terres-

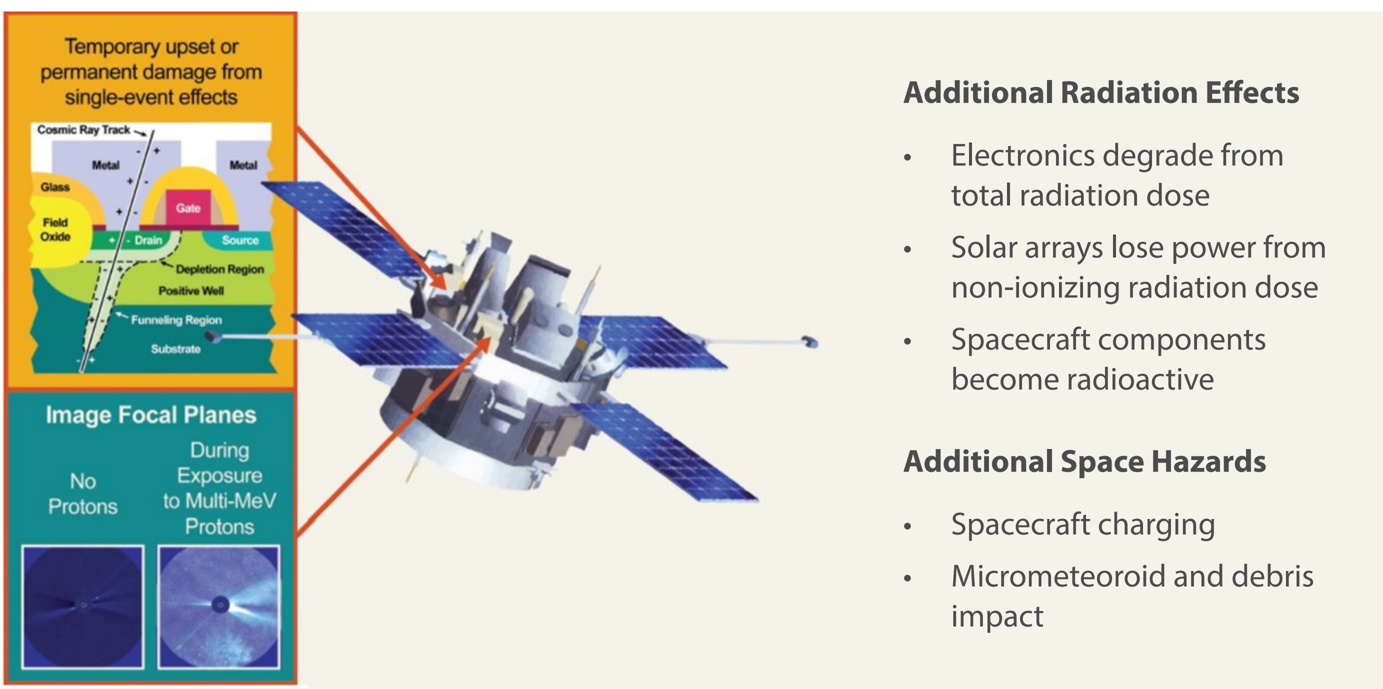

Figure 3-1. EMI Radiation Effects on Military Satellites [35].

trial sources of EMI. Most of these are man-made. However, some are natural, with lightning being the most impactful natural source. The sudden surge of current and high voltage produced by a lightning strike generates a broad-band radio wave powerful enough to interfere with radio communications. This can knock out communications on the ground and in the air and hinder essential communication with commercial, military, and aerospace crafts. Furthermore, the strike itself can damage aircraft or ground facilities, which is why lightning is an especially important design consideration for aircraft [38]. Other natural emitters of EM radiation include rain, dust and snowstorms, fires, and other natural events. However, all these sources present a low threat of EMI.

Man-made sources of EMI can be broken down into two broad categories—unintentional and intentional (see Figure 3-1). While the list included in Figure 3-1 is not exhaustive, it gives a good overview of just how many sources must be considered in designing different devices and systems. Unintentional radiators are devices that conduct electrical currents and generate EM waves because of their operation. As explained in the Introduction, when a current passes along a wire, circuit board, or other path, some EM field is radiated out, away from the source. For example, electric motors not only carry currents in their coils but also use rotating magnetic fields to generate torque. The passing of the current through the coil and the rotating magnetic fields generate enough EM radiation that they can interfere with other nearby devices if proper shielding is not used.

Intentional sources constitute an even longer list than unintentional sources. These are all the devices used for communications or measurement—any device that transmits a signal (no matter the distance) is an intentional source of EM radiation. The more obvious examples of intentional radiators include cell phones, transmitters, laptops, etc. However, measuring devices also transmit signals, such as an X-ray machine or a laser-beam rangefinder, and are also intentional radiators that must be considered. To narrow the field of potential intentional radiators applicable to any design, it is important to consider the intended application of the device(s) being built and what other electronic systems are typical of the setting in which it is to be used. This is not as useful an exercise for highly mobile devices like cell phones.

3.2 DEFENSES

Regardless of the source, the strategies for defending against EMI are universal and apply across all situations. Defenses, or methods for mitigating and preventing EMI, can be generally broken up into regulation, shielding, and infrastructure defense. These categories cover most of the methods necessary to ensure reliable and continuous use of electronic devices and avoid catastrophic failure in most situations. These methods are effective in times and places of peace and cooperation, but more robust methods may be necessary in hostile or wartime situations.

3.2.1 Regulation

The first line of defense is regulating the sources. Regulations apply to everything from the materials used in a device to the amount of radiation leakage allowed to the frequency at which the device can emit. Appendix C in "Electromagnetic Shielding" by Celozzi et al. [39] contains a thorough list of the regulations and standards for measuring EMI across international regulatory bodies. Many of these standards were initiated by the U.S. Department of Defense (DoD) in the early days of radio. As the electronic age grew in importance from communications to computing, instruments, and more, the need to control unwanted emissions also grew. Now there are organizations like the FCC, the NSA, and the International Electrotechnical Commission (IEC) who regulate and produce standards and policies across a broad range of electronics topics. Not only do these regulations and standards apply across all civilian electronics applications, but there are also military standards (MIL-STDs) for weapons systems, avionics, military communications systems, and many more DoD applications.

A list of standards, regulations, and agencies is given in Section 4.0 of this report. The list can be used as a point of reference for determining design requirements and standards of EMI and electromagnetic compatibility (EMC) for any device or system being built and for retrofitting or upgrading legacy systems. These regulations and standards guarantee that devices can operate simultaneously in shared spaces. As technologies advance, revising old standards and implementing new standards will be necessary to maintain harmonious operation of all devices.

3.2.2 Shielding

Shielding is based on the use of materials to either reflect, absorb, or perform both activities against EM radiation. This was discussed previously in Section 1.0, and materials are discussed in significantly greater detail in Section 5.0.

3.2.3 Defense Infrastructure (DI)

The greatest challenge lies in the infrastructure sector. Infrastructure is large and diffuse and by its very nature, difficult to defend. Further complicating things, much of the critical infrastructure is under civilian control by many different agencies or private owners. Civilian companies oversee their own maintenance and upkeep, which may not be conducted on a schedule—or in a manner—beneficial to civilian or government customers. Delays in maintenance, a lack of proper upkeep, misaligned goals or intentions, and other issues can lead to gaps or failures in infrastructure capabilities, performance, and protection. With much of the critical infrastructure privately owned, the DoD depends on commercial infrastructure to support its normal operations, despite it not being immediately under the jurisdiction of the DoD.

The portions of infrastructure controlled by the DoD are known collectively as the DI. This spans everything from military bases, air strips, and dams and levees to fuel pipelines, GPS satellites, power grids, and communications installations. The DoD is required to maintain its own facilities under PDD-63, issued in 1998 by President Clinton [40]. The directive identifies 10 infrastructure sectors, which are given in Table 3-1 (pictorial examples are shown in Figure 3-2, where the images represent the wide-ranging scope of things classified as critical infrastructure).

Legacy technologies up through the 1990s are almost entirely obsolete in the modern day, and most, if not all, of it has been overhauled since their inception. The increasing pace of technological advancements throughout the last half-century, and especially the last two decades, has outpaced the policy directives written to protect the infrastructure. This leaves any number of vulnerabilities that can be exploited and used against the United States or any other target nation in an attack. In the event of global conflict, the rules and regulations that organize day-to-day activities do not apply. Therefore, it is prudent that the United States should prepare for enemies to use EM radiation attack(s) as a method to disrupt critical equipment, both mobile and fixed. "Jamming" radio communications is one of the oldest examples of this; today, there is concern about collateral exoatmospheric effects of a HEMP and terrestrial effects of a HEMP on ground stations that could knock out satellite communications, as could attacks on satellites by directed energy weapons. To protect against jamming and attacks on communications infrastructure, system redundancy is key. In this case, redundancy can also mean multiple systems that operate via multiple modalities. Communications equipment should be able to transmit at multiple frequencies, and back up communications systems should be available if one or more primary systems are interfered with (e.g., a multiband radio, satellite radio, and signal light might all be included in a unit's communication equipment). New and evolving threats to critical DI are expected to continue to emerge in the future [41], and appropriate defense responses will be necessary to address them, including new and up-to-date policies.

Table 3-1. The 10 DI Sectors as Given on the Wikipedia Page [39]

Financial Services	Defense financial services support activities related to officially appropriated funds. These activities include the disbursement of cash, receipt of funds, and acceptance of deposits for credit to officially designated Treasury Department general accounts. This sector also provides financial services to individuals and on-base organizations, including deposits, account maintenance, and safekeeping. The Defense Finance and Accounting Service is the lead component for this sector.
Transportation	The defense transportation system includes resources that support global DoD transportation needs. These include surface, sea, and lift assets; supporting infrastructure; personnel; and related systems. The Transportation Command is the single manager for this sector.
Public Works	Public works includes four distinct physical infrastructure sectors: electric power, oil, and natural gas; water; sewer; and emergency services, such as fire, medical, and hazardous material handling. This DI sector is composed of networks and systems, principally for the distribution of the associated commodities. The Corps of Engineers is responsible for coordinating the assurance activities of this sector.
Global Information Grid/ Command Control (GIG/C2)	The GIG/C2 are two combined sectors that support overall asset assurance for critical infrastructure protection (CIP). The GIG is the globally interconnected set of personnel, information, and communication capabilities necessary to achieve information superiority. C2 includes assets, facilities, networks, and systems that support mission accomplishment. The Defense Information Systems Agency is the lead component responsible for these sectors.
Intelligence, Surveillance, and Reconnaissance (ISR)	The defense ISR infrastructure sector is composed of facilities, networks, and systems that support ISR activities, such as intelligence production and fusion centers. The Defense Intelligence Agency is responsible for coordinating the assurance activities of this sector.
Health Affairs	The health care infrastructure consists of facilities and sites worldwide. Some are located at DoD installations; however, the DoD also manages a larger system of nonDoD care facilities within its health care network. These health care facilities are linked by information systems. The Office of the Assistant Secretary of Defense, Health Affairs is the designated lead component for this sector.
Personnel	The defense personnel infrastructure sector includes many assets hosted on component sites, a network of facilities, and information systems linking those sites and facilities. In addition to being responsible for its own assets, this sector also coordinates commercial services that support the personnel function. These services include recruitment, record-keeping, and training. The Defense Human Resources Activity is the designated lead component for this sector.
Space	The defense space infrastructure sector is composed of both space- and ground-based assets, including launch, specialized logistics, and control systems. Facilities are located worldwide on both DoD-controlled and private sites. This sector is led by the United States Strategic Command.
Logistics	The defense logistics sector includes all activities, facilities, networks, and systems that support the provision of supplies and services to U.S. forces worldwide. Logistics includes the acquisition, storage, movement, distribution, and maintenance of material and supplies. This sector also includes the final disposition of material no longer needed by the DoD. The Defense Logistics Agency is the lead component for this sector.
Defense Industrial Base	The defense industrial base consists of DoD product and service providers from the private sector. The services and products provided constitute critical assets for the DoD. The lead component for this sector is the Defense Contract Management Agency. For those cases when infrastructure protection requirements affect more than one defense sector, the DoD has set up special function components that support the implementation of CIP.

Figure 3-2. Examples of Critical Infrastructure: (Left) Bayou Bienvenue Vertical Lift Gate [42] and (Right) Short-Wave Radio Tower by the TRI Austin Lab Facility for Long-Range State Police Communications (Also Supports Multiple Cell Transceivers) *(Source: TRI Austin)*.

The issues are so complex that writing a single piece of legislation to protect all the critical parts may not be possible. There is no overarching piece of legislation explicitly protecting infrastructure in the United States. However, there have been several presidential directives on the issue, and Wikipedia has a list of actions undertaken, mostly by the DoD, to protect systems [40]. Presidential directives, such as PDD-63, have filled the gaps. Most recently, Congress passed a more limited law aimed at cybersecurity, the Cybersecurity and Infrastructure Security Agency Act of 2018 [43]. This act created the Cybersecurity and Infrastructure Security Agency, which aims to strengthen the United States' resilience to cyberattacks as well as identify threats to critical infrastructure (e.g., the recent attack on the Colonial Pipeline that caused gas shortages across the eastern United States).

A selection of examples of relevant legislation and executive orders includes the following:

- Critical Infrastructure Protection Act appended to the FY2017 National Defense Authorization Act, Section 1913 "EMP and GMD Planning, Research and Development, and Protection and Preparedness," Public Law 114-328 (23 December 2016).
- White House, "Executive Order on Coordinating National Resilience to Electromagnetic Pulses" (26 March 2019).
- FY2020 National Defense Authorization Act, Section 1740 "Electromagnetic Pulses and Geomagnetic Disturbances," Public Law 116-92 (20 December 2019).

The unclassified reports of the Congressional EMP Commission are also definitive for informing public policy and can be found at www.firstempcommission.org.

3.3 IMPLEMENTATION

There are many ways shielding can be devised to protect against EMI—from large, building-level installations to the small metal coverings used on computer processing chips. The applications constitute a broad range of uses across the civilian and military sectors, and new applications are being developed regularly in parallel with advancing technologies. Selected examples are used here to illustrate the myriad and diverse ways that EM shielding and other defense measures are used to protect devices and infrastructure.

3.3.1 Civilian

3.3.1.1 Microwave Oven

A very common example of everyday use of EM radiation is the microwave oven. Microwaves use centimeter-length radio waves to excite the water molecules in food, thereby heating it up. However, if a microwave oven leaked this radiation into the surrounding room, it would pose a serious health risk. The basic physics of microwave EM heating is covered by Volmer in "Physics of the Microwave Oven" [44]. The degree of shielding needed for a microwave includes a screen and a seal for the door. The metal screen imbedded in the glass acts as a mirror and reflects the microwaves back into the oven chamber. The screen is a simple, straightforward, and effective measure. The door seal, however, is more complicated. In the early days of microwave ovens, simple, compressible, conducting seals would degrade over time and therefore leak radiation. Radiation detectors were even sold for a time for people to check their home microwaves for leaks. In modern designs, a choke structure is built into the door, hidden below the surface. This device uses destructive interference to zero out the EM field around the edges of the door. Since the choke is not exposed, it remains effective over the life of the microwave oven. This seal ensures that EM radiation remains below the watts-per-square-meter level at the door joint and significantly below that as one moves away from the oven door [45].

3.3.1.2 Building Construction

Materials used in office and other building construction projects act as EM shields. For example, filler materials are being developed that can be added to plaster [5] or gypsum particle board [46] (drywall) to increase its shielding properties. In an article from *Advances in Materials Science and Engineering* [5], carbon fibers were added to create electrically conductive paths within plaster. In another article from *Journal of Materials in Civil Engineering* [46], FeSiB ribbons were added to accomplish the same effect. Depending on the material used and its geometry, different frequency ranges can be shielded, and different degrees of reflection or attenuation can be accomplished. Any means to shield against EM radiation adds some degree of cost to the materials required. As a result, current efforts are trending toward focusing on adding small amounts of low-cost additives to traditional building construction materials [3].

3.3.1.3 Telecommunications

Telecommunications are central at all levels of operation in civilian and military life. A very good overview of the issues for civilian and military applications is given in Military Aerospace and Electronics [47]. As noted in the article of this reference, "Aerospace and defense applications, platforms, and environments are undergoing a digital transformation, and the proliferation of portable electronics devices and embedded electronics systems is contributing to a significant increase in RF emissions that could cause interference, data corruption, or worse."

EMI problems for telecommunications occur in wired and wireless devices. In wired devices, an example EMI problem is magnetic induction from alternating current (AC) power mains being too close to data cables and causing interference in the form of voltage spikes. Data centers and internet provider router facilities consider these noise sources and address all EMI issues through architectural design and traditional shielding when constructing buildings. When an AC current flows in a wire, regardless of the intention, the wire acts as an antenna and radiates EM waves at different frequencies. The higher the frequency, the more power is radiated. As modern electronics advance to higher speeds, higher frequencies are needed, and more EM radiation is produced. Electronic enclosures are designed to keep EM radiation from escaping, but every connector into or out of the enclosure is a possible source of leaks. Currently, new types of connectors are being developed that incorporate the connector into part of the shield. Gaskets and flexible seals to block EMI are constantly being improved with the developments of new materials and the use of previously developed materials in novel ways. A thorough overview of the current state of these materials and designs is given by Chung in "Materials for Electromagnetic Interference Shielding" [48].

Wireless communications have a different set of challenges. Since these devices are all essentially radios of one type or another, they function by emitting and receiving EM radiation. As a result of their specific frequency operation, these devices need to be shielded from all other frequencies except the one of interest. To achieve this, the antenna needs to be isolated from the rest of the electronic circuit. Mobile craft (e.g., cars, aircraft, etc.) containing wireless communication equipment are very challenging EM shielding targets, as weight, size, and, in some cases, the types of materials that can be used, become critical design issues. Different parts of the circuit must be isolated from each other as well as from the outside world (keeping power supplies isolated from transceivers to ensure that stray voltage does not affect any incoming/outgoing signals). New materials are being developed to block EM signals, usually by absorption and not reflection, to meet these needs. For example, three-dimensional (3-D)-printed plastics have been modified to contain nanomaterials that block EMI [49]. The ability to "coat" these components in this way offers a unique capability that did not previously exist [50]. In addition, greater numbers of systems are being deployed that use navigational tools (such as GPS to navigate). One example of this is radio-controlled drones (or unmanned aerial vehicles [UAVs]) that must receive signals to navigate and communicate with GPS to provide feedback to the operator.

3.3.2 Military

3.3.2.1 GPS

The GPS network was established, and is still operated, by the U.S. military. There are currently 31 operational GPS satellites in the U.S. network, 8 of which are legacy satellites and 23 of which are modern satellites. Initially, GPS operated on two frequency bands with only two signal codes. The L1 frequency band, operating at 1575.42 MHz, first carried the course/acquisition code for civilian and military use and the precision/secure (P/Y) code for encrypted military use [51]. The L2 band, operating at 1227.60 MHz, first carried only the P/Y code for additional military use.

However, because of the precise broadcasting frequency and the range over which the signal travels (weaker frequency over longer distances), GPS is highly susceptible to jamming and spoofing. For example, Ukraine has reported that Russian forces jammed GPS and cellular communications in EM attacks in 2020 [52]. And, not only is jamming a military threat, but it is used against civilian and federal operators as well. Cheap, small, and easy-to-use jamming devices are a common tool used by criminals and other citizens; can affect nearby vehicles, homes, or businesses; and are difficult for law enforcement to identify and track down [53]. An article by *Military & Aerospace* gives an example of how one of these devices affected an airport [54]:

> In another incident measured at Boston Logan Airport in Massachusetts, the airport's ground-based aircraft-approach system recorded temporary anomalies caused by a simple cigarette lighter-powered electronic jammer in a vehicle passing nearby the airport.

In addition to jamming, spoofing of GPS satellites via cyberattacks is anticipated to be a tactic employed in future attacks against U.S. operations. Due to these emerging and imminent threats, the United States has been taking strides to modernize and expand its GPS infrastructure.

Three new dual-use civilian and military GPS signals are being rolled out on new satellite launches, and the military M-code is also in development [55]. In 2005, the United States began launching a new series of satellites (GPS Block IIR-M) with the L2C signal for civilian use, which provides higher accuracy, especially in dual-frequency receivers, and operates on the L2 band. The L5 frequency band, which operates at 1176 MHz, is a dedicated emergency frequency for aviation. It began launching on the Block IIF satellites in 2010 and will continue to be rolled out, along with the L2C signal band into the mid-2020s. The final new civilian signal, L1C, enables international interoperability with other positioning, navigation, and timing systems and operates on the L1 band. This signal began launching on Block III satellites in 2018 and will be rolled out through the late 2020s. The M-code, a secure signal being developed for military use, is still being designed and implemented. Once operational, this signal will provide additional security to U.S. navigation and GPS signal use from spoofing, jamming, and other attacks by adding redundancy in communications.

3.3.2.2 Heat-Seeking Missile Countermeasures

A simple example of how EMI is used intentionally and effectively in the military is by using heat-seeking missile countermeasures. The techniques used are explained by Ryan McDaniel in an article in *Aerospace & Defense Technology Magazine* [56]. Heat-seeking missiles use infrared (IR) signals to lock onto the heat signature of an aircraft engine, which presents a very bright target and can be tracked up to three miles away. Flares or chaff may be used to divert a heat-seeking missile, but they have a short burn time and there is a limited supply on any given aircraft. Instead, to spoof the tracking system on the missile, a block of high-temperature material can be heated until it produces a significant enough IR signal to simulate the aircraft's heat signature. An enclosure around the super-heated block modulates the output of the IR signal, which interferes with the targeting and tracking technology of the missile, thereby redirecting and sending it off course. The block may be directly mounted to the aircraft or towed behind it in a manner to achieve the same effect. McDaniel states that even as missile technologies have improved, so too have the refinements in this countermeasure technique, and it remains a viable approach.

3.3.2.3 Future Implementation of EMI as a Weapon

Within the military specific sphere, all the examples discussed here apply to day-to-day operations of the military. Wartime fighting becomes even more complicated. As an example, much of our military weaponry has shifted to autonomous electronic systems. These systems are subject to EMI by natural/human source, intentional jamming by adversaries that can disorient guidance and control system, or spoofing, by which a signal is sent that replaces a standard navigation signal. This is how Iran was believed to have taken control over and crashed a drone aircraft [57].

Special mention should be made of the ongoing technological revolution in non-nuclear EMP weapons (NNEMPs), which are becoming more powerful, miniaturized, lighter weight, and deliverable by cruise missiles or drones. The marriage of NNEMP warheads to drones or cruise missiles, preprogrammed or equipped with sensors to follow high-power electric lines and target control centers and transformers, introduces a major new threat to national power grids [58].

A non-explosive, high-power microwave warhead, for example, can emit repeated bursts of electromagnetic energy to upset and damage electronic targets. Such a warhead, attached to a programmable drone or cruise missile, could follow the powerlines to attack numerous transformer and control substations until its energy is exhausted.

Relatively small numbers of NNEMP cruise missiles or drones—perhaps only one capable of protracted flight—could inflict a long, nationwide blackout. Reportedly, as noted earlier, according to a classified study by the U.S. Federal Energy Regulatory Commission, disabling just 9 of 2,000 U.S. extra-high-voltage transformer substations could cause cascading failures that would crash the North American power grid [59].

The "cascade failure" problem, warns Dr. Carlo Kopp, makes modern digital societies highly vulnerable to NNEMP attack [60]:

> Digital infrastructure is highly interconnected and thus interdependent. Because of common reliance on power grid, telecommunications cable and wireless connections, local and remote servers, single and multiple site clouds

> and grids, consequently, a mass destruction effect in one geographical area can cause cascading failures as interdependent systems fail…*Damage effects are thus no longer localized in extant, e.g., destroying a server or Cloud in Washington, D.C. may cripple dependent systems globally.*

Thus, NNEMP might be able to achieve results similar to a nuclear HEMP attack in blacking out power grids, though the NNEMP attack would probably take hours instead of seconds.

Another potential instance that will require shielding in the future is personnel protection from microwave attack. This type of attack is a directed energy attack that disables soldiers, rendering them non-functional by heating the outer layers of their skin. This type of attack was recently employed by China against Indian troops as part of a border dispute [61, 62].

SECTION 04 STANDARDS FOR EMI AND INSTRUMENTS

Designing EM shielding is a complex task, and measuring a design's effectiveness is not always straightforward. The goal of any design is to prevent unintended interference, but any potential missteps can easily derail an effective design, such as improper material selection, gaps or holes in the construction, or poor circuit design. To effectively design EM shielding and test a device's SE, regulations and standards for both tests and designs are necessary. Many of the most used and referenced standards are MIL-STDs. SCL 49 was one of the first military regulations on EMI. Over decades of revision and growth, it has become the current standard MIL-STD-461E. This and other military standards, such as MIL-STD-137 [39], are used by both the military and civilian companies to design and measure SE.

As time has passed, other organizations have had to create standards for EM applications within their control or purview. Some of the largest organizations include, but are not limited to, the Institute of Electrical and Electronics Engineers (IEEE), ASTM International (ASTM), NSA, FCC, American National Standards Institute (ANSI), Comité International Spécial des Perturbations Radioélectriques (CISPR; English: International Special Committee on Radio Interference), IEC, and International Telecommunication Union (ITU). Some of these organizations are U.S. based, while others are international bodies. Depending upon the application, standards from both international and/or national sources may apply, although the growth of independent national standards has created barriers to product development and trade through conflicting or redundant requirements.

Each of these standards is used for specific applications and defines how the measurements are to be made, which units to use, the geometry of the measurement, etc. Examples of this are seen in Figure 4-1, which shows the required geometry to measure the shielding of an enclosed space, and Figure 4-2, which shows the geometry required to measure the SE of different materials. Measurements are made on SE, EM transmission, EM immunity, effectiveness at different frequencies, effectiveness

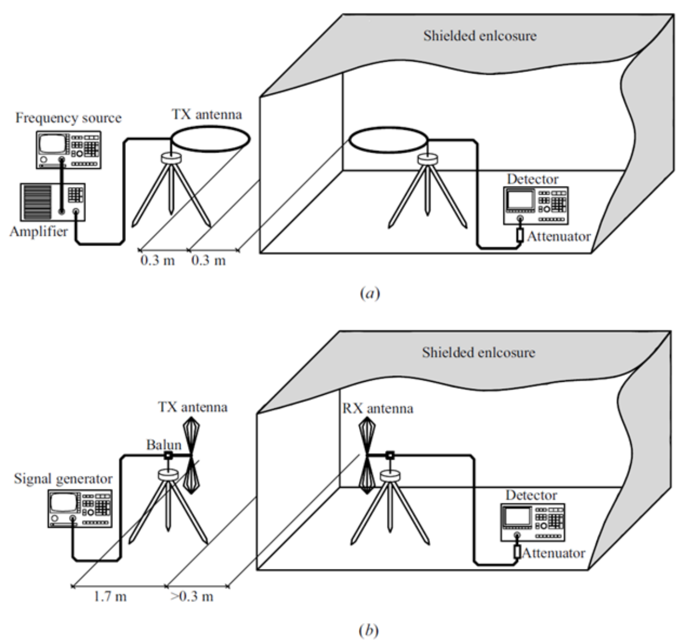

Figure 4-1. IEEE STD-299 Measurement Setup: (a) Low-Frequency Range and (b) Resonant and High-Frequency Range. IEEE STD-299 Is Designed to Measure Shielding of Enclosed Rooms Like a SCIF (Figure Reproduced From Celozzi et al. [39]).

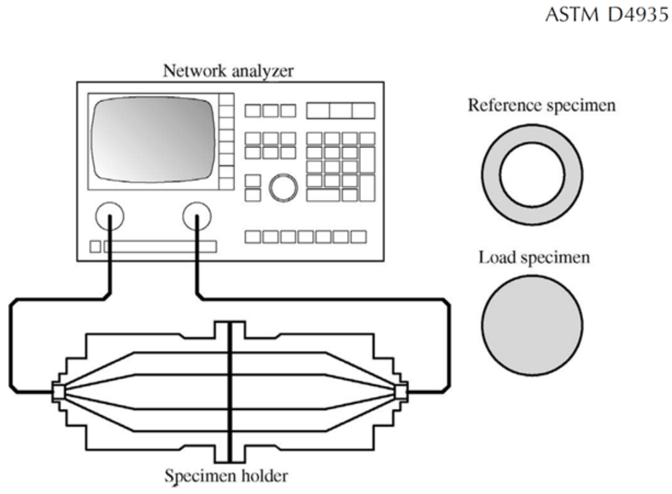

Figure 4-2. ASTM Standard D4935 Is Applied to Measure the SE of Planar Materials (Reproduced From Celozzi et al. [39]).

with different transmission patterns (pulsed, continuous, etc.), and many other parameters, depending upon the device requirements and application.

While standards are very important in quantifying the SE of materials, they can be expensive to measure. Setup can take many hours, and instruments must be calibrated, which are expensive. There are situations in the laboratory when a device needs to be shielded, and all that is needed is a comparison of available materials to shield a particular device. Cost considerations can be important when working in universities and other labs, especially in labs with limited resources. To this end, a group working in the Philippines published a simple method to measure the SE of common shielding materials using an inexpensive, commercially available field strength meter [63]. This simple tabletop measurement is shown in Figure 4-3. The result is the ability to make simple comparisons between different materials without going through the time and expense for a fully standardized test. For finished products that must pass inspections, this method is insufficient. However, in labs developing new materials for shielding applications, intelligently employed workarounds like these can save time and money and accelerate the research process.

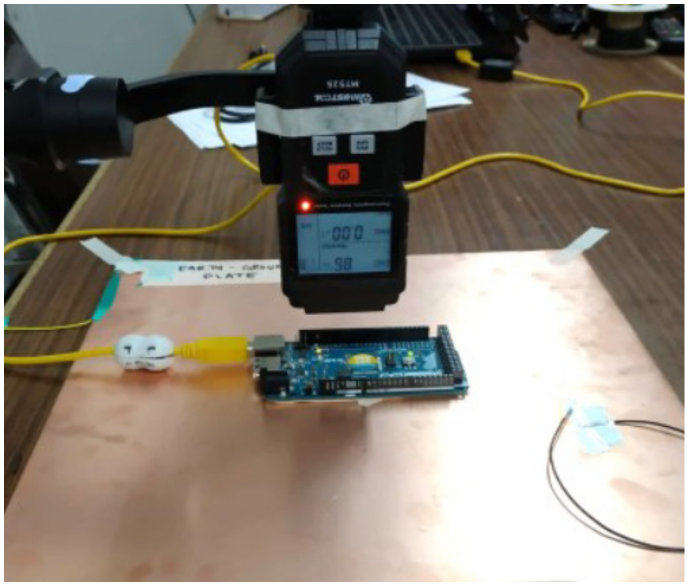

Figure 4-3. Arduino Mega ADK Rev3 Used as the Radiation-Emitting Test Device [64].

The book *Electromagnetic Shielding* [39] includes a list of current standards in Appendix C. This list is included in Table 4-1; this is a valuable reference on the details of how shielding is used and how standards are defined and measured. As previously noted, shielding is a complex problem. Chapter 3 in *Electromagnetic Shielding* [39] gives several different "figures of merit" for measuring the effectiveness of EM shielding. Ultimately, when making comparisons between systems, great care must be taken to use the correct definitions.

Table 4-1. List of EMI/EMC Standards Provided in Celozzi et al. [39]

Military Standards/Military Handbooks (MIL-STD/MIL-HDBK)
MIL-STD-285. "Military Standard. Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of." U.S. Government Printing Office (GPO), Washington, D.C., 25 June 1956.
MIL-HDBK-1195. "Military Handbook—Radio Frequency Shielded Enclosures." U.S. GPO, Washington, D.C., 30 September 1988.
MIL-HDBK-1857. "Grounding, Bonding, and Shielding Design Practices." U.S. GPO, Washington, D.C., 27 March 1998.
MIL-HDBK-419A. "Military Handbook—Grounding, Bounding, and Shielding for Electronics Equipment and Facilities." U.S. GPO, Washington, D.C., 29 December 1987.
MIL-STD-462D. "Military Standard. Measurement of Electromagnetic Interface Characteristics." U.S. GPO, Washington, D.C., 11 January 1993.
MIL-STD-461E. "Department of Defense Interface Standard. Requirements for the Control of Electromagnetic Interface Characteristics of Subsystems and Equipments." U.S. GPO, Washington, D.C., 20 August 1999.
MIL-STD-1377. "Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding Hazards of Electromagnetic Radiation to Ordnance, Measurement of." U.S. GPO, Washington, D.C., 1971.
National Security Agency (NSA)
NSA 73-2A. "National Security Agency. Specification for Foil RF Shielded Enclosure." NSA, Fort George G. Meade, MD, 15 November 1972.
NSA 65-5. "National Security Agency. RF Shielded Acoustical Enclosures for Communications Equipment: General Specification." NSA, Fort George G. Meade, MD, 30 October 1964.
NSA 65-6. "National Security Agency. Specification for Shielded Enclosures for Communications Equipment: General Specifications." NSA, Fort George G. Meade, MD, 30 October 1964.
NSA 94-106. "National Security Agency. Specification for Shielded Enclosures." NSA, Fort George G. Meade, MD, 24 October 1994.
Comité International Spécial des Perturbations Radioélectriques (CISPR)
CISPR 14-2. "Electromagnetic Compatibility–Requirements for Household Appliances, Electric Tools and Similar Apparatus—Part 2: Immunity–Product Family Standard." International Special Committee on Radio Interference, 15 November 2001.
CISPR 20. "Sound and Television Broadcast Receivers and Associated Equipment. Immunity Characteristics—Limits and Methods of Measurement." International Special Committee on Radio Interference, 27 November 2006.
CISPR 11. "Industrial, Scientific, and Medical (ISM) Radio-Frequency Equipment—Electromagnetic Disturbance Characteristics–Limits and Methods of Measurement." International Special Committee on Radio Interference, 25 June 2004.
CISPR 13. "Sound and Television Broadcast Receivers and Associated Equipment—Radio Disturbance Characteristics–Limits and Methods of Measurement." International Special Committee on Radio Interference, 13 March 2006.
CISPR 14-1. "Electromagnetic Compatibility–Requirements for Household Appliances, Electric Tools and Similar Apparatus—Part 1: Emission." International Special Committee on Radio Interference, 13 November 2005.
CISPR 15. "Limits and Methods of Measurement of Radio Disturbance Characteristics of Electrical Lighting and Similar Equipment." International Special Committee on Radio Interference, 17 January 2007.
CISPR 22. "Information Technology Equipment—Radio Disturbance Characteristics– Limits and Methods of Measurement." International Special Committee on Radio Interference, 20 March 2006.
International Electrotechnical Commission (IEC)
IEC 61547. "Equipment for General Lighting Purposes—EMC Immunity Requirements." IEC, 20 September 1995.
IEC 61000-6-1. "Electromagnetic Compatibility (EMC)—Part 6-1: Generic Standards–Immunity for Residential, Commercial, and Light-Industrial Environments." IEC, 9 March 2005.
IEC 61000-6-2. "Electromagnetic Compatibility (EMC)—Part 6-2: Generic Standards–Immunity for Industrial Environments." IEC, 27 January 2005.

IEC 61000-4-3. "Electromagnetic Compatibility (EMC)—Part 4-3: Testing and Measurement Techniques—Radiated, Radio-Frequency, Electromagnetic Field Immunity Test." IEC, 7 February 2006.
IEC 61000-6-3. "Electromagnetic Compatibility (EMC)—Part 6-3: Generic Standards–Emission Standard for Residential, Commercial, and Light-Industrial Environments." IEC, 17 July 2006.
IEC 61000-6-4. "Electromagnetic Compatibility (EMC)—Part 6-4: Generic Standards–Emission Standard for Industrial Environments." IEC, 10 July 2006.
IEC 61000-2-5. "Electromagnetic Compatibility (EMC)—Part 2: Environment—Section 5: Classification of Electromagnetic Environments. Basic EMC Publication." IEC, 22 September 1995.
IEC 61000-4-21. "Electromagnetic Compatibility (EMC)—Part 4-21: Testing and Measurement Techniques–Reverberation Chamber Test Methods." IEC, 26 August 2003.
International Telecommunication Union (ITU)
ITU-T K.42 Recommendation. "Preparation of Emission and Immunity Requirements for Telecommunication Equipment—General Principles." Telecommunication Standardization Sector of ITU, May 1998.
ITU-T K.34 Recommendation. "Classification of Electromagnetic Environmental Conditions for Telecommunication Equipment—Basic EMC Recommendation." Telecommunication Standardization Sector of ITU, July 2003.
ITU-T K.43 Recommendation. "Immunity Requirements for Telecommunication Equipment." Telecommunication Standardization Sector of ITU, July 2003.
ITU-T K.60 Recommendation. "Emission Limits and Test Methods for Telecommunication Networks." Telecommunication Standardization Sector of ITU, July 2003.
ITU-T K.38 Recommendation. "Radiated Emission Test Procedure for Physically Large Systems." Telecommunication Standardization Sector of ITU, October 1996.
ITU-T K.48 Recommendation. "EMC Requirements for Telecommunication Equipment—Product Family Recommendation." Telecommunication Standardization Sector of ITU, September 2006.
Other
ANSI C63.4. "Methods of Measurement of Radio-Noise Emissions From Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz." ANSI, 30 January 2004.
ANSI-SCTE 48-3. "Test Procedure for Measuring Shielding Effectiveness of Braided Coaxial Drop Cable Using the GTEM Cell." ANSI and Society of Cable Telecommunications Engineers (SCTE), Exton, PA, 2004.
ASTM E1851. "Standard Test Method for Electromagnetic Shielding Effectiveness of Durable Rigid Wall Relocatable Structures." ASTM, West Conshohocken, PA, 2004.
ASTM D4935 (Withdrawn). "Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials." ASTM, West Conshohocken, PA, June 1999.
Code of Federal Regulations, Title 47, Part 15. "Radio Frequency Devices" (Subpart A—General; Subpart B—Unintentional Radiators; Subpart C—Intentional Radiators). FCC, 10 January 1998.
FCC/OET MP-4. "FCC Procedure for Measuring RF Emissions From Computing Devices." FCC—Office of Engineering and Technology (OET), July 1987.
IEEE STD-299–2006. "IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures." IEEE, Piscataway, NJ, 28 February 2007.

SECTION 05 MATERIALS FOR EMI SHIELDING

The challenges to EMI and shielding against it are well known and grounded in basic physics. Recall that an electromagnetic wave has two components—the electric field vector and the magnetic field vector. The challenge with shielding against these two components depends upon the frequency. In general, at low frequencies (DC to ~10-kHz range), an enclosure made of material that is a good electrical conductor, such as a metal, is enough to screen the electric field from passing through, but the magnetic field passes through easily because there are no magnetic dipoles in the material to block it. To this end, magnetic shielding often uses materials that are strongly ferromagnetic, such as iron, nickel, and cobalt, to couple with the magnetic field, preventing it from passing through the enclosure and instead diverting it around the enclosure. A simple example of this is the ferrite core. This device is often used on the signal lines and power cords of sensitive laboratory instruments, although it is noted that these act only on common-mode noise (signals or noise that flow in the same direction in a pair of lines) and not normal mode noise (signals or noise that flow in opposite directions in a pair of lines).

Moving to higher frequencies (greater than ~10 kHz), a material's conductivity becomes the paramount parameter. The magnetic component of the field induces currents in a conductor, known as eddy currents, that, in turn, produce a magnetic field opposite to the induced field. This is called the back electromotive force and results in a reflection of the external magnetic field. In addition, the eddy currents convert some of the incoming energy into heat by ohmic heating from the electrical resistance of the conductor. The combination of this reflection and loss to heating blocks the magnetic field from passing through the shielding material. These eddy currents are utilized in electromagnetic braking for trains and roller coasters to stop the high-speed vehicles without the need for friction brakes with contacting brake pads [64].

For lower frequency (<10 kHz) electric field components, a Faraday cage (or a Faraday bag) is an effective shield. Conducting electrons make the material behave like a mirror, as the free electrons in the material react to the electromagnetic field and form a barrier at the surface impacted by the incident wave. In general, the higher the electrical conductivity of a material, the better the material acts as a mirror to any incident EM wave. At lower frequencies, a Faraday cage is more than sufficient to protect any device. Traditional materials for shielding against an electric field are generally made of bulk metals like nickel, iron, silver, copper, etc., which tend to be heavy and prone to chemical corrosion. However, a Faraday cage can be made of metal mesh, which is generally cost effective.

Most present-day materials research and development are being conducted on the study and creation of new and more effective materials for EM shielding applications, particularly those effective in the higher frequency ranges. Given the rapid proliferation of electronics and the rise of 4- and 5-GHz communications, high-frequency material EM shielding is now a vast area of research. While currently available commercial materials are proven for shielding applications, many of them are heavy (high density), expensive, inflexible, opaque, and/or limited in supply, among other drawbacks. Current materials research focuses on overcoming these limitations by either improving on current materials or developing entirely new ones with better properties.

One example of improved materials is the use of modern shielding materials impregnated with ferromagnetic nanoparticles to increase the SE of materials when employed for lower frequency applications. The EM shielding processes that take place in these materials operate slightly differently from traditional magnetic shielding (which uses a closed volume to complete a magnetic loop and trap the magnetic field to prevent it from passing through the material). For materials impregnated with ferromagnetic nanoparticles, the particles interact with the field in such a way as to dissipate the energy of the passing field. This process produces the best SE at higher frequencies, i.e., >1 MHz. In terms of electric field shielding, the goal of using advanced materials is for shielding to increase the reflectivity and/or heat losses (conversion of electricity to heat) within the material. As always, an ultimate goal is producing materials capable of providing better SE values for less volume and less mass.

5.1 CURRENT MATERIALS

Materials-based EM shielding technology has been used for close to a century since the dawn of the electronic age to try to mitigate interference from nearby EM waves that disrupted the operations of electronic devices. The discovery of EMI in early electronics led to the development of early shielding materials, most of which are still in use in some capacity today.

The ferromagnetic materials used to shield the low-frequency magnetic spectrum are known as Mu-metals and include a blend of primarily iron and nickel, along with other metals at smaller concentrations (an example of these metals is shown in Figure 5-1 [65]). Mu-metals are malleable, but heavy, and susceptible to shocks and further mechanical working (bending) after the annealing process, which can degrade performance. An alter-

Figure 5-1. Mu-Metal Enclosures Used to Create EM Shielded Areas [65].

native to Mu-metals is Metglas ("a thin, amorphous, metal alloy ribbon produced by using rapid solidification processes to create unique ferromagnetic properties that allow the ribbon to be magnetized and demagnetized quickly and effectively with very low core losses" [66]). Ferrite materials are also used for magnetic shielding at higher frequencies [3] and include manganese-zinc, nickel-zinc, strontium, barium, and cobalt to block eddy currents and reduce reflected current inside a cavity structure [67]. Ferrites are used to make the magnetic cores in devices requiring highly conducting materials, such as transformers, antennas, and electric motors.

To shield from interfering effects of an electric field, enclosures are made of very good conductors, such as copper, brass, aluminum, steel, silver, or even gold. Silver and copper can be electroplated in highly commercialized processes, and gold can be made into very thin sheets that allow it to be used economically from a weight and cost perspective. In addition, silver and gold both have very good conductivity and corrosion resistance. These metals are often used as parts of composites and have many applications. Copper, for example, is still used in shielding electrical wires. Aluminum, copper, and brass (and other metals) are used in metal mesh and gaskets (see Figure 5-2). These commercially available metal solutions are most often incorporated into everyday electronics but may not be the best choice for upcoming shielding challenges the DoD will face. All computers (desktops, laptops, tablets, smartphones, etc.) are still enclosed in a metal box or metal foil on the inside of a plastic casing to meet FCC emission standards. However, metals do have drawbacks. Besides being expensive, they can be heavy and susceptible to corrosion and are dense, brittle, or lack impact resistance, making this class of material less favorable for use in new devices [68]. To address these issues and push the boundaries of existing research, new materials, such as polymers, graphene, and nanomaterials, are being developed for modern shielding applications.

Flexible graphite is often used when a typical metallic is ineffective. Flexible graphite is natural flake graphite (carbon—usually >95%) that is screened and subjected to an acid-cleaning treatment. Flexible graphite is mainly used for the sealing industry. Flexible graphite sheets are mainly used in the electric power, petroleum, and chemical industries. Flexible graphite paper in these industries is mainly used in machinery, pipes, pumps, valve seals, and many other applications.

Coated polymers and conductive polymer matrices [49] are advantageous in that they effectively absorb EMI (via multiple reflections) rather than reflecting it (as single reflections can potentially interfere with other devices in the local environment [3]). In addition, these types of materials are desirable, as they are lightweight and have improved processability (it is easier to melt and process a polymer than a metal).

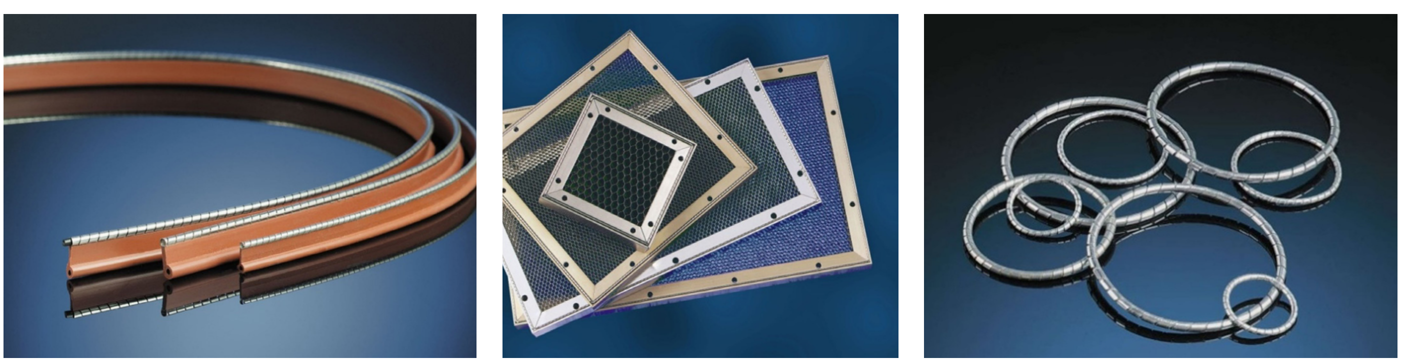

Figure 5-2. EMI Sealing Gaskets (Left), EMI Shielding Vents (Middle), and EMI Sealing O-Rings (Right) From Spira Manufacturing Corporation *(Source: https://www.spira-emi.com).*

Some polymers can conduct electricity within themselves without the need for additional conducting materials. Intrinsically conducting polymers (ICPs) can conduct electricity due to the conjugated bonds (alternating single and double bonds) between atoms within the polymer chains (see Figure 5-3). This enables the mobility of π-electrons (loose electrons), which act as mobile charges. The electric conducting property of ICPs can be modified through doping or de-doping. Some ICPs include polyaniline, polypyrrole, polyacetylene, polypyrrole, polyaniline, and polyphenylene. The use of ICPs is still under development since several problems exist concerning their mechanical and chemical stability. They are more extensively used as components to composites containing metal nanoparticles and carbon filaments.

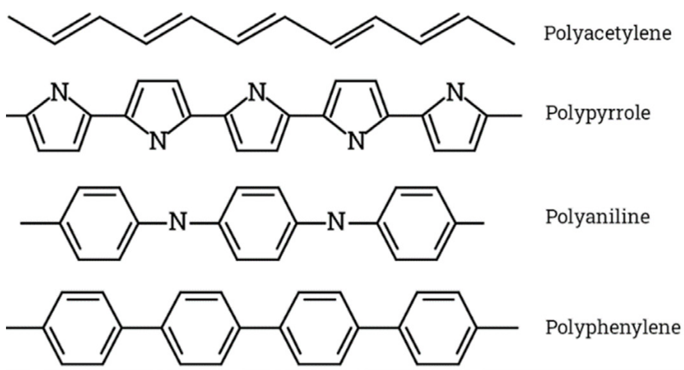

Figure 5-3. Alternating Single and Double Bonds Between Atoms in the Chains of Various Polymers That Can Provide the Bulk Material With Electrical Conductivity *(Source: Doyle Motes)*.

Non-electrically conducting polymers (common examples include acrylonitrile butadiene styrene, polylactic acid, polyethylene, and polyamide [also known as nylon]) can be filled with conducting particles (usually submicron or nanosized fillers) of metals, such as copper, nickel, or steel (see Figure 5-4). Polymers with these fillers have been developed for use today but are still a research subject in new materials, as new and better formulations and applications are still being devised. One encountered example of this that has appeared in the last 3–5 years is conductive material added to

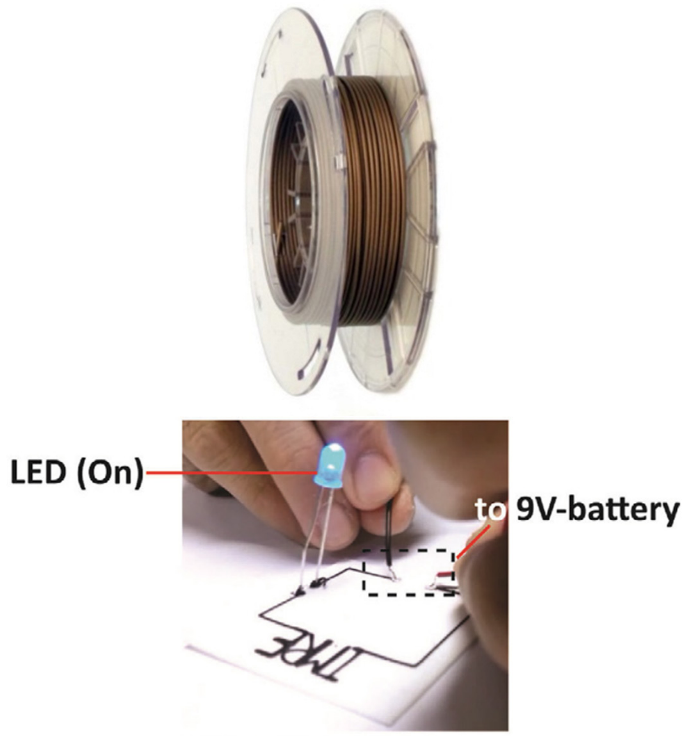

Figure 5-4. Application of Added Conductive Material (Metallic Particles) to Non-Conductive Material (Polymer) for Use as Coatings, Where Copper Is Mixed With Polylactic Acid to Create 3-D-Printed Electronic Circuit Paths [69].

3-D-printer filament, which can provide a "plastic" conducting path to allow construction of circuits (and if applied properly, EMI shielding).

Another material system that can provide EMI shield is carbon allotropes, which include materials like exfoliated graphite, graphene, carbon fibers, and carbon nanotubes. These are used as filler materials for EMI shield composites and operate primarily via absorption of EMI. Graphene, carbon fibers, and carbon nanotubes are used as filler materials due to their high aspect ratios and are commonly embedded in polymers, ceramics, cement, and metals to create rigid structures. For high-frequency shielding applications, graphene and carbon nanotubes are mostly used because the dimensions of these materials are less than the skin penetration depth of the generated eddy current.

Graphene, a single atom sheet of graphite, is typically used in multiple layers for all manner of applications, including EM shielding, aerospace industry, and medical equipment [3]. Graphene has excellent electrical, thermal, and conducting properties, making it a valuable and versatile shielding material. Despite several commercially available applications for exfoliated graphene as shielding for sealing surfaces (gaskets), films, coatings, and filaments [70], significant research continues into improving this material and its synthesis. Graphene is limited in terms of its SE by the number of layers used, as an increase in number of layers equates to a decrease in electrical conductivity until a bulk conductivity equivalent to graphite is eventually reached.

Another option is reduced graphene oxide(s) (RGO), which can be optimized by controlling the surface chemistry and defects. It is also easier to scale up the synthesis of RGO. (The authors note that within the literature, there can be ambiguity regarding the terms "reduced graphene oxide" and "graphene," which have been used interchangeably.) When graphite is exfoliated, the resulting material is usually around 10 atomic layers thick. Some researchers have referred to this material as graphene, which it is not (it has also been referred to as "few layer graphene"). Graphene, which is a single atomic layer of carbon in the graphite crystal structure, is being researched for EMI shielding because it is mostly transparent to optical light and very electrically conductive. There is interest in using it to replace indium tin oxide as the conducting layer on touchscreen displays.

In addition to metallic nanoparticles, nanocomposites, also known as nanofillers, are being used as additives in new and alternative shielding materials to boost SE and conductivity [3]. Nanocomposites overlap with graphene and other carbon allotropes (which are used as nanofiller materials) and polymers (used as the matrix for nanofillers), as well as metals. They are excellent candidates for use in the development of transparent shielding materials. Currently, nanocomposites are being used in building materials like sheetrock and cement to improve SE of rooms and buildings.

5.2 NEW MATERIALS AND APPLICATIONS

New materials and applications for EM shielding often follow the better, faster, cheaper mantra. These materials are required to be lighter, more flexible, transparent, and capable of operating at temperature extremes and/or operating at higher frequencies while maintaining or improving SE over traditional and current materials. New materials are not always true "new" materials but can be existing materials that are discovered to have conducting or other EM shielding properties not previously known. In addition, new materials may be improvements upon, or new formulations of, current materials to better tune and refine their SE. New applications requiring new or improved materials include transparent materials for touchscreens, flexible materials for easier fabrication and manufacturing, materials for wearables and fabrics, and higher frequency materials for 4G and 5G communications and the eventual advent of 6G communication. Military-specific, new applications include transparent materials for cockpits and avionics instruments, significantly stronger shielding materials to protect against EMP and microwave attacks (as well as flexible materials for wearable protection to these attacks that integrate with the human body or human worn textiles), lighter materials for portable communication devices, and more rugged materials for use in advanced warfare situations. There are countless more new and emerging applications, but the goal remains to find better and more suitable materials for these applications.

The recently published *Advanced Materials for Electromagnetic Shielding: Fundamentals, Properties, and Applications* [3] is a good resource for a review of newly developed materials. Because the research landscape advances at such a rapid pace, this is not a complete compendium of the state of the art in advanced materials but an extensive compilation, with thousands of references to current research. The first five chapters provide background on the basics of shielding. Chapter 6 is about DC magnetic fields. Chapters 7–14 cover recent developments in new materials (up to 2018).

Chapters 15–17 relate to applications and new designs and materials, and Chapter 18 is concerned with the mechanical characteristics of shielding materials and methods used to measure them. It is important to note that many materials that might have excellent electrical characteristics might also be difficult to use due to poor mechanical properties, such as machinability, hardness, brittleness, thermal expansion, etc. Therefore, consideration should be given to the specific needs of the application and not just the electrical properties of the material.

More recently (2020), *Materials for Potential EMI Shielding Applications, Processing, Properties, and Current Trends* was published [71]. Similarly to Jaroszewski et al. [3], this book covers a wide range of EMI topics. The first three chapters cover background and theory, and the next chapters cover the following:

- Naturally derived materials for potential EMI shields
- Thermoplastic polymer composites
- Thermoset polymers
- Metal-embedded matrices
- Elastomer-based materials
- Polymeric blends
- Biodegradable polymeric materials
- Nanomaterials (carbon and hybrid polymeric)
- Carbon-based reinforced composites
- Ceramics
- Concrete
- Textiles
- High-temperature EMI shields

Metamaterials are an interesting new class of shielding materials (covered in Chapter 16 of *Advanced Materials for Electromagnetic Shielding...* [3]). The term metamaterial is slightly misleading, as the "material" in question is a geometric arrangement of materials, which results in EM properties that are very different than the bulk materials. An example of a metamaterial is seen in Figure 5-5, where a combination of printed copper antennas arranged at right angles to each other on a fiberglass material provides a negative refractive index, which greatly enhances the shielding that would be gained from using copper alone. The total array consists of 3 × 20 × 20 unit cells with overall dimensions of 10 mm × 100 mm × 100 mm (0.39 in × 3.94 in × 3.94 in). In this way, common everyday materials can be arranged in new ways that provide very uncommon results to the bulk electromagnetic

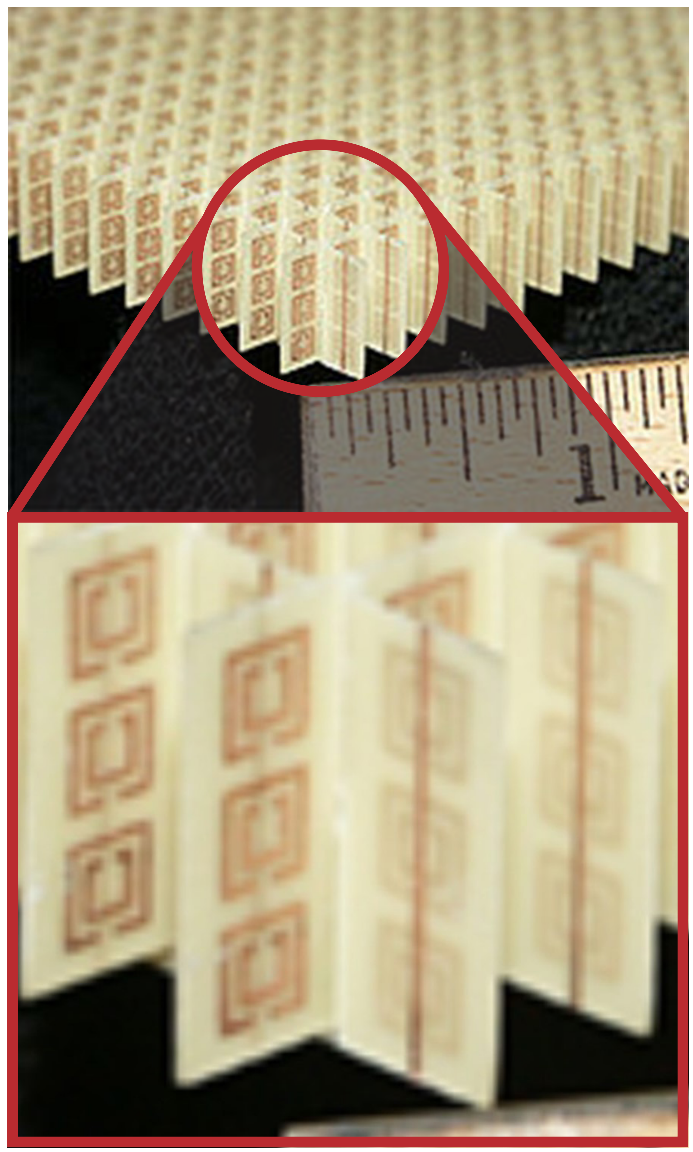

Figure 5-5. Negative-Index Metamaterial Array Configuration Constructed of Copper Split-Ring Resonators and Wires Mounted on Interlocking Sheets of Fiberglass Circuit Board *(Source: NASA).*

properties. These materials are made by altering the structure of bulk materials (such as layering or arrangement) via chemical or mechanical modification.

The manipulation of the refractive index in metamaterials is defined by Snell's Law of refraction:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2),$$

where n is the refractive index and θ is the angle of refraction with respect to the normal to the interface (see Figure 5-6). In the figure, the velocity is lower in the second medium ($v_2 < v_1$), and the angle of refraction θ_2 is less than the angle of incidence θ_1, i.e., the ray in the higher index medium is closer to the normal.

At certain frequencies, a metamaterial can be engineered to have a negative refractive index. In this case, the wave can be bent backward, i.e., θ_2 can be negative. This opens a very wide range of interesting possibilities for EMI shielding in devices. For example, a flat metamaterial can focus divergent waves to a point—in other words, even though it is flat, the device works like a lens. One could imagine a metamaterial taking divergent EMI, focusing it to a point in space inside a device that is reserved to contain now point-source EMI, removing the bulk effects of EMI, and placing them in an unimportant part of a device (analogous to "putting it in time-out"). In other configurations, known as cloaks (like in Star Trek), incoming waves are bent to go around a device and emerge on the other side, continuing onward as if the shielded device is not there (see Figure 5-7 as an example). From a visible light perspective, the light carrying information about the background behind the object being cloaked makes it to the observer rather than being blocked by the object being cloaked. It is also possible to design a metamaterial to have an imaginary ($\sqrt{-1}$) index. In this case, the incoming wave cannot enter the metamaterial at all—it is completely blocked, creating a perfect shield. The implications of this material are clear—this is an invisibility cloak. For visible light applications, the user would be invisible. For electronic devices, they would operate almost as they would from a purely theoretical perspective, with no interaction with EMI whatsoever.

Metamaterials are wavelength dependent, meaning that they can also be used as wavelength—specific antenna or as wavelength filters. Figure 5-8

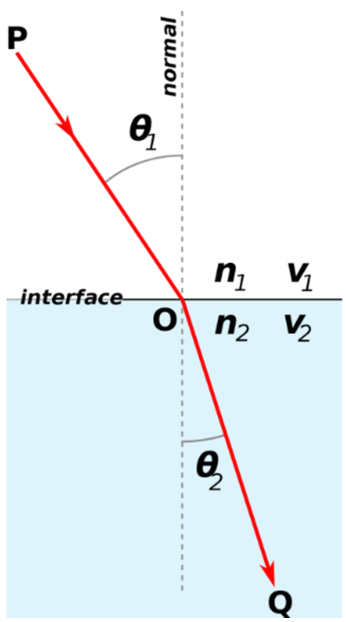

Figure 5-6. Refraction of Light at the Interface Between Two Media of Different Refractive Indices, With $N_2 > N_1$, and a Result (Straw in a Transparent Medium Filled With Water) [72].

Figure 5-7. Refraction of Light Used to Produce a Cloaking Effect: (Left) a Coat Seen Without a Special Device in Optical Wavelengths and (Right) the Same Coat Seen Through the Half-Mirror Projector Part of the Retroreflective Projection Technology [73].

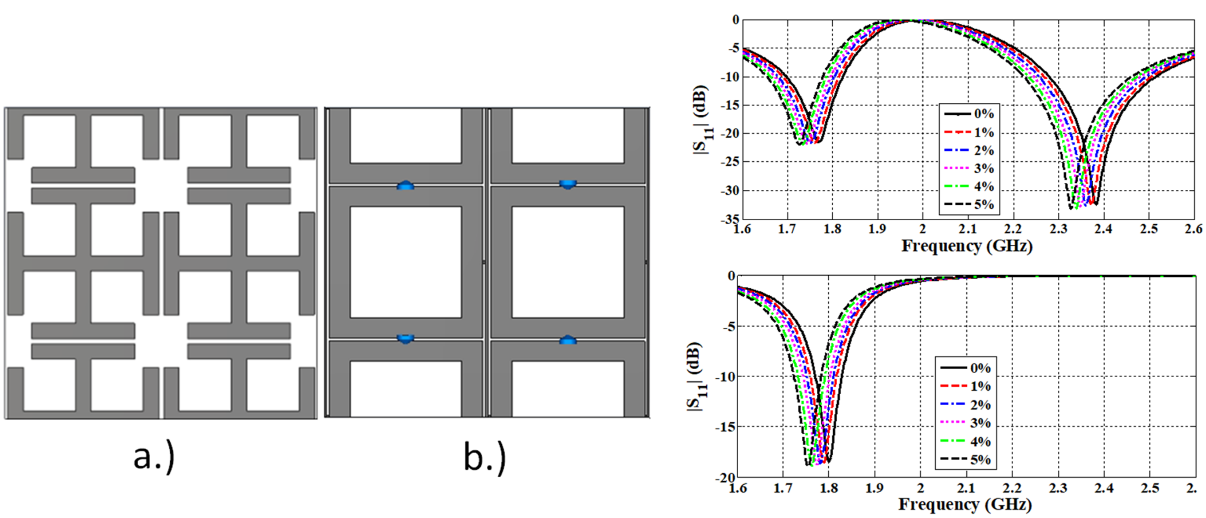

Figure 5-8. Metamaterial Examples Showing How Different Geometries, Configurations, and Circuits Can Produce Different EM Responses: (a) Loaded Cross Dipole Design, (b) Active Rectangular Ring With PIN Diodes (Shown in Blue) and Vertical Bias Lines, (Right Top) Subsequent Sensor Responses for the OFF State, and (Right Bottom) ON State *(Source: Doyle Motes)*.

shows how a signal can be shielded or transmitted at different wavelengths. This is a rapidly developing field, with significant research being conducted by the different branches of the DoD.

One new class of metamaterial in development is MXenes (Figure 5-9). MXenes are a class of two-dimensional, inorganic compounds. These materials consist of several-atoms-thick layers of transition metal carbides, nitrides, or carbonitrides and combine metallic conductivity of transition metal carbides and hydrophilic nature because of their

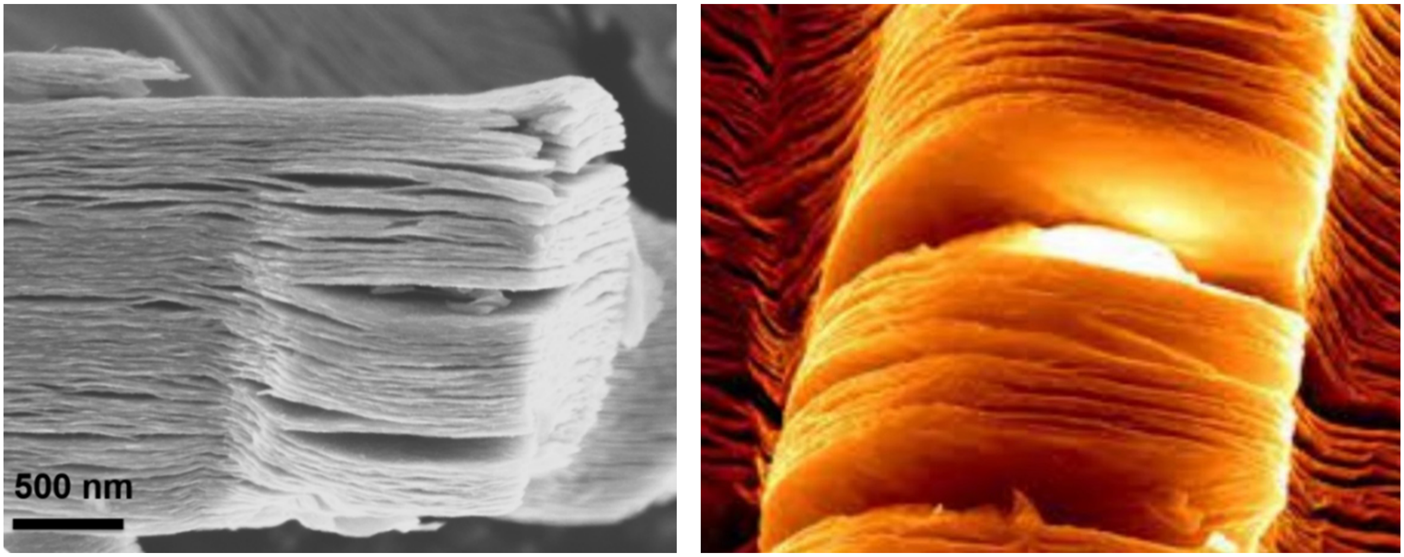

Figure 5-9. Scanning Electron Microscope Images of Layered MXenes *(Source: Prussianblue1403)*.

hydroxyl or oxygen terminated surfaces.

Different MXenes have several different and unique properties, depending on the constituent materials. MXene monolayers have a high electron density at the Fermi level and are predicted to be metallic. Only MXenes without surface terminations are predicted to be magnetic. Cr_2C, Cr_2N, and Ta_3C_2 are predicted to be ferromagnetic; Ti_3C_2 and Ti_3N_2 are predicted to be antiferromagnetic. None of these magnetic properties have yet been demonstrated experimentally.

Transparent conducting electrodes have been fabricated with titanium carbide MXene, showing the ability to transmit approximately 97% of visible light per nanometer thickness. The performance of MXene transparent, conducting electrodes depends on the MXene composition as well as synthesis and processing parameters. Nb_2C MXenes exhibit surface-group-dependent superconductivity. Scientists at Drexel University in the United States have created spray-on antennas that perform as well as current antennas found in phones, routers, and other gadgets by painting MXene's onto everyday objects, widening the scope of the Internet of things considerably.

These materials are made by chemical modification of bulk materials, resulting in layered materials (as shown in Figures 5-9 and 5-10) with unique EM properties [74]. The unique EM properties of MXenes arise from the structure of the materials. The journal A*dvanced Functional Materials* ran a special issue on MXenes in 2020 [74]. While the development of MXenes is still in its early stages, the current research indicates great potential for many applications, including EM shielding.

A more recent review of common materials used for EM shielding by Chung [48] gives a more up-to-date presentation of ongoing research. In addition, Chung provides a list of common pitfalls and mistakes when measuring the SE of materials. When comparing the SE of different materials, it is important to consider how the measurements are made and avoid committing mistakes in the process. The list of possible errors is an excellent guide for those seeking to design and test improved materials.

5.2.1 The 3-D-Printed Materials for Shielding

Advanced materials for shielding applications need to be formed into various shapes to be useful. Many of the new materials under research and development are based on polymers. These polymers are modified by the addition of materials, such as carbon black, carbon fibers, graphene nanoparti-

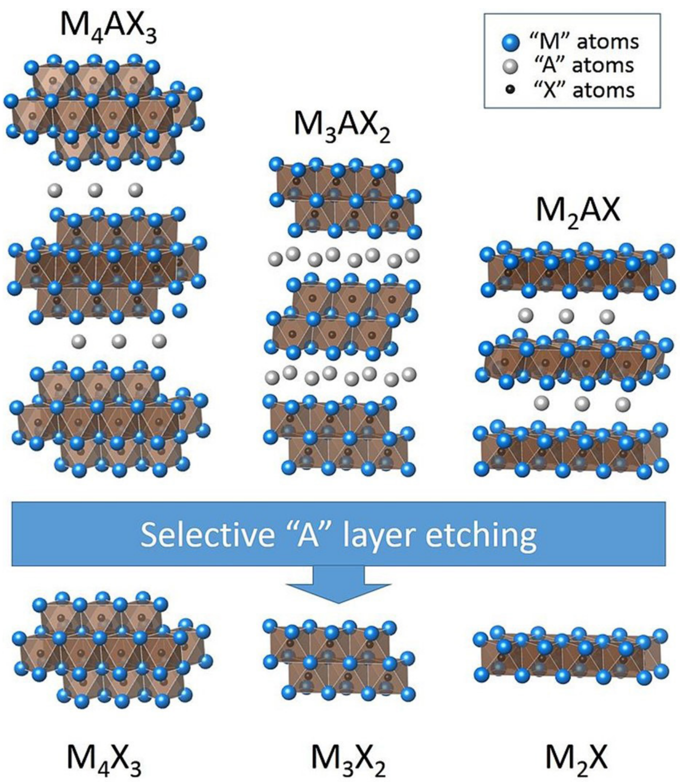

Figure 5-10. MXenes Are Produced by Selective Etching of the "A" Element From the MAX Phase Structure *(Source: Prussianblue1403)*.

cles, and carbon nanotubes (CNTs). These additives are electrically conducting and either reflect EM waves or absorb them and convert the energy to heat. However, there are challenges in adding conducting elements to polymers. First, the additive must mix well with the polymer, or the conductors can wind up clustered in isolated pockets and not be electrically connected (via percolation theory). Improvements in dispersion are often achieved by chemical modification of the additives, reducing the interface free energy between the polymer and additive. Dispersion can also be improved by mechanical working, such as injection molding or compression molding of the part. Molding plastic parts is extremely cost effective when large numbers are produced. However, when a small number of parts are needed, the cost of making a metal mold can be prohibitive. This makes additive manufacturing, i.e., 3-D printing, a very attractive method of producing small quantities or prototype parts.

There have been several recent papers exploring the manufacture of 3-D-printed shields. The first paper compared several commercially available filaments for use in a 3-D printer [49]. In a more recent paper, Verma et al. explored the effects of printer direction and other parameters on the shielding performance of structured materials [75]. The 3-D-printed metamaterials were compared with conductive filaments vs. parts painted with silver epoxy (to make conductive elements) [76]. While the split-ring resonator printed with conducting polymer worked, it was not as good as a metamaterial made of copper. Another approach by Wang was to print a 3-D scaffold coated with CNTs and then hot press it to imbed the CNTs into the scaffold [77]. In a conference paper, conducting filaments were used to create a sandwich structure with conducting polymer fillings to measure the complex dielectric constant of the structure [78].

In a paper from 2019, 3-D printing was tested as a method for rapid prototyping of EMI device shields [79]. The conclusion was that while the prototypes worked, they were still not as effective as molded or pressed materials. As previously mentioned, controlling the distribution of conducting additives within a polymer is a challenge. This is even more true for 3-D printing [80]. While most of the work in 3-D printing of shields has concentrated on polymer-based materials, 3-D printing of metals is a developing technology. Magnetic shields can be printed with metal, Ni-5Mo-15Fe alloy (or permalloy-80), as demonstrated by Vovrosh et al. [81].

Three-dimensional printing is a rapid developing technology. Currently, shielding produced this way is not quite as effective as more traditional forming methods. Nevertheless, commercial manufactures are selling materials for use in printing conducting parts, and upgraded parts to enable using these materials are being sold.

SECTION 06 MANUFACTURING AND MARKET FOR EMI SHIELDING MATERIALS

The EM shielding manufacturing and materials market is a large industry, with thousands of players internationally. According to the North American industrial sourcing platform http://www.thomasnet.com [82], there are 377 companies listed under "EMI/RFI Shielding Suppliers" and over 600 companies listed under the collective "Shielding" category for the North American continent. The range of services provided by manufacturers spans from producing bulk materials that can be turned into shielding products, such as metal meshes, composites, graphene, etc., to making the final shielding end products themselves, such as metal enclosures, ferrite cores, and shielded connectors. As an example of a material supplier, Parker Chomerics supplies a broad range of materials, from conducting paints to electroplating metals onto plastic parts, and injection molding thermoplastics with fillers that make them effective as EM shields [83]. Other companies supply materials and manufacturing products, such as Hexcel [84], who supply 3-D-printer filaments loaded with additives to make customized EM shielding parts, as well as fabricate finished parts for customers using their print files, if desired (see Figure 6-1 for an example).

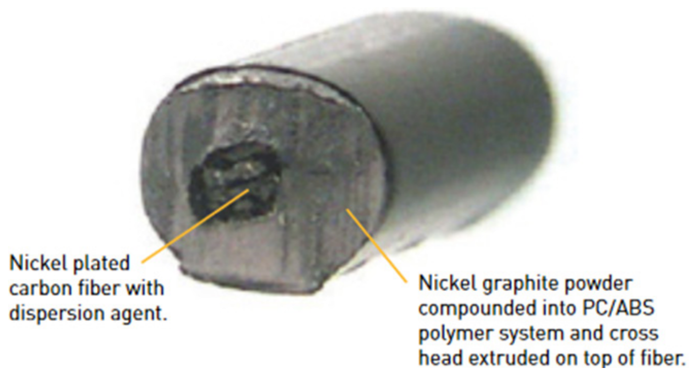

Figure 6-1. Cross Section of Thermoplastic for Injection Molding EM Shielding [83].

Additional manufacturers are also producing materials and shielding products around the globe, especially in countries with large electronics manufacturing industries. The robustness of the domestic and global markets provides manufacturers with many different options in their shielding designs. At the same time, recent disruptions in the global supply chain have led to shortages of materials where there are instances of single-source or large-market share production. One example of this is the power grid failures in Texas in February 2021 caused by an unusually strong winter storm that adversely affected polymer production (an important component of modern, lightweight composite, shielding materials). Composites World reported that the winter storms shut down production for major Gulf Coast petrochemical companies who supply raw material for resins necessary in electronics and computer chip manufacturing, thereby exacerbating supply chain issues already ongoing due to COVID-19 [85].

In addition to supply chain shortages, there is also a risk to production caused by dependence on foreign sources for precious metals. The U.S. Geological Survey reported in 2016 that the United States "was 100 percent dependent on foreign sources for 20 of the 90 mineral commodities that USGS tracks" [86]. The United States relies heavily on China, as well as on other countries like Canada, Brazil, and South Africa, for large portions of its precious metals' imports (Figure 6-2). This dependence on

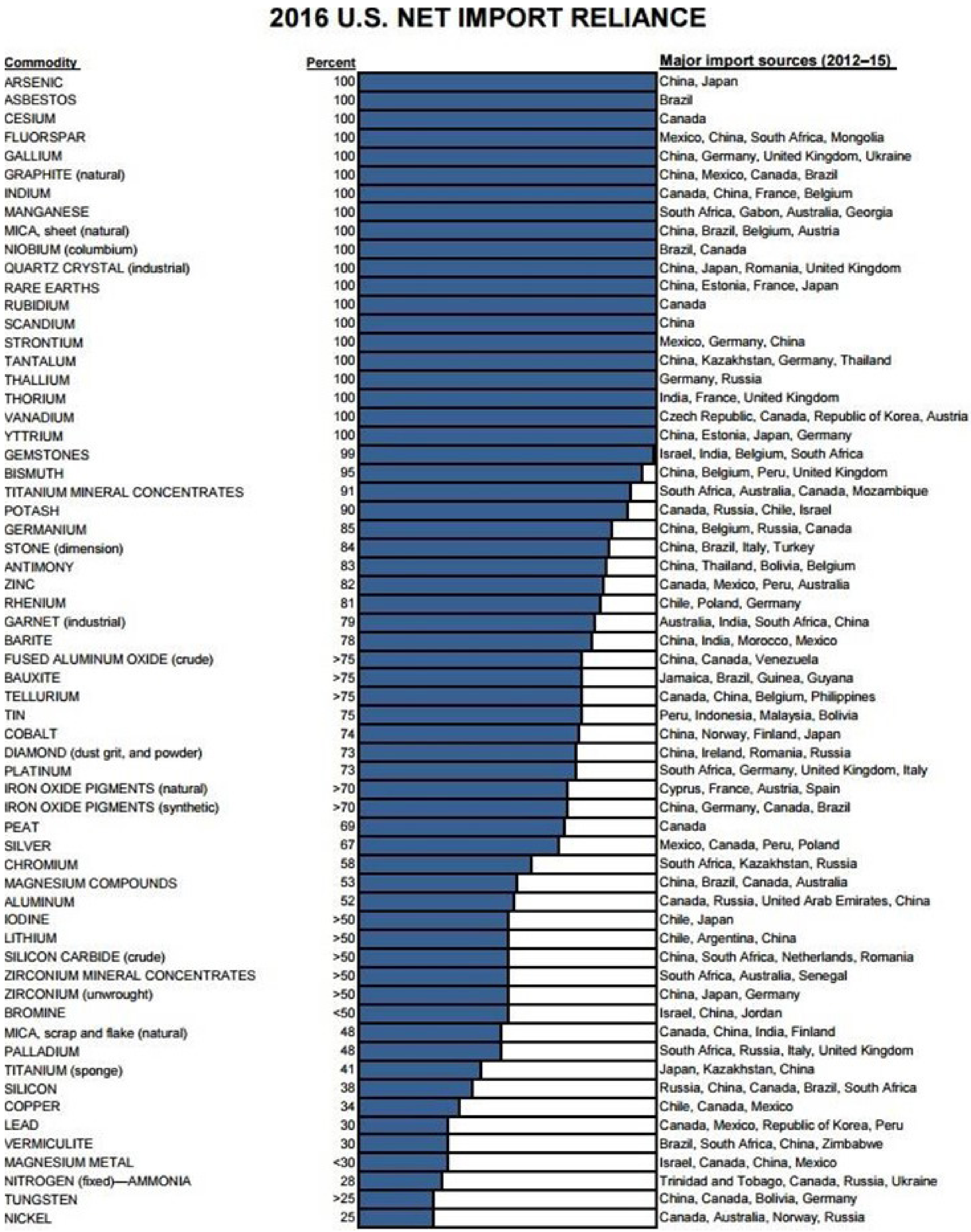

Figure 6-2. Reliance on Foreign Countries for Precious Metals Used in Military and Consumer Electronics and Shielding [86].

foreign supply could be threatened by blockades, tariffs, and other disruptions in the event of political fallout, wartime, natural disaster, or other factors. All these facts point to the need for more resilience in the supply chain through diversification of suppliers, manufacturers, and producers.

Demand for EM shielding very closely follows demand for electronics, and demand for electronics has grown at increasingly higher rates over the decades. With sales forecasted to continue growing over the next five years [87], EM shielding demand will also continue to rise. The market growth is being driven by several factors, including growing demand for consumer electronics like cell phones, laptops, and gaming consoles, increasing demand for networking and information technology hardware, and growing electronics use in the automotive industry [88]. With the deployment of 5G networks, the growth of work-from-home and business automation, and the development of electric vehicles, the need for reliable supplies of EM shielding and materials will be even more critical. Credence Research has a market forecast for global EM shielding of over $5 billion per year, with a growth rate of 6% [89]. Graphical representations of the specific markets are shown in Figures 6-3 and 6-4.

These two competing trends—growing demand and restricted supply—are driving up materials costs to recent and all-time highs. In October 2001, copper was at a low of $0.60 USD/lb, whereas in June 2021, copper reached ~$4.40 USD/lb, according to Trading Economics [90]. Steel has also been steadily increasing in price, with a growth of approximately $275 USD/ton in early 2016 to ~$925 USD/ton in the second quarter of 2021 [91]. Other metals are seeing recent increases over the last 5–10 years but have not hit historical market highs. Aluminum, for example, has experienced significant price swings, ranging from a low of $1,445 USD/ton in late 2015 to ~$2,425 USD/ton in mid-2021, but has still not reached the market high of $3,070 USD/ton seen at the end of January 2008

Figure 6-3. Global Market by Material [89].

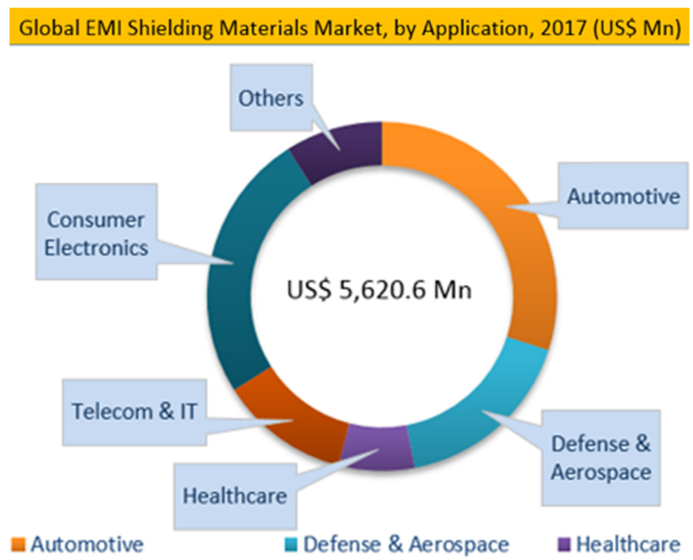

Figure 6-4. Global Market by Application [89].

[92]. COVID-19, global shortages of labor, shipping disruptions, natural disasters, and a multitude of other factors have combined to generate extreme force on the global market. Continued pressure from the effects of recent events will only increase the prices for materials markets that are already strained.

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SECTION 07 CONCLUSION

EMI will continue to be ubiquitous throughout the world. The continuing and increasing adoption of consumer electronics (including the rapidly modernizing Third World) means that EMI levels seen today are likely only a harbinger of those in the future.

With so much of the United States' military arsenal containing integrated electronic components, participating in various forms of electronic warfare, or requiring the highly controlled research and development of electronic components, there is a great need that proper EMI shielding is understood and implemented throughout the branches of the DoD. This is made even more important considering the amount of money, man hours, and political capital that China is dedicating to research, development, and implementation of electronics within its armed forces. In addition, as the United States begins to explicitly expand military operations into Earth orbit and beyond via the Space Force and Air Force branches of the DoD, these forces will undoubtedly encounter new EMI challenges that were unplanned for and must be dealt with and overcome to ensure superiority.

The United States' ability to effectively arm its military with the tools they need to fight and win wars in the modern era against modern enemies depends on ensuring a robust DI and maintaining the civilian critical infrastructure so that it can properly and effectively support the dense infrastructure. Wrapped within these requirements is ensuring that research and development into new materials, existing materials, and new engineering methodologies combat EMI that interferes with U.S. military operations and leverage EMI to interfere with the operations of enemies. Areas of weakness have been identified, such as the United States' continued dependence on foreign, and, in many cases, hostile countries for the raw materials required for both the fabrication of electronic components and shielding equipment. It is extremely important that steps be taken to remedy this, such as developing domestic resources or expansion to mining operations not claimed by other countries (such as extraction of seawater or ocean floor). We need to ensure that the materials dealing with EMI remain available in the required production quantities and they continue to be improved.

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