Project Number: ECE-PCP - 0801

POWER SUPPLY FOR MRI ENVIRONMENT

A Major Qualifying Project Report:

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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Date: April 30, 2009

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1.0 Introduction

Magnetic Resonance Imaging (MRI) has become an important diagnostic tool, because it is a noninvasive way to diagnose almost any person at any age. In 2003, 10,000 MRI units were in existence worldwide. This number increased to 26,503 MRI units in 2008 (Hornak, 2008). About 75 million MRI scans are performed every year (Hornak, 2008). Using magnetic fields, MRI can create images of the human brain, spine, and nearly every other part of the human body. This can eliminate the need for exploratory surgery. MR can also help diagnosis many health related issues such as carotid artery disease, screen for intracranial aneurysms, and screen for renal artery stenosis.

An MRI room is a harsh electromagnetic (EM) environment for electronics. Sometimes a patient monitor is needed to monitor the patient’s physiological status. Monitoring takes place when a patient is unable to alert health care providers about pain, cardiac problems, or respiratory problems. This patient monitor needs to be designed to function correctly within the constraints of the EM environment. Shielding can enclose electronic devices in order to attenuate the strength of magnetic fields to a level at which the device can survive. Without proper shielding, the magnetic fields produced by the MRI scans might damage electronics as well as pull ferromagnetic objects into the bore of the MRI. Conversely, interference from electronics has the potential for causing false images to be obtained from the MRI. For these reasons and more, there are special patient monitoring systems that are designed to work within an MRI environment.

Philips provides one such patient monitoring system. This product can monitor a patient’s blood pressure, blood oxygen level, respiration, and much more. It is designed to survive the MRI environment and not affect imaging. Patient vital signs are taken by a base unit that is a minimum of one foot away from the MRI magnet. In the observation room, a wireless monitor displays all readings.

Currently, power supplies in the MRI environment have limited functionality according how closely they can be placed near the MRI unit. This is due to the magnetic field that is present, which causes some power supplies to fail. An object with ferromagnetic material will be pulled into the MRI machine, and become attached to the MRI magnet. In order to prevent power supplies from being drawn into the MRI machine, Velcro strips are commonly used to keep power supplies attached to the floor. A long, shielded cable is used to connect the power supply to the patient monitor it powers. This approach goes against two key features of an MR patient monitor. Cost needs to be kept to a minimum, but the shielded cable is expensive. Mobility is also needed, and the range of the patient monitor is limited by the shielded cable it is attached to. Ideally, the power supply should be attached to the patient monitoring unit. This would lower the cost of the shielded cable that connects the power supply to the patient monitor, because it can be shorter. The mobility of the patient monitor will also be increased, because the power supply is not attached to a fixed point.

An AC to DC power supply suitable for an MRI compatible patient monitor will be the focus of this MQP project. This power supply will address the shortcomings of the current design mentioned above. The Philips patient monitor requires an AC to DC power supply that converts a worldwide line input of 100, 120, 220, or 240 Volts AC at 50 Hz or 60 Hz to an 18 Volt, 5 Amp DC output. The resources behind designing a power supply board can be extensive. A great deal of testing needs to be performed. A custom power supply would need be produced relatively quickly for completion of the project, and may not be at the same quality of a off the shelf power supply, which has had years of resources given to it. Any power supply would also have to comply with safety regulations regarding patient monitoring systems, such as IEC60601. Because such a power supply would have already gone through the regulation process, it would just need to be qualified for the purposes of this project.

This project will require research into the basic principles of MRI in order to understand what to expect from the environment. This will be useful to help predict noise on the power line, the strength and frequency of electromagnetic interference produced by these power lines, and unacceptable interference that can be produced by the power supply. Research in electromagnetic compatibility, shielding techniques, and filtering will help decide what designs will be considered to protect the AC to DC power supply from the MRI environment. This will require the selection of a off the shelf power supply. Test procedures will be researched and created in order to test design options. Also, a test procedure that can emulate an MRI would be helpful so that scheduling field tests with a hospital will be minimized. Research and/or consultation will also be needed to create the casing and shielding for the power supply. Both of these tasks will require some mechanical design to create.

The deliverables that will come from this project are as follows:

- Research into shielding techniques
- Research into testing which could emulate an MRI room. This is important so that hospital field tests can be kept to a minimum. In general, hospital tests are hard to schedule, and provide small windows in which to test designs
- Provide a prototype for a new power supply which can supply 18 Volts DC at 5 Amps to an MRI compatible patient monitor. This power supply will need to survive the MRI environment, and not interfere with the MRI imaging process

2.0 MRI

This section will discuss some of the principles in magnetic resonance imaging (MRI). The focus of this section will be the magnetic fields and radiofrequency pulses which make the MRI environment a challenge for electronics design.

2.1 Magnetic Resonance

To understand the concepts behind the MRI, magnetic resonance (MR) first needs to be understood. MR is a concept based on the spin of an atom's nucleus. This spin occurs naturally, and creates a magnetic field parallel to the axis of rotation. There are a select group of elements, which have a net spin and therefore can be detected in MRI. These elements include ^{1}H, ^{2}H, ^{31}P, ^{23}Na, ^{14}N, ^{13}C, and ^{19}F. Without the presence of a magnetic field, any volume of tissue contains a collection of nuclei with random orientation. The seven nuclei mentioned above will produce magnetic fields created by their spin. The direction of the magnetic field of each of these nuclei will depend on the random orientation of that nucleus's axis of rotation. The magnetic field of each nucleus is of equal magnitude. However, a vector addition of a very large number of these magnetic fields will produce a net magnetization of approximately zero in the volume of tissue.

When placed in a magnetic field (B_0), the specified nuclei will align slightly away from the direction of the magnetic field at an angle (θ) (Haacke et al, 1999). However, these nuclei will not remain in this orientation. Instead, they will have an axis of rotation parallel to the magnetic field. For a better understanding of how this works, refer to Figure 1. The magnetic field (B_0) is directed along the z axis. The vector μ shows the orientation of the nucleus' axis. The nucleus will rotate in this orientation around the z axis at a frequency ω_0, which is called the Larmor frequency. This frequency is dependent on the strength of the field and on the specific molecule being imaged (water, fat, etc) (Haacke et al, 1999). The angle $d\Phi$ is the phase difference as the nucleus rotates at the Larmor frequency. This is relative the angle at which the nucleus begins its rotation. Because each nucleus is randomly oriented away from the z axis, the net magnetization perpendicular to the magnetic field is zero. However, because each nucleus is spinning around the z axis over time, the net magnetization will not be zero. When there is no magnetic field present, the nuclei no longer are oriented about the z axis, and instead return again to their random orientation in the volume of tissue.

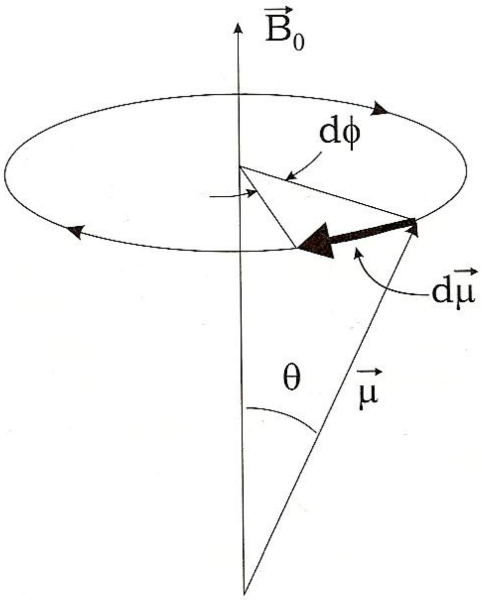


Figure 1: Nucleus Alignment in Magnetic Field (Haacke et al, 1999)

Magnetic resonance is a process of absorption and reemission of energy. Atoms will be subjected to a magnetic field, resulting in a fraction of the protons aligning with the magnetic field. At this point, the atoms will be in a low energy state. To get to a high energy state, the atoms will absorb photons. This energy is defined in eq. (1) (Hornak, 2008).

$$E = h\ \omega_0 \tag{1}$$

where h is Plank's constant ($6.626\text{x}10^{-34}$ J s), E is energy, and ω_0 is the Larmor frequency. The atom will absorb some of this energy at the Larmor frequency, and then reemit this energy at the same frequency. The atom will then return to the original low energy state, and reemit the energy it absorbed. It is this reemitted energy that can be captured and observed. A loop of wire is used to induce a voltage from the emitted energy of each nucleus. This induced voltage, which is called the free induction decay, will decay over time as the atoms emit their absorbed energy and return to their original state (Brown and Semelka, 1999). The free induction decay consists of many frequencies superimposed onto each other. From these frequencies, images can be created.

2.2 MRI Basic Principles

Magnetic Resonance Imaging (MRI) uses the concepts of magnetic resonance with some additional concepts of its own. The first principle of MRI is the DC magnetic field to orient the nuclei with atomic spin. Some clinical MRI systems can achieve up to 10 Tesla, but typically up to 3 or 4 Tesla MRI machines are used. The strength of static magnetic fields use in MRI is increasing with new generations of MRI machines, because the signal to noise ratio increases linearly with the strength of the magnetic field. This is because there is larger percentage of nuclei aligned with the magnetic field as the magnitude of the magnetic field increases. To keep magnetic field levels outside the MRI bore at a constant level, higher magnetic fields in MRIs lead to the need for shielding. Usually, shielding in accomplished through additional coils. Figure 2 shows a magnetic field map of a shielded MRI.

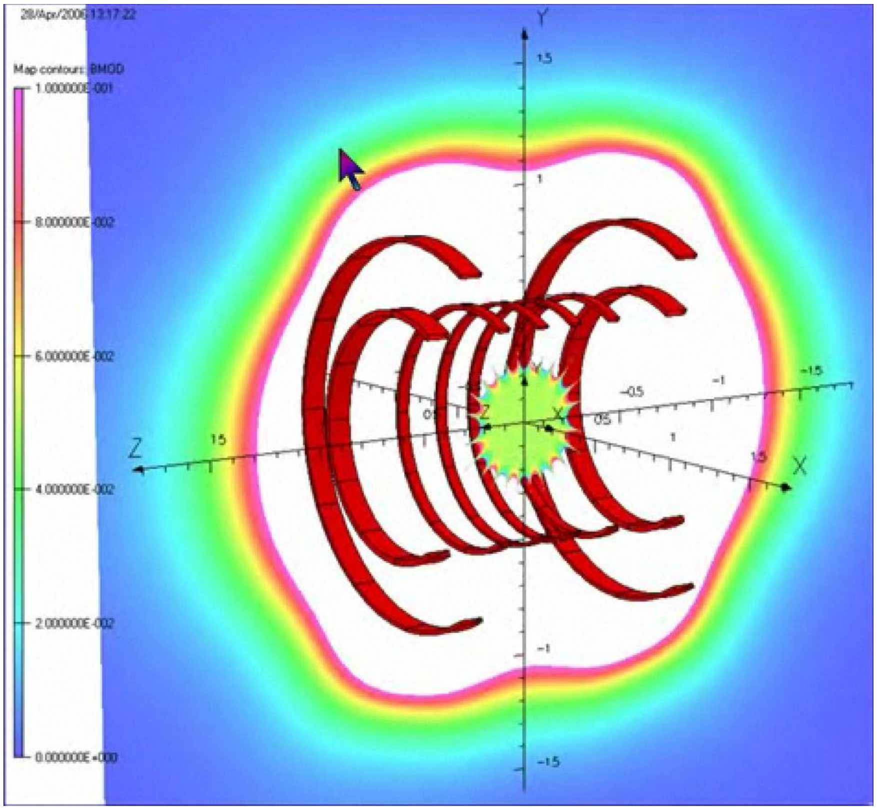


Figure 2: Magnetic Field Map of a Shielded MRI (Overweg, 2006)

The purpose of the shielded MRI is to attenuate the magnetic fields leaving the MRI for safety purposes. With the typical shielded magnet seen above, the magnetic field outside of the MRI is proportional to $1/r^5$ (Overweg, 2006). There will be a significant drop off when moving away from the magnet. However, the magnetic fields seen in the MRI environment are strong enough, even with a significant drop off, to damage electronics and pull magnetic objects.

An additional concept important to MRI is the use of gradient fields that create differences in the magnetic field. Gradient fields are generated by current flowing through individual loops of wire mounted together into a single gradient coil. These gradient fields cause rapid changes in the magnetic field that can be in the kilohertz range or smaller, depending on the speed of the gradient. When the gradient is introduced, the Larmor frequency of the atoms in a body that were once uniform in the presence of the magnetic field will vary with location due to the gradient field. Each location now corresponds to a different frequency, and these frequency differences become a kind of coordinate system.

It is important to understand what frequency values the Larmor frequencies can take on, because these will be the frequencies that can't be interfered with by the patient monitor power supply. Different molecules of the body will have different Larmor frequencies if subjected to the same magnetic field. This is dependent on the gyromagnetic ratio (γ) (Brown and Semelka, 1999). Water and fat are examples of nuclei that experience different Larmor frequencies. The magnitude of the magnetic field applied to an atom will also affect the Larmor frequency. Eq (2) gives an understanding of the impact of the gyromagnetic ratio (Hornak, 2008).

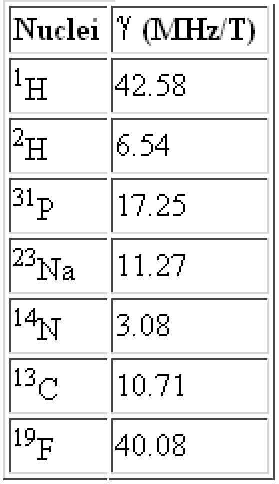
$$\omega_0 = 2 \pi \gamma B_0 \qquad \textbf{eq (2)}$$

Images are created of these different molecules by recognizing the frequency at the location that was scanned. In order to obtain the MR signal as a function of frequency instead of time, a Fourier transformation is used. This information is then processed, and an image is created. This project is not too concerned with the imaging process. This project is concerned with the levels of interference between the MRI and power supply.

The patient is subjected to pulses of radiofrequency energy. The purpose of these radiofrequency pulses is to change the orientation of a selected grouping of atoms to the high energy state. This high energy state is called the anti-parallel state. In this state, atoms are tilted at an angle of 90° with respect to the magnetic field. As shown by eq (1), the radiofrequency energy will be a pulse at the Larmor frequency in order to excite the atom. Remember that the Larmor frequency is proportional to the magnetic field. Because the magnetic field has a linear change due to the gradient field, Larmor frequencies will be different at each location (Brown and Semelka, 1999). This means that the range of frequencies for the radio frequency energy can be selected so that only desired sections of the body are tilted into the anti-parallels state. This is useful when MRIs are only needed of select areas, such as the brain or heart. Frequencies corresponding to those areas will be used. Without a radio frequency pulse to enter the high energy state, atoms are oriented along the magnetic field.

The radio frequency energy applied in MRI is usually a uniform magnitude of excitation among a range of frequencies with some center frequency. The bandwidth of the radio frequency energy will allow for selected regions of tissue to be excited. For this project, it is important to know the frequencies of these pulses, because it will play a part in interference issues. These frequencies are dependent on the nuclei and magnetic field intensity. This dependence is represented by the gyromagnetic ratio. Table 1 contains a list of each nucleus that has a net spin along with their gyromagnetic ratio.

Table 1: Nuclei and Their Gyromagnetic Ratio (Hornak, 2008)



Nuclei	γ (MHz/T)
^{1}H	42.58
^{2}H	6.54
^{31}P	17.25
^{23}Na	11.27
^{14}N	3.08
^{13}C	10.71
^{19}F	40.08

Static magnetic fields seen from an MRI can be as low as 0.2 Tesla and exceed 4 Tesla. The element predominately used in MRI is the proton in the ^{1}H hydrogen atom (Brown and Semelka, 1999). Using eq (1) and the values for the static magnetic field and gyromagnetic ratio, the Larmor frequencies might reach as low as 3 MHz (0.2 Tesla) and exceed 170 MHz (4 Tesla) for ^{1}H. If MRIs reach as high as 8 Tesla, which is the current limit for adults, children, and infants above the age of one month (Hornak, 2008), Larmor frequencies as high as 425 MHz may be seen for ^{1}H. This is a wide range of frequencies that must not be interfered with.

When the radio frequency energy is no longer introduced, every atom will return to their origin orientation. Frequency and phase maps are created of each atom by the unique magnetic field located at each point (Brown and Semelka, 1999). These maps are what create MRI images.

2.3 Artifacts and Other Interference

MRI images are susceptible to image artifacts. Artifacts are pixels in an MRI image that do not accurately represent the anatomy being shown. An important aspect of this project is to ensure that no artifacts will be created by the power supply being designed. Sources of artifacts include the physical motion of the patient, limitations in measurement process, and external sources. This project's concern is with the external source, which would be the patient monitor power supply. One source of artifacts is time varying signals detected by the receiver. Artifacts from this source will appear as lines of constant frequency in the image. The largest concern of interference will be emissions in the range of the RF pulses used by the MRI. Any interference from devices on these frequencies will be received by the receiver coil, and cause errors in MRI images. As stated above, these can will RF pulses can range from 8.5 MHz to 170 MHz. However, as the strength of magnetic fields increase this range will increase.

The increasing strength in the MRI magnetic field also poses a concern to the power supply. Interference with the static magnetic field and gradient field will not be of concern, because the power supply will not be able to produce any magnetic field close to the scale of the MRI. Instead, the interference onto the power supply by the MRI is a concern. Ferromagnetic materials in electronics components such as inductors and transformers can saturate under the magnetic field. This saturation will cause large increases in current that can damage the power supply itself. The patient monitor power supply may therefore have to be shielded from the magnetic fields present from an MRI, as well as shield the MRI from emissions in the range specified that originates from the power supply.

3.0 Electromagnetic Shielding

Due to the intense magnetic fields of an MRI, the AC to DC power supply that will be selected is likely to need some sort of shielding. Also, radiated emission from the AC to DC power supply and any cabling connected to it may cause artifacts to appear on the MRI image. Both these issues are related to electromagnetic interference. A solution to electromagnetic interference applied to an electrical device is to create an electromagnetic shield. This shield will attenuate electromagnetic interference according to three physical features of transmission losses introduced by the electromagnetic shielding. These features, which can be seen in Figure 3, are external reflection, absorption, and internal reflection.

3.1 Physical Features of Shielding

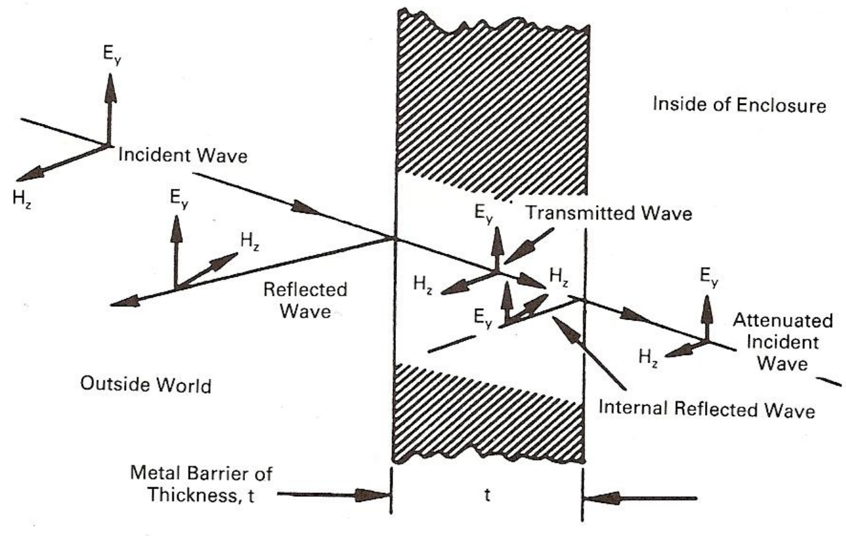


Figure 3: Effects of Shielding (Hemming, 1992)

The first attenuation of a shielding enclosure occurs when the amplitude of an incident wave is reflected from the surface of the electromagnetic shield. This attenuation is due to the fact that there is an impedance mismatch between the air to metal boundary. External reflection loss is dependent on both the surface and wave impedance. It is helpful to think of this as a transmission line system. The input impedance would be the impedance of the source in air, and likewise the transmission line impedance would be represented by the surface impedance of the shielding material. A mismatch will introduce a reflection back to the source. The surface impedance of the electromagnetic shield can be expressed by the eq 3 (Hemming, 1992).

$$Z_s = [\, j\omega\mu\, (\, \sigma + j\omega\varepsilon\,)\,]^{1/2}\ \Omega \qquad \textbf{(3)}$$

where Ω, μ, σ, and ε are resistance, permeability, conductivity and permittivity, respectively.

The surface impedance, Z_s, is a function of the source type, which is either an electric or magnetic field, and the distance from the source to the shield. There are various equations for the external reflection loss depending on the type of source, which includes magnetic fields, plane-waves, and electric fields. Plane-waves and electric fields have high impedance, and will have external reflection losses from the air to metal boundary. This allows for thin shielding. Magnetic fields have low impedance. For magnetic fields, there will be internal reflection losses from the metal to air boundary, but external reflection losses will be negligible from the air to metal boundary. Magnetic fields require thick shielding as well (Barnes, 1987). Reflection losses of shielding will be important for the interference from the power supply onto the MRI, but not for shielding the power supply from the magnetic fields present in the MRI. This is because constant magnetic fields can be diverted, but not reflected. The effectiveness of this feature of shielding will be diminished by interface connections such as screws, rivets, and welds. Bowing or waviness to the shielding will cause slits or gaps which will allow for leakage. It is important to make sure that the shielded enclosure is as close to a homogeneous wall or material as possible.

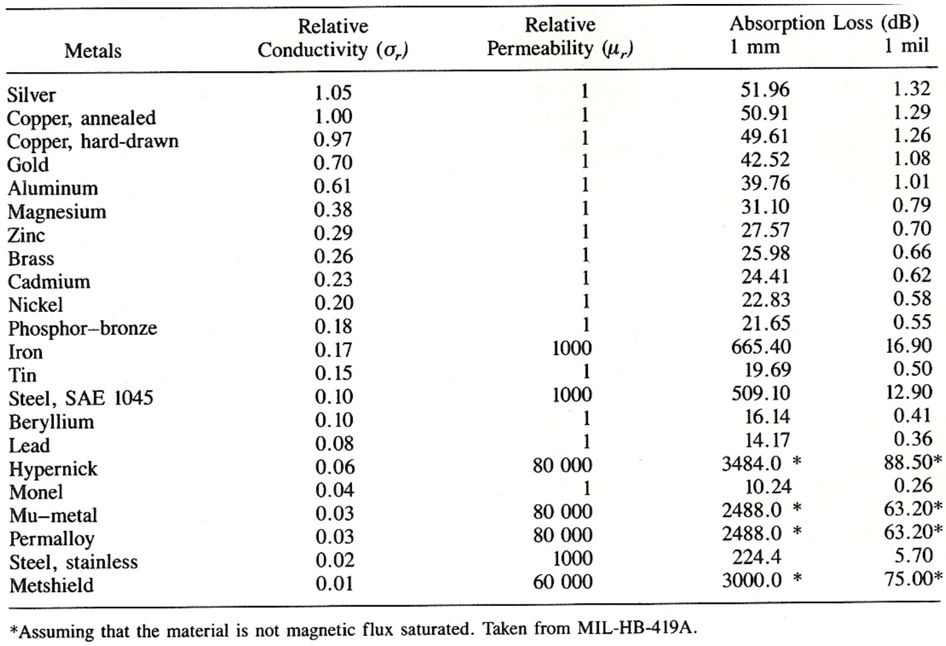
Energy that is not reflected is then absorbed by passing through the shielding. In a transmission line system, this would be the losses incurred while the wave propagates along the transmission line. This absorption loss can be expressed in the following equation (Hemming, 1992).

$$A = 1.314[(\omega \cdot \mu_r \cdot \sigma_r /(2\pi)]^{\frac{1}{2}} \cdot d \qquad \textbf{(4)}$$

where d, μ_r, and σ_r are shield thickness, relative permeability to air, and relative conductivity to copper.

It is important to realize that the relative permeability will not remain constant for all frequencies. Shielding materials will have specific frequency ranges in which they are more effective due to its relative permeability. Below is a table of the electrical properties of shielding materials at 150 kilohertz, as well as a graph displaying the relative permeability of shielding materials at low frequencies. Mumetal and permalloy have a relative permeability of over 10,000 at low frequencies, and are still an effective shielding material at higher frequencies. In fact, they are more effective material than most other shielding materials for magnetic fields at both low and high frequencies. These look to be the most likely candidates for shielding. Absorption will be more effective for the RF pulses present in an MRI environment than for the magnetic fields present. The absorption of low frequency magnetic fields will require more thickness. This is evident when looking at eq 4.

Table 2: Properties of Shielding Materials at 150 kHz (Hemming, 1992)



Metals	Relative Conductivity (σ_r)	Relative Permeability (μ_r)	Absorption Loss (dB) 1 mm	1 mil
Silver	1.05	1	51.96	1.32
Copper, annealed	1.00	1	50.91	1.29
Copper, hard-drawn	0.97	1	49.61	1.26
Gold	0.70	1	42.52	1.08
Aluminum	0.61	1	39.76	1.01
Magnesium	0.38	1	31.10	0.79
Zinc	0.29	1	27.57	0.70
Brass	0.26	1	25.98	0.66
Cadmium	0.23	1	24.41	0.62
Nickel	0.20	1	22.83	0.58
Phosphor–bronze	0.18	1	21.65	0.55
Iron	0.17	1000	665.40	16.90
Tin	0.15	1	19.69	0.50
Steel, SAE 1045	0.10	1000	509.10	12.90
Beryllium	0.10	1	16.14	0.41
Lead	0.08	1	14.17	0.36
Hypernick	0.06	80 000	3484.0 *	88.50*
Monel	0.04	1	10.24	0.26
Mu–metal	0.03	80 000	2488.0 *	63.20*
Permalloy	0.03	80 000	2488.0 *	63.20*
Steel, stainless	0.02	1000	224.4	5.70
Metshield	0.01	60 000	3000.0 *	75.00*

*Assuming that the material is not magnetic flux saturated. Taken from MIL-HB-419A.

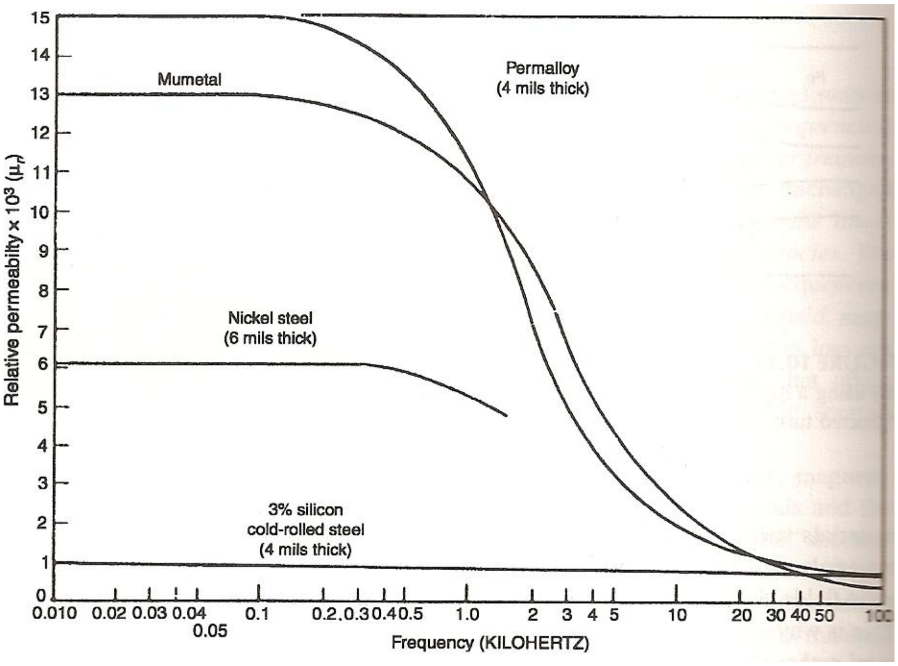


Figure 4: Permeability of Shielding Materials (Haacke et al, 1999)

One of the difficulties in shielding design is that the ferromagnetic materials should not be saturated; otherwise they will lose their ability to attenuate the magnetic field. One solution to this is to create a double-layered shield. The outer layer will have a low relative permeability and low susceptibility to saturation. This will reduce the incident magnetic field and allow the second shield to work properly (Paul, 2006).

Just as the incident wave hitting the surface of the shielding was reflected, any remaining incident wave inside the shielding will be attenuated by the internal reflection losses introduced by the second metal to air boundary. In a transmission line system, this internal reflection loss would be similar to the reflection loses due to a mismatch of impedances between the transmission line and the load. For most cases, only the initial reflection losses and absorption losses need to be calculated. This second reflection loss is usually negligible. This is especially the case for most materials when shielding against waves in the Megahertz range (Hemming, 1992). However, as mentioned before, this will be a factor of transmission loss for low frequency magnetic fields.

3.2 Engineering Aspects of Shielding

There are some rules of thumb in shielding for safety margins. These safety margins are additional attenuation loss above the minimum requirement for interference on the power supply from the MRI as well as on the MRI from the power supply. In general, shielding should provide at least 20 dB of attenuation above the required attenuation levels at frequencies above 10 MHz. Shielding should also provide at least 10 dB above requirement at 10 MHz, and 6 dB above requirement below 100 kHz (Hemming, 1992). Of all these frequency ranges, low frequency magnetic shielding is the most difficult shielding to achieve. Using these safety margins will ensure that interference is at an acceptable level. For this project's applications, there are two areas of concern. The first is low frequency magnetic fields. The static magnetic field and gradient field may affect ferromagnetic devices such as transformers and inductors in the power supply. These ferromagnetic devices may reach their saturation points. This will cause large currents in the device that may damage the power supply. The second area of concern is interference from the power supply in the order of Megahertz. This may come from the device output, the switching frequency, or some other high frequency source within the device.

All the losses that were described rely on the fact that a continuous layer of shielding material is used to attenuate fields. When a layer of shielding is not continuous, the shielding loses effectiveness, as fields are now allowed to penetrate the shielding without being attenuate as the shield was designed. Penetration of the electromagnetic shield is the biggest challenge for shielding design. Seams are one area of concern. The most reliable shielding seam is welded. However, it is expensive because there must be a minimum thickness, which is usually 16 gauge or higher (Hemming, 1992). This type of seam has the best performance. Seams can also be clamped. If there is not a continuous metal to metal seal, then this can provide a source of leakage. Plane wave shielding is usually the most difficult for this type of seam, because plane waves will cause the most leakage. A sandwich seam uses waveguide-beyond cutoff principle for RF seals. Unlike other seaming approaches, it does not rely on continuous metal to metal seals. This is good for high frequency performance, because this is where the reliance on continuous metal to metal seals can cause issues. Copper tape can also be used. However, it does not allow for highly effective shielding above 60 dB.

A requirement of shielded enclosures is that all external connection to the inside of the shielding enclosure must be filtered. This is due to the interference on wiring outside of the shielded enclosure. The most common filters used for shielded enclosures are reflective filters, which are combinations of capacitors and inductors mounted inside a sealed metal can. It is important to note that any inductors used in filtering must be non-ferrous core. This is due to the fact that any ferromagnetic materials used for inductors could be saturated due to the magnetic fields present in an MRI environment. Reflective filters, made for low sources and impedances, most commonly use a T shaped combination of inductors and capacitors, while those made for high sources and impedances most commonly use a pi shaped combination (Hemming, 1992). Low pass filters are the most common filter for electromagnetic compatibility. Filters are characterized by their attenuation at given frequencies, impedance levels, voltage ratings, current rating, size, weight, temperature, and reliability. The filtering mentioned above will be a concern for the AC line input to the power supply. The largest concern is the noise on top of the AC power signal. This would most likely be due to the RF pulses of the MRI. The output to the patient monitor will also be of concern. Again, any high frequency interference in the Megahertz range cannot emanate from the output line. In order to prevent this, shielded wire will be needed.

4.0 AC to DC Power Supply Selection

The first step of designing proper shielding and filtering for a patient monitor power supply is to select a capable AC to DC power supply. The selection process will need to be an objective weighting of various aspects of the AC to DC power supplies that are important to take into account. These aspects will be referred to as *decision factors*. This process of deciding the best available AC to DC power supply will use a matrix for a visual aid. This matrix will list all the decision factors considered for selecting an AC to DC power supply. These decision factors were determined in discussion with Paul Bailey, who is the Philip's project manager. Each decision factor will be weighted on a scale of 0 to 100, with 100 being the most important. To relate each AC to DC power supply to another, grades will be assigned to each AC to DC power supply for each decision factor. Each AC to DC power supply will be graded on a scale of 0 to 10 for each decision factor. Grades will be multiplied by the decision factor it corresponds to. Then, totals will be added to determine the best AC to DC power supply. There are four AC to DC power supplies that will be evaluated. These are the Elpac MVA100, the Emerson LPS174-M, the SL MINT1110A, and the Tectrol 1402. All of these AC to DC power supplies have data sheets available in the Appendix, except for the Tectrol 1402. The data that was used to relate the Tectrol 1402 to the other power supplies is part of a Philips report. This report was not included in this document.

4.1 Knockout Criteria

A must for each AC to DC power supply is 90 Watts of output power. The AC to DC power supply will provide 18 Volts at 5 Amps. If a power supply cannot supply this in some form, it will not be considered for this application. This will be considered *knockout criteria*. This decision factor is weighted at 100, as it is a must. The Elpac, Emerson, and SL AC to DC power supplies all provide this amount of power. They are all graded at 10. The Tectrol 1402 however only supplies 35 Watts of power. However, three 1402s can be combined in parallel for the power needed. For this reason, the Tectrol 1402 was given a 5.

There are two other factors that are knockout criteria. The first is that these AC to DC power supplies must fulfill medical standards such as UL/IEC 60601-1-2 and CSA 22.2, because they are powering patient monitoring equipment. The other is that these supplies must have universal inputs. This means that they must be able to operate with power outlets anywhere in the world. These decision factors are weighted at 100, because all AC to DC power supplys must fulfill these conditions. All supplies meet these conditions, and receive a 10 for a grade.

4.2 Emissions and Magnetic Field Susceptibility

These factors are radiated emissions, conducted emissions, output noise, and magnetic field susceptibility. A 3 Tesla MRI machine will be one of the more predominant environments the power supply will face. However, MRI machines are now reaching levels of 5 Tesla, and levels will increase further in the future. Emissions in the Megahertz range will be unwanted, because this will interfere with the MRI at the Larmor frequencies. These factors will determine what needs to be shielded or filtered later in the design process. The less emissions or magnetic susceptibility will mean that less shielding will be required. This may save money, and simplify design. These design factors were given a weight of 80.

The first consideration is magnetic field susceptibility. The Tectrol 1402 was tested with a real MRI and survived. It was given a 10 for susceptibility. The SL and Elpac supplies were tested using an electromagnetic to simulate the MRI. The SL supply passed. However, it did not survive in a true MRI environment, so it was only given an 8. The Elpac supply did fail to operate once after increasing the magnetic field significantly in an instant. However, this was a onetime incident that could not be replicated. It passed otherwise. It was therefore given a 7. The Emerson supply was not tested, because it was eliminated from consideration early in the decision making process.

Emissions testing was also completed on all supplies. Two types of emission test were performed. The first, *radiated emissions* testing, used an antenna to measure emissions from the power supply. The second, *conducted emissions* testing, monitored noise on the AC power cable. With the exception of the Tectrol 1402, supplies were tested at 90 Watts and 18 Watts. The Tectrol 1402 cannot supply 90 Watts unless connected together with others. For this reason, emissions are expected to be additive when 90 Watts is needed. The Astec supply did not perform well, and was given a 1 accordingly. The SL and Elpac supplies both performed well, and were very close. Each was given a 9. The Tectrol 1402 performed well at low power, but again it is expected to perform worse when multiple supplies are connected. It is unsure what this will result it. It was therefore given a 5.

4.3 Reliability

Reliability is an important aspect of this design. An operating temperature range of 10°C to 40°C is the minimal requirement. A storage temperature range of -15°C to 50°C is the minimal requirement. If a supply cannot operate at the maximum temperature range, additional cooling solutions are needed. This will only complicate the design. A humidity rating of 80% is also needed. These are general reliability requirements. Because of the emphasis on reliability, this decision factor was given a weight of 90. The Tectrol 1402 is used with many Philips products, and has reportedly performed well. However, one concern was noticed while reading its datasheet. Beyond 35°C, power will linearly decline to 25W at 55°C. This could be a concern because the power supply will only be able to dissipate heat through the casing. The 1402 was given a reliability grade of 9, because it is used is many reliable Philips products. The Emerson and SL power supplies were given a grade of 6, because of their high operating ranges for temperature and humidity. However, very little information is known otherwise. The Elpac power supply has lower operating ranges, so it received a grade of 5. Again, little will be known about these other supplies until they are tested for performance with the final design.

4.4 Ease of Design

Ease of design is another factor that should be taken into consideration. Ease of design is the ease at which an AC to DC power supply can be integrated into an enclosure and conduct thermally. AC to DC power supplies that have ways to attach to an outside cover will make mechanical design easier. If the AC to DC power supply also includes a thermal contact to dissipate heat it will also help to keep the unit within the desired temperature range. These design factors were given a weight of 70. The Emerson supply offers space for thermal contacts, and is able to be mounted with its current casing. However, Emerson offers very little customization if modifications are needed. It received a grade of 7. The SL power supply offers much of the same, except that modifications can be made to the unit. It received a grade of 10. The Elpac power supply is small and offers little room for thermal contacts, and dissipates most heat through metal contacts of the side of the unit. It received a grade of 5. The 1402 will include a cover that can dissipate heat, and heat sinks can easily be added. The 1402 can also be easily held inside the shielded enclosure. For this reason, the 1402 was given a grade of 9.

4.5 Cost

There are other design characteristics which are easier to explain, such as cost. This was weighted with a 70. However, quality is the most desired characteristic. Therefore, cost can be sacrificed for important performance related decision factors. Three Tectrol 1402s will be needed. However, these will be about two thirds of the cost of the Emerson power supply. Both the Elpac and SL power supplies are close in price, which is about two thirds the price of three Tectrol 1402s. The Elpac and SL supplies were given 10s. The Tectrol 1402 was given a 7. The Emerson power supply was given a 4.

4.6 Conversion Efficiency

Conversion efficiency is an important decision factor for many reasons. The better the efficiency, the less power is wasted. This will also reduce the heat generated in the device. This decision factor was given a weight of 80, because it serves as an important part of other factors. A test was performed to determine the efficiencies of each AC to DC power supply. Two international AC line extremes of 270 Volts AC at 66 Hertz and 88 Volts AC at 47 Hertz were used. The results of this test are shown in Table 3. The Elpac power supply was given a 10 due to it being the best. The SL power supply was given a grade of 7, as it performed lower than the Elpac power supply. Both the Emerson and Tectrol 1402 performed poorly. They were both given a 3.

Table 3: AC to DC Power supply Efficiency

Power Supply	**Input Voltage (V)**	**Input Frequency (Hz)**	**Load Current (A)**	**Power In (W)**	**Power Out (W)**	**Efficiency (%)**
Emerson	270	66	5	116	90	77.586
Emerson	270	66	1	35	18	51.428
Emerson	88	47	5	118	90	76.271
Emerson	88	47	1	35.1	18	51.282
SL	270	66	5	106.1	90	84.825
SL	270	66	1	25.3	18	71.146
SL	88	47	5	108.7	90	82.796

SL	88	47	1	23.9	18	75.313
1402	270	66	1.66	40.9	29.88	73.056
1402	270	66	0.33	14.8	5.94	40.135
1402	88	47	1.66	39	29.88	76.615
1402	88	47	0.33	9.2	5.94	64.565
Elpac	270	66	5	97.3	90	92.497
Elpac	270	66	1	21.8	18	82.568
Elpac	88	47	5	100.7	90	89.374
Elpac	88	47	1	21.5	18	83.720

4.7 Size

The ideal power supply design will be able to mount on the patient monitor. So, size is a concern. The smaller the AC to DC power supply, the more options there are for mounting onto the patient monitor. This decision factor was given a weight of 75. The smallest power supply was the Elpac power supply, and was given a grade of 10. The SL power supply received a 9, because it was slightly larger than the Elpac power supply. The Emerson power supply was much larger than the 1402 and other power supplies. However, three 1402s are needed to achieve the desired power output. Therefore, the Emerson power supply received 4, while the 1402 received a 4. Three 1402s equal approximately one of the Emerson power supplies. Dimensions can be seen in the data sheets in the Appendix section.

4.8 RoHS

RoHS (Restriction of Hazardous Substances) is a directive that restricts the use of hazardous materials. It bans electrical and electronic equipment from being sold on the EU market if they contain more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl, and polybrominated diphenyl ether flame retardants. This would be important for the sale of this product in the EU. This was given a weight of 60. The Elpac, SL, and Emerson power supplies are RoHS compliant, and receive a grade of 10. The 1402 power supply is not, but can be converted to RoHS in the future. The 1402 will receive a 7, because it is not yet a reality.

4.9 Leakage Current

Limitations on leakage current are due to the risk of shock from touching the casing. IEC 60601 is a standard that only allows for 500µA of leakage current. A power supply with less leakage current provides more leeway when designing external filters. This was given a weight of 65. The SL power supply has a leakage current of less than 50µA, and was given a 10 due to it being the best. The Emerson power supply has a leakage current of less than 100µA, and was given a grade of 7. The Elpac power supply has a leakage current of less than 100µA normally, but can possibly reach 200µA in international applications. It was given a grade of 5. The 1402 power supply has a leakage current of less than 500µA with the multiple supplies needed to reach 90 Watts of power. Therefore, it was given a grade of 1.

Table 4: Decision Matrix

Decision Factor	**Weight**	**Elpac MVA100**	**Emerson NSF110**	**SL MINT1110A**	**Tectrol 1402**
18V @ 5A	*100*	*10*	*10*	*10*	*5*
Medical Standard	*100*	*10*	*10*	*10*	*10*
Universal Input	*100*	*10*	*10*	*10*	*10*
Magnetic Susceptibility	80	7	NA	8	10
Emissions	80	9	1	9	5
Reliability	90	5	6	6	9
Ease of Design	70	5	7	10	9
Cost	70	10	4	10	7
Efficiency	80	10	3	7	3
Size	80	10	4	9	2
RoHS	60	10	10	10	7
Leakage Current	65	5	7	10	1
Total		8555	6225*	9180	7015

** Magnetic Immunity not performed, so rating is incomplete*

Without any testing, it looks as though the SL and Elpac power supplies are the best candidates for the MRI power supply. The SL MINT1110A appears to be the better supply of the two, and will be the first choice for this project’s applications. However, testing for emissions, susceptibility, and reliability will be important in ensuring each power supply’s ability to fill the project’s needs. Even though each power supply has been tested by its manufacturer, it is important to ensure that it will survive the environmental conditions the power supply will face. Table 4 shows the grades, weights, and totals determined in this decision process.

5.0 Testing Protocol

There are many concerns for a power supply design for an MRI environment. Most of those concerns deal with radiated emissions and magnetic susceptibility. The first three tests described in this section will focus on emissions from the power supply. The fourth test described in this section will focus on the MRIs effects on the power supply. All the other tests in this section are for reliability purposes. Because the power supply is powering a patient monitor, reliability testing will be very important. All testing will be done with the SL MINT1110A as well as the Elpac MVA100. After the initial testing with the AC to DC power supplies, the prototype power supply will be tested. The finished product will then have to go through addition testing to be sold to hospitals.

5.1 Output Monitoring

Purpose: To measure frequencies which make up the DC output of the power supply. If the power supply output contains noise at the Larmor frequency range, then there will be a possibility of interference with the MRI imaging. Filtering the output and shielding the output cable would be two ways to eliminate the noise.

Procedure: Using an oscilloscope and spectrum analyzer, the frequencies of the power supply output will be measured. Two different electrical loads will be used at different operating extremes. These loads will draw the current extremes, which are 1 and 5 Amps, a typical load range of patient monitors. Two different AC operating extremes of 88 Volts AC at 47 Hertz and 270 Volts AC at 66 Hertz will be used.

5.2 Conducted Emissions

Purpose: To measure frequencies which make up the AC input of the power supply. If the power supply input contains noise at the Larmor frequency range, then there will be a possibility of interference with the MRI imaging. Unfortunately, the AC input cable will be a standard, non-shielded IEC320 cable. Filtering may reduce this noise.

Procedure: Using a spectrum analyzer, the frequencies of the power supply output will be measured. Two different electrical loads will be used at different operating extremes. These loads will draw the current extremes, which are 1 and 5 Amps, a typical load range of patient monitors. Two different AC operating extremes of 88 Volts AC at 47 Hertz and 270 Volts AC at 66 Hertz will be used.

5.3 Radiated Emissions

Purpose: To determine RF emissions from the power supply. Any emissions in the Larmor frequency can be received by the MRI, and cause artifacts in the imaging process. A shielded enclosure will be created to prevent this interference.

Procedure: After a finished prototype is made, screening will be performed in a Philips test room. This room is a small, shielded enclosure that will screen for the various Larmor frequencies that can interfere with the MRI. The project prototype will be powering a 3160 unit. This 3160 unit is a Philips Healthcare/Invivo brand patient monitor that is compatible for the MRI environment. The 3160 unit will be place in its designated area in the chamber. The power supply will be placed next to the 3160 unit. Each measurement made at a specific frequency will have its own emissions limit. The Mr. Fusion prototype must be 5 dB below the limit at each frequency. The 5 dB will be a safety margin to ensure that the power supply will not interfere with MRI imaging. At least ten tests will be carried out. Multiple tests will provide multiple measurements, and provide some idea if there are any spikes that may occur over time. This will be the last test for radiated emissions before testing the final product in an MRI environment. Once in an MRI environment, any radiated emissions will appear as constant lines in the MRI image. This will determine whether or not the power supply is interfering with the MRI. The first MRI testing will be performed at the Philips' complex at Gainesville, Florida. If the product passes all testing at Gainesville, three MRI facilities will be used for testing.

5.4 Magnetic Immunity

Purpose: The static magnetic field of the MRI will be the greatest concern, as well as the gradient fields around the 1-100 kHz range. Components with ferromagnetic material in the power supply can be pushed into their saturation points by the large magnetic field. This will cause a surge in current that may not be protected. This surge may destroy other components, and therefore destroy the power supply itself. Therefore, testing needs to be done to determine what magnetic field levels will cause the power supply to fail in operation.

Procedure: First, a general screening will be made at the Philips test center. A DC magnetic field is needed for complete testing. In order to accomplish this, a DC magnet was made. This magnet was created by looping 8 gauge wire around a C clamp made of iron and steel. The shielded enclosure will be placed in the gap of the core. This gap can be adjusted to the enclosure's size. The magnet is discussed in section 6. A gauss meter will be used to measure the field both outside and inside the shielded enclosure, against one of the walls. The output of the power supply will be measured, as well as the temperatures at transformers and other areas of the power supply. Data will be collected using a data logger. This will give an idea for the attenuation the shielded enclosure provides. Only relative measurements can be provided by this test. An AC power supply can also be used to test gradient field levels. Therefore, this electromagnetic will only be able to serve as the initial magnetic immunity test.

When a finished product is created, an MRI environment will be used to measure magnetic susceptibility as well. The power supply will start away from the MRI, and gradually be moved toward the MRI. The power supply will move along an axis that is oriented horizontally alone the center of the MRI. During testing, a gauss meter will show the strength of the magnetic field at each point. Different orientations will be used at each point as well. Measurements will be made at the output of the power supply to ensure that it is operating as it should. Temperature measurements at points on the power supply will also be measured. This will determine if the power supply is being interference with by the MRI.

5.5 Thermal Imaging

Purpose: Because the AC to DC power supply will be enclosed, air will not be able to move through the unit. The main source of heat dissipation will be through the walls of the shielded enclosure. In order to keep components below their temperature limits, heat sinks may need to be added. Thermal Imaging will help determine whether this is the case.

Procedure: Thermal mapping is a collection of images and data taken of the power supply while it is operating. The power supply will be under the maximum load condition of 5 Amps. This is to ensure that the unit is dissipating maximum heat. Images were taken during using an infrared camera. Images will give approximate temperature readings. The areas with the greatest temperature, or hot spots, will be identified. These hot spots will then be tested through the use of thermocouples. Thermocouples can be connected to a data logging device, and the temperature can be more accurately measured.

5.6 Temperature and Vibration Testing

Purpose: For reliability purposes, the power supply will be ran at the extremes for temperature it will face while in operation and storage. Vibration will also ensure that the product is not damage during movement. This is important, as the patient monitor is mobile. This is to ensure that the product will remain functional during use.

Procedure: The power supply will be place in a test chamber, which will cycle through various temperatures. The chamber will change to temperature extremes, and then dwell for 3 hours. The high operating temperatures will be 40°C, 45°C, and 50°C. The low operating temperatures will be 10°C, 5°C, and 0°C. Storage temperatures of -20°C and 70°C will be tested as well. The dwell time for these temperatures will be closer to 10 hours. After successful testing, the temperature will be cycled from 50°C to 0°C. The chamber will stay at either temperature for a 2 hour dwell period, and then change to the other temperature. Meanwhile, the power supply will be cycled through various input conditions. Two different AC operating extremes of 88 Volts AC at 47 Hertz and 270 Volts AC at 66 Hertz will be used. The power supply will also go through on and off cycles. If this is successful, vibration will be added to the beginning of each 2 hour dwell. During this testing, the output of the power supply will be monitored and logged. This will allow for the test to be run without the need of an observer. All information of device misbehavior will be saved and time stamped.

5.7 Humidity Testing

Purpose: For reliability purposes, the power supply will be run at the humidity extremes that it will face while in operation and storage. This is to ensure that the product will remain functional during use.

Procedure: Using another test chamber, the power supply will be tested in humidity. The power supply will spend one day in the chamber under conditions of 45ºC and 95% humidity while operating. It will then spend a day in the chamber under conditions of 60ºC and 85% humidity for storage. Finally, the power supply will spend another day in the chamber under conditions of

45ºC and 95% humidity while operating. During the testing, the output of the power supply will be monitored and logged.

5.8 Altitude Testing

Purpose: For reliability purposes, the power supply will be ran at the extremes for altitude it will face while in operation and storage. This is to ensure that the product will remain functional during use.

Procedure: Using another test chamber, the power supply will be tested in humidity. The power supply will spend one day in the chamber under conditions of -10ºC at 9900ft without power. It will then spend a day in the chamber under conditions of 50ºC at 9900ft while operating. Finally, the power supply will spend another day in the chamber under conditions of 10ºC at 9900ft while operating while operating. During the testing, the output of the power supply will be monitored and logged.

5.9 Magnetic Pull

Purpose: Because of the intense magnetic fields present in MRIs, metallic objects will be pulled towards the magnetic. The power supply will be subject to pull from the MRI's magnetic field when placed on the ground. In order to ensure that the power supply is safe and will not harm both the patient and the MRI, magnetic pull tests need to be performed.

Procedure: The power supply will be subject to a DC magnetic field. The power supply will be attached to a meter which can measure the force exerted on the power supply by the magnetic field. The power supply should not be pulled with a force more than a tenth of its weight. If the power supply is pulled by a force less than a tenth of its weight, then gravity will ensure that the power supply is not pulled into the MRI magnet. Measurements will be made both with the magnet made for magnetic testing as well as at the Gainesville complex.

5.10 Power Line Testing

Purpose: Voltage spikes and drop outs will occur on the AC line. Hospital power often is subject to these conditions. In fact, it is often the most common place for these occurrences. Therefore, the power supply must be tested under these conditions to ensure that it will not fail.

Procedure: The AC line of the power supply will be placed into an AC power generator. This generator is capable of creating the surge and power dropout conditions such as brownout and blackout that will occur. The power supply will be connected to an oscilloscope. Unlike the reliability tests, the AC line tests are fast. Data logging will not be able to see any problems that occur, unless the power supply is permanently damage. For this reason, the oscilloscope will be used to monitor the power supply output.

5.11 Safety Testing

Purpose: Two tests fall under safety testing. The first is leakage current testing. The Mr. Fusions power supply cannot have a leakage higher than 500 µA according to safety regulations. This is to protect any users from receiving a substantial shock. The second test is ESD testing. This is to ensure that a user cannot harm the power supply from the buildup of static shock.

Procedure: For leakage current testing, the power supply is placed into a unit that measures the leakage current. The power supply will be powering the 3160 unit. As for ESD testing, the power supply will be shocked with 8 kV spikes. This will simulate human static shock. The output of the power supply will be monitored to ensure that ESD will not affect operation.

6.0 Electromagnet for DC Magnetic Field Testing

One aspect of this project is to protect the power supply from magnetic fields that would otherwise cause the device to deviate from its desired performance. It is not practical to use a real MRI for initial testing, due to limited availability. Therefore, either a permanent magnet or an electromagnet can be used to emulate the MRI environment. The benefit of an electromagnet is the ability to control the magnetic field. The field can be turned on or off. When turned on, varying current in the electromagnet's coils will allow for variable magnetic fields. The electromagnetic will be used to measure both power supply susceptibility to magnetic fields and the effectiveness of magnetic shielding.

Figure 5 shows the test setup used for DC magnetic field testing. A C-clamp was used as the electromagnet's core, which coils are wrapped around. These coils will create a magnetic field directed through their center. The C-clamp is a combination of steel and iron, which are both materials with a high permeability. The magnetic field is directed across a gap of the C-clamp. Directing the field across a gap allows for a concentrated field. Because the C-clamp gap can be varied, the magnetic field can be increased by shortening the gap as much as possible. Also, the magnetic field will decrease rapidly moving away from the gap. This limits the safety issues present in the lab area. Another safety issue with the electromagnet was presented by the large amounts of current through the coils. The wire used for the coils was rated for temperatures up to 90 °C. After a certain period of time (depending on the magnitude of the current), the coils would reach their maximum rated temperature. To extend this period of time, a fan was used to cool the electromagnet. The temperature of the electromagnet was measured with an infrared temperature sensor as well as thermocouple wire. The thermocouples were attached to a data logger, which made graphing the temperature over time possible.

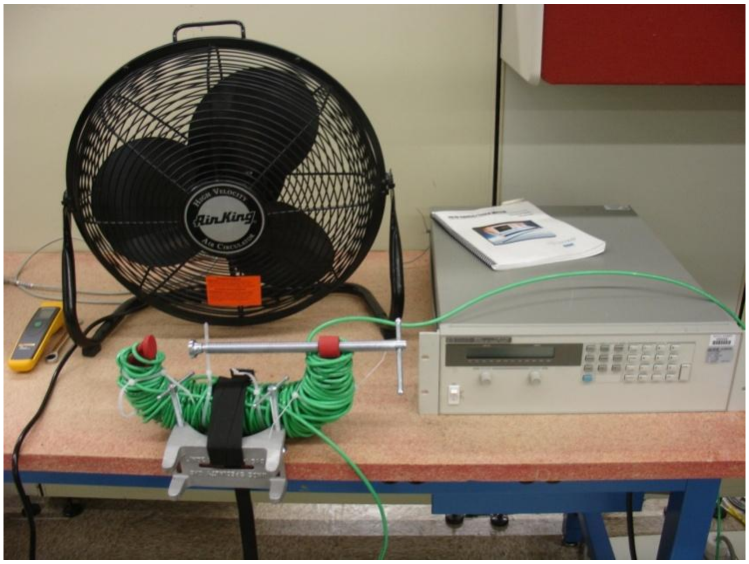


Figure 5: Electromagnet for DC Magnetic Field Testing. A fan is used to cool the coils. The power supply to the right is driving the current of the coils.

As stated, the magnetic field can be increased by varying both current and gap size. The largest DC supply available to this project without purchase could provide up to 105 Amps. The gap size was limited by the size of the device under test. Tables of initial data on the magnet's magnetic field can be found on the following page. This data was composed using a DC power supply that could provide only a maximum of 60 Amps. A 105 Amp supply was used later in experimentation, because the magnetic field intensity was not strong enough using the 60 Amp maximum of the previous supply.

Tables 5 and 6 show the field measurements taken for varying current levels and gap lengths. These field measurements can be estimated using a "magnetic circuit". The magnetic circuit uses circuit analysis to show the properties of the electromagnet. The first component of the magnetic circuit is a voltage source that represents the magnetomotive force. This is equal to the number of turns multiplied by the current (NI). The other components of the circuit are resistances that model the steel C-clamp, the adjustable iron bar, and the air gap. The current in this circuit is the magnetic flux. The magnetic circuit for the electromagnet can be shown in Figure 6.

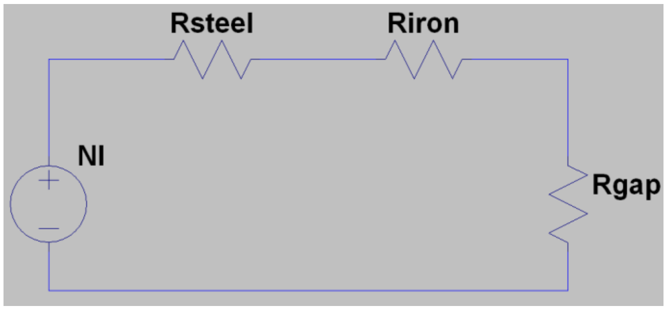


Figure 6: Magnetic Circuit

The number of turns in the electromagnet is approximately 140. The resistance of each material is equal to L/(μA), where L is the length, μ is the permeability, and A is the area. R_{steel} is equal to 886 N/(m A^2). The other resistances, R_{iron} and R_{gap}, are dependent on the length of each. R_{iron} is equal to 981*L N/(m $A)^2$. R_{gap} is equal to 196*L N/(m $A)^2$. Obtaining the magnetic flux, which is simply obtaining the current of the magnetic circuit, will in turn provide the information for the magnetic field. The equation for magnetic flux is the following

$$\Phi = \int_S B \cdot dS \qquad \textbf{eq. (1)}$$

where Φ, B, and S are magnetic flux, magnetic field, and surface area. In Tables 5 and 6 are both the expected and measured magnetic fields.

Table 5: Magnetic Field with Varying Current, 1'' Gap, measured at left end of gap

Current (Amps)	Voltage (Volts)	Resistance (Ohms)	Power (Watts)	Measured Magnetic Field (kilogauss)	Expected Magnetic Field (kilogauss)
10	0.685	0.0685	6.9	0.225	0.159
20	1.354	0.0677	27.1	0.265	0.318
30	2.054	0.0685	61.6	0.31	0.476
40	2.754	0.0689	110.2	0.35	0.635
50	3.525	0.0705	176.3	0.41	0.794
60	4.205	0.0701	252.3	0.43	0.953

Table 6: 60 Amps through Coils, Magnetic Field measured at left end and midpoint of gap

Gap (inches)	Magnetic Field @ Left End (kilogauss)	Expected Magnetic Field (kilogauss)	Magnetic Field @ Midpoint (kilogauss)
2	0.34	0.069	0.175
3	0.32	0.059	0.1
4	0.315	0.052	0.068
5	0.315	0.046	0.055
6	0.31	0.042	0.045
7	0.31	0.038	0.038

From the expected magnetic fields, it looks as though the electromagnet is not performing as well as expected in Table 5 when current was increased. However, increasing the gap did not have as great an effect as expected, as Table 6 shows. In this case, the electromagnet outperformed expectations. There may be some variation in the measurements, but these are interesting results. It may be due to eq. 1 assuming one layer of wire wrapped around the electromagnet. In fact, multiple layers were wound. However, the cause is uncertain.

The first magnetic testing was performed with both the Elpac and the SL power supplies. This test would determine the magnetic susceptibility of the power supplies. Each supply placed inside the C clamp, as shown in Figure 7. A load of 5.3 Ohms was placed on the DC output to represent the 90W maximum load that a patient monitor would draw. Each supply was tested along each of its three axis. The gap was decreased to the size of the power supplies at each axis. These dimensions are located in each supply's datasheet, found in Appendix A. A data logger was used to measure the output voltage and temperature of magnetic components (transformers and inductors). This data was taken every tenth of a second. The reason for the quick sampling time was to see the AC ripple on the 18 Volt output. If either power supply malfunctioned, the data logger would be able to show it. An increase in temperature in any magnetic component might indicate if it was the part that malfunctioned.

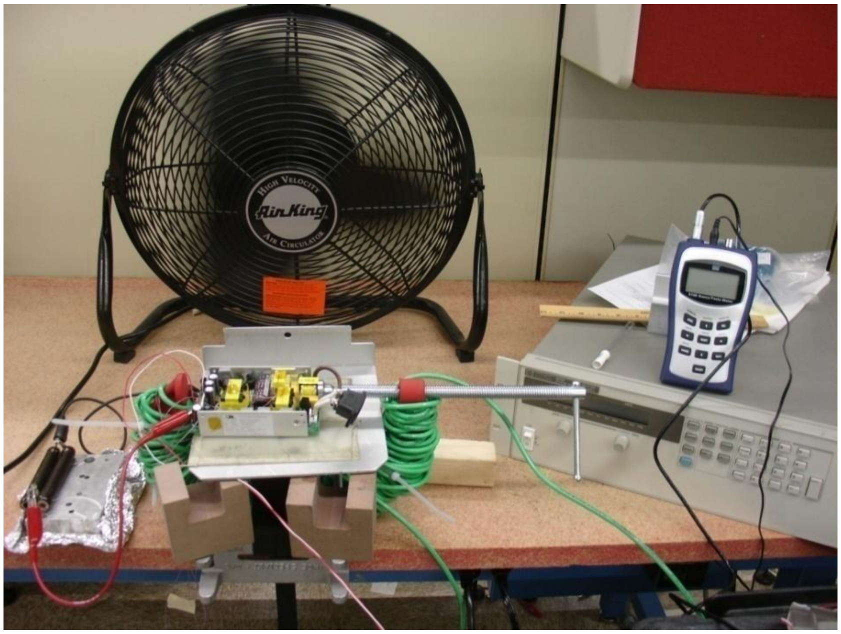


Figure 7: Testing setup for electromagnetic

Initially, the current in the coils was increased by 10 Amps until the limit of 60 Amps was reached. However, both supplies were able to survive the magnetic fields applied to each axis. Therefore, a DC power supply was used that could provide up to 105 Amps. Again, both power supplies were able to survive the magnetic fields applied to each axis. However, there was an issue presented by the Elpac supply. When increasing from 0 to 60 Amps, the output voltage dropped out. The supply was unplugged and then reconnected, which fixed the problem. Additional trials of rapid magnetic field changes were performed, but the Elpac supply did not show the failure again. No failures occurred while testing the SL supply. The largest magnetic field measured was either 1 kilogauss or 1.8 kilogauss. There is an uncertainty with the gauss meter used. The gauss probe was place perpendicular to the magnetic field as instructed. However, placing it horizontally and vertically presented two different measurements.

The results are uncertain as to whether or not the power supplies need much in terms of magnetic shielding. This was due to the inability to emulate totally the magnetic fields present in the MRI environment. At the bore of a Philips MRI, the magnetic field parallel to the MRI bed was measured at 1.2 kilogauss. The magnetic field perpendicular to the MRI bed was measured at 0.55 kilogauss. The magnetic field vertical to the MRI bed was measured at 0.25 kilogauss. All these measurements were taken as close to the bore as possible at the point the power supply would be mounted on a patient monitor.

Magnetic field intensities tested with the electromagnet surpassed the perpendicular and vertical magnetic field intensities seen in the MRI environment. However, the 1.2 kilogauss field parallel to the MRI bed could only be replicated by the electromagnet with a very narrow gap corresponding to the vertical dimensions of both supplies. Because the power supply will be oriented similarly to Figure 7, there was too large of a gap to obtain the 1.2 kilogauss field intensity that was desired. Also, magnetic fields were only tested one axis at a time. The presence of magnetic fields along each axis could add up to an intensity that could cause failures in the power supply.

In order to obtain a true answer as to whether or not the power supply will survive in the MRI's magnetic field, a magnetic susceptibility test using an MRI was needed. For this test, both the Elpac and the SL supplies were tested with both a 1.5 Tesla and 3.0 Tesla Philips MRI. Each supply was tested at the height it would be mounted onto the MRI patient monitor.

7.0 Shielded Enclosure Design

The following is a section devoted to the design and calculations associated with the shielded enclosure.

7.1 Shielded Enclosure Dimensions

The purpose of a shielded enclosure is to shield the power supply from magnetic fields of the MRI, attenuate radiated noise from the power supply that affects MRI imaging, and help dissipate heat from the power supply. The first area of concern with this shielded enclosure is size. The ultimate goal of this project is to place the power supply underneath the MRI patient monitor. So, the first step of the design process was to realize the special constraints. The shielded enclosure is limited to dimensions of approximately 0.114 x 0.305 x 0.041 meters (4.5'' x 12'' x 1.6''). While these are the absolute maximums, an even smaller enclosure will allow for extended lifetime of the power supply as new patient monitors become smaller.

Using the SL power supply's dimensions, an inner width needs to be at the least 0.076 meters (3''). Additional space will be needed in order to compensate for tolerances in the manufacturing process. The ideal situation is to have all three sides of the power supply's bracket to contact the side walls. The reason for this is to obtain the best heat transfer through the enclosure. Contact with three walls of the enclosure presents two problems. The first is that the bracket of the SL power supply will not perfectly contact the enclosure due to roughness of the two metals. By applying thermal grease between the metal bracket of the power supply and the enclosure, there will be complete contact between the two. The second problem is the ability to contact three sides of the enclosure. With tolerances added to the enclosure dimensions, the power supply will only contact two sides. In order to remedy this, thermal pads can be added between the power supply's bracket and the enclosure.

There are constraints on the length of the enclosure as well. In additional to the 0.305 meter (12'') limit of space, 0.0254 meters (1'') will need to be taken off each side. The reason for this is to add mounting holes to the enclosure. These mounting holes allow for the power supply to be attached to the underside of a patient monitor. This allows for a maximum of 0.254 meters (10'') for the actual enclosure. Half of this space will be occupied by the power supply, which is approximately 0.127 meters (5'') in length.

Using the SL power supply’s dimensions, an inner height needs to be at the least 0.0305 meters (1.2’’). A cover would be screwed in over top of the bottom part of the shielded enclosure. Height will be the limiting factor in wall thickness. There is an overall maximum height of 0.0407 meters (1.6’’). Mesh will need to be included to fill in the gaps between the enclosure and cover with material to attenuate any radiated fields. The reason for this is to limit the EMI that is present due to leakage from the cover. Allowing some spacing for mesh, the maximum wall thickness will be approximately 0.00318 meters (0.125’’).

The following sections will include calculations to determine how thick the walls of the enclosure should be, and if any additions, such as fins for thermal dissipation, will be needed.

7.2 Attenuation Models

Attenuation of the power supply’s electromagnetic interference (EMI) is of importance. It is the coils of the MRI that pick up the radiated energy absorbed by the patient. Because these coils are very sensitive to noise, the EMI from the power supply needs to be attenuated. The shielded enclosure will be part of this attempt to limit the power supply’s EMI.

EMI can be generated by either conducted or radiated interference. Conducted interference occurs when the generator of EMI creates a large antenna through the cabling to which the generator is connected. This usually occurs most on the AC line cord that the generator uses. This type of interference problem can be solved through shielded line cords and placing a low pass filter in the line cord. This is not the type of interference that will be solved with a shielded enclosure, however. Radiated interference occurs when the generator radiates electromagnetic or magnetic fields by itself to the receiver. This type of interference will be solved through the shielded enclosure.

Now that the focus is on radiated interference, the next step to creating an attenuation model is determining the type of radiation emitted from the power supply. First, it needs to be determined the receiver’s distance relative to the radiator (the power supply). Distance, in this case, needs to be looked at in terms of wavelengths. At frequencies in the range of 1 to 150 MHz, the wavelength is in the range of 300 meters to 2 meters. The power supply, attached to the patient monitor, can be right near the bore of the MRI magnet. Specifically, this is within 2 meters, and means that the radiation on the MRI coils from the power supply will be in the near field for almost all of the frequencies this project is concerned with.

As a rule of thumb, generally the near field of radiation is located in a radius from the radiator that is one sixth of the wavelength. (Hemming, 1992) Around this distance, the radiation is located in the far field. The far field of the radiation is where the radiation fields resemble a plane wave. The radiation fields rely on the inverse of the distance (1/r) from the radiation source. In the near field, radiation fields rely on factors of 1/r, $1/r^2$, and $1/r^3$. Radiation fields no longer resemble a plane wave. Instead, the radiation fields resemble more of either an electromagnetic or magnetic field. With the power supply, radiation fields will most likely resemble magnetic fields. This is due to the transformers that are used in the power supply. Like the magnet created for testing, the transformers are constructed with wires wound around a magnetic core. This will create the magnetic interference.

Some simulations were created in Matlab to look into the issue of attenuation. The goal of the simulations was to determine how varying thickness would perform for attenuation. These thicknesses are 0.003175, 0.001588, 0.000794, and 0.000397 meters (1/8'', 1/16'', 1/24'', and 1/32''). Two types of materials, aluminum and steel, were used for these calculations. This project was only concerned with attenuation in the frequency range of 1 to 150 MHz, as these are the range in which the Larmor frequencies are present. There are two equations that we are concerned with to model the attenuation from the enclosure. These equations are for reflection loss and absorption loss. The equation for reflection loss is given as the following for magnetic fields in the near field(Hemming, 1992)

$$\text{Reflection Loss [dB]} = 20 \log [1.173 (\mu_r / f \sigma_r)^{1/2}/d] + 0.0535\, d\, (f \sigma_r / \mu_r)^{1/2} + 0.354 \quad \textbf{eq (2)}$$

where d, f, μ_r, and σ_r are distance from shield in meters, frequency, relative permeability, and relative conductivity, respectively. μ_r and σ_r will change with frequency. However, to make calculations easier constant values were used. The μ_r and σ_r values for aluminum are 1 and 0.61. The μ_r and σ_r values for steel are 100 and 0.02. It can be seen that the reflection losses are not dependent on thickness. Figure 8 shows the expected reflection losses for an ideal aluminum and steel enclosures. These ideal enclosures have no imperfections or holes that would cause leakage. However, they will be relatively accurate.

It can be seen from Figure 8 that steel will have reflection losses well below the reflections losses provided by aluminum. Because the relative permeability of steel changes over frequency, this result is not entirely accurate. However, even with an overestimate of 1000 for the relative permeability, steel is still below the reflection losses for aluminum. This makes aluminum that much more of an effective EMI shield than steel in terms of reflection.

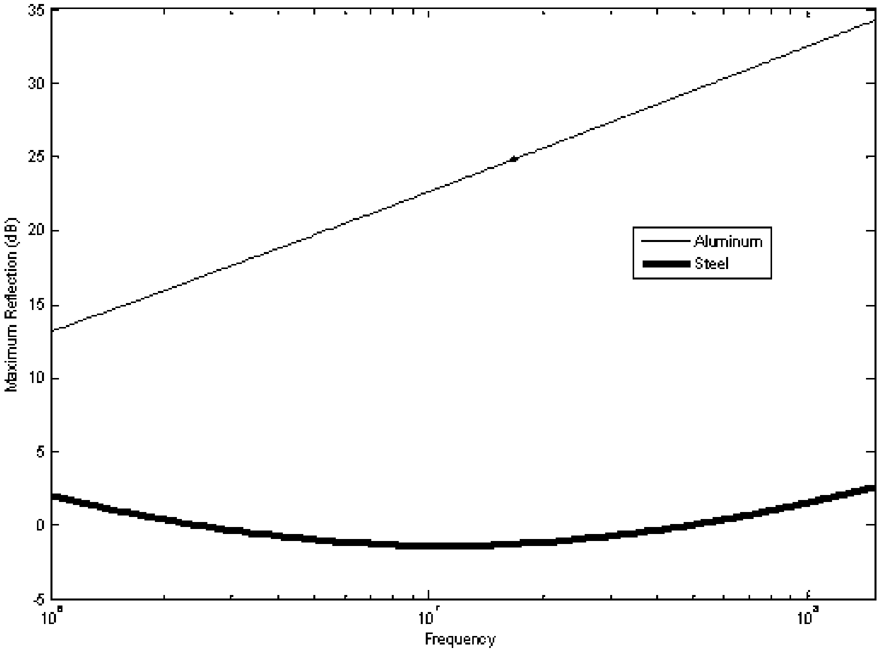


Figure 8: Reflection Losses for Aluminum and Steel Shielding

The second losses that occur with a shielded enclosure are absorption losses. For absorption loss, considerations for near field and far field do not need to be taken into account. The equation for absorption losses is given as (Hemming, 1992)

$$\text{Absorption Loss [dB]} = 1.314\ d \sqrt{}\,(f\ \mu_r\ \sigma_r) \qquad \textbf{eq (3)}$$

where d, f, μ_r, and σ_r are shield thickness in centimeters, frequency, relative permeability, and relative conductivity, respectively. The same values for μ_r and σ_r were used. Absorption loss for four different shield thicknesses, which are 3.175, 1.588, 0.794, and 0.397 milli-meters (1/8'', 1/16'', 1/24'', and 1/32''), was calculated. In Figures 9 and 10, line thickness corresponds to shield thickness.

From the results of the simulation, it can be seen that absorption loss is a more important factor than reflection loss and that changing the thickness has a significant effect on the absorption loss. For a more accurate representation of the aluminum enclosure that will be used, leakage from connector holes, screw holes, and gaps in the lid would need to be taken into consideration. Again, the same analysis can be done for steel. It can be seen that steel is much better than aluminum in terms of absorption losses.

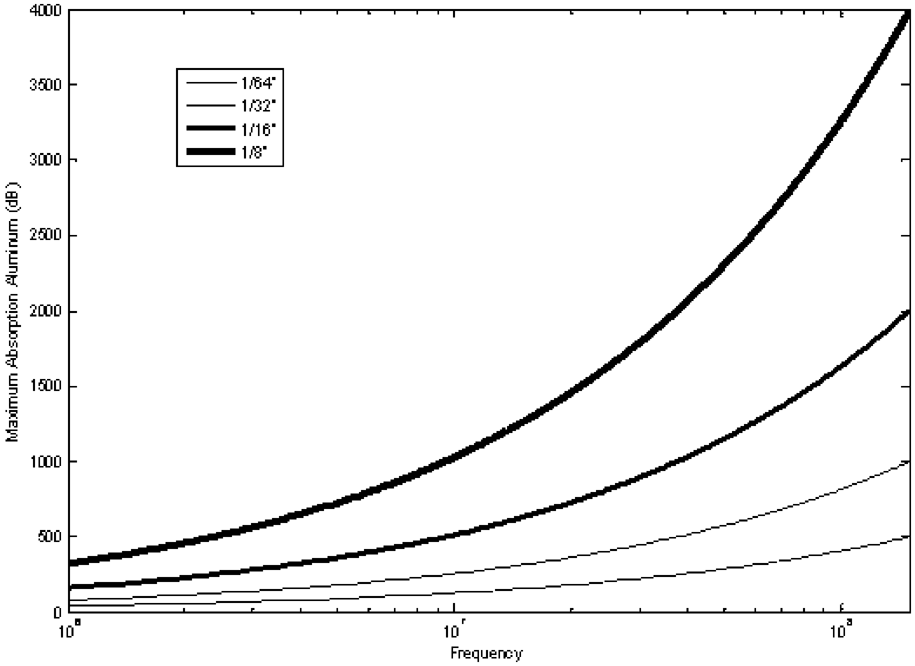


Figure 9: Absorption Losses for Aluminum Shielding

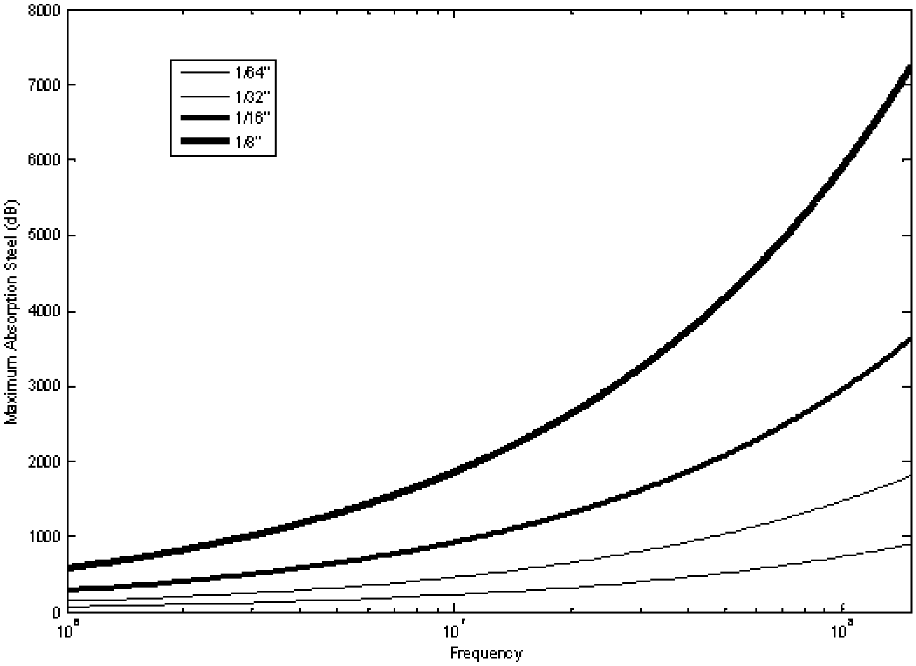


Figure 10: Absorption Losses for Steel Shielding

Figure 11 shows the total attenuation for both steel and aluminum with a thickness of 1/64’’. This is a combination of both reflection and absorption losses. While a more accurate estimate would show more attenuation for steel at lower frequencies, it can be seen that there will be a significant amount of attenuation even with a small thickness. At 1 MHz, aluminum provides over 50 dB of attenuation. With a more accurate estimate, steel might be able to provide over 100 dB of attenuation at 1 MHz. 50 dB of attenuation is good enough for this project.

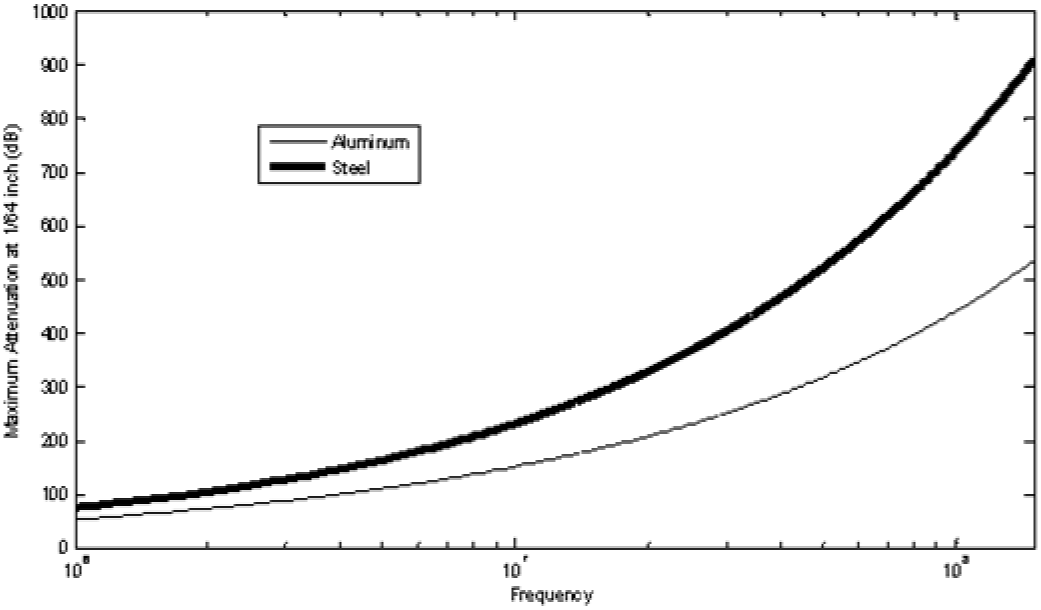


Figure 11: Total Attenuation for Both Steel and Aluminum of 1/64'' Thickness

There will be a limiting factor to how thin the shield can be. which is related to the skin depth. The skin depth is the depth needed for the aluminum or steel to attenuate an incident wave by 1/e through absorption. The skin depth (in inches) of aluminum and steel is found using the following equation

$$\delta = 6.604 / \sqrt{(\, f \, \mu_r \, \sigma_r \,)} \ \ [\text{cm}] \qquad \textbf{eq (4)}$$

where f, μ_r, and σ_r are frequency, relative permeability, and relative conductivity. Using the same values for μ_r and σ_r of aluminum, we get a value of 83 μm for 1 MHz and a value of 5.3 μm for 150 MHz. Using the same values for μ_r and σ_r of steel, we get a value of 1.5 μm for 1 MHz and a value of 0.12 μm for 150 MHz. Again, these are the extreme values of frequencies this project concerned with. The importance of this skin depth comes into effect regarding multiple reflections inside the enclosure. When an incident wave is reflected back inside the shielded enclosure, it will continue to reflect off another wall of the shielded enclosure. This continues as the incident wave gets reflected and absorbed. If the shield thickness is much greater than the skin depth, these multiple reflection can be disregarded and only the first reflection needs to be taken into consideration.

To take a look into what ratio of thickness to skin depth will cause losses due to multiple reflections, the equation for multiple reflection loss is needed. (Paul, 2006)

$$M_{db} = 20\log_{10} | 1 – e^{-2t/\delta} e^{-j2t/\delta} | \qquad \textbf{eq (5)}$$

where t/δ is the ratio of thickness to skin depth. Figure 12 below shows a graph of multiple reflection loss according to this ratio. It can be seen that a ratio of at least two to one is needed. The best multiple reflection loss value is zero. A negative number means that the shielding effectiveness of the enclosure is being compromised.

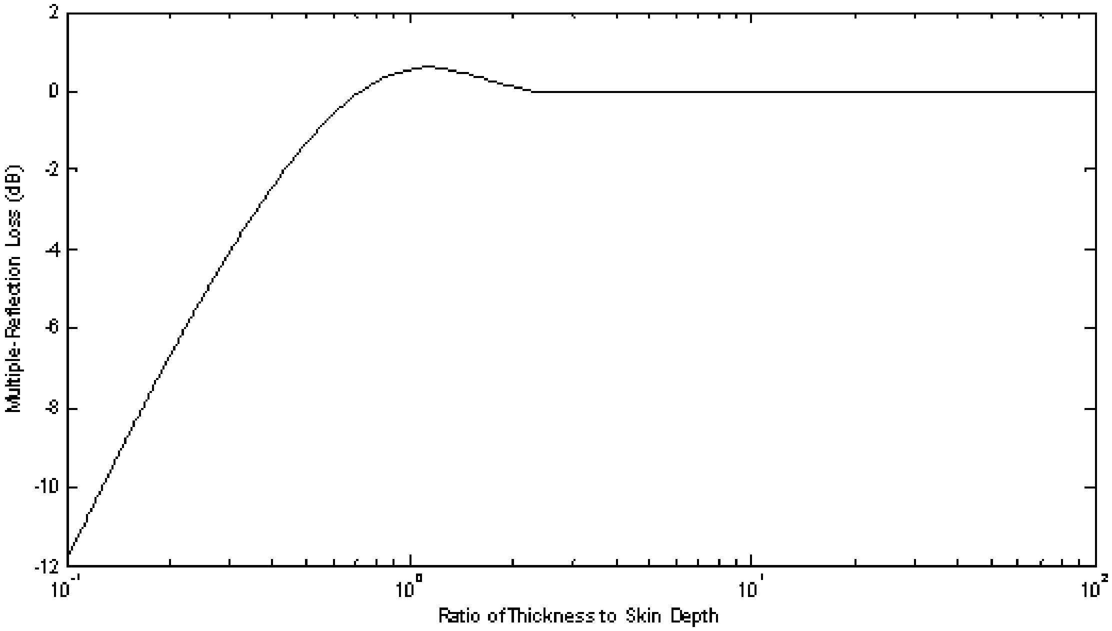


Figure 12: Multiple-Reflection Loss vs. Ratio of Thickness to Skin Depth

7.3 Thermal Models

Thermal dissipation can also dictate how thick the shield can be. The thermal model used here will be a simple one dimensional analysis along four planes. For now, it is assume 3 walls of the power supply can be contacted with the aluminum enclosure via thermal grease. The thermal resistance between the aluminum enclosure and the bracket of the power supply will be small. Looking at thermal grease products through various distributors such as Newegg, a low-cost thermal grease has a thermal resistance as high as 0.03 K/W (Kelvin per Watt). It is now assumed there is a perfect contact, as opposed to having the power supply imperfectly contacting the aluminum due to roughness of the surface.

All the following thermal characteristics were found using Introduction to Heat Transfer by Bergman et al.

The thermal resistance of the aluminum is the variable, because the thickness of the aluminum can be varied according to this equation(Bergman et al, 2007)

$$R_{cond,\ aluminum} = L/kA \qquad \textbf{eq (6)}$$

where L, k, and A are the thickness, thermal conductivity, and area. The thermal conductivity for aluminum can approximately be around 180 W/m*K (4.572 W/inch*K), but can be larger (approximately 237 W/m*K) the purer the aluminum. 180 W/m*K was assumed to be the thermal conductivity, because it would be the largest resistance and thus the worst case. For the sides of the power supply, the area is equal to about 38.7 cm^2 (1.2 inches by 5 inches = 6 $inches^2$). R_{cond} is approximately 0.0364L. For the top and bottom of the power supply, the area is equal to about 96.8 cm^2 (3 inches by 5 inches = 15 $inches^2$). R_{cond} is approximately 0.0146L.

Heat will be dissipated through the aluminum enclosure by both convection and radiation. The thermal resistance from aluminum to air by radiation is given by (Bergman et al, 2007)

$$R_{rad}= 1/h_rA \qquad \textbf{eq (7)}$$

where h_r and A are the radiation heat transfer coefficient and area. The equation for h_r is given as (Bergman et al, 2007)

$$h_r = \varepsilon\sigma (T_s + T_{sur}) (T_s^2 + T_{sur}^2) \qquad \textbf{eq (8)}$$

where ε, σ, T_s, and T_{sur} are emissivity, conductivity, surface temperature, and surrounding temperature. Given ε is approximately 0.82 for anodized aluminum, a conductivity of a surface temperature of about 326 K, and an ambient of 296 K, h_r is equal to 5.5 W/m^2K (0.0035 $W/inch^2*K$). The surface temperature and ambient temperature were found through an extended use test of the power supply within the enclosure. A 90 Watt load was connected to the power supply, and allowed to operate. Thermocouples measured temperature data on each side of the enclosure, both inside and out. Allowing the power supply to run for an extended period of time removed any thermal capacitance from affecting the results. Figure 13 shows the results of that test.

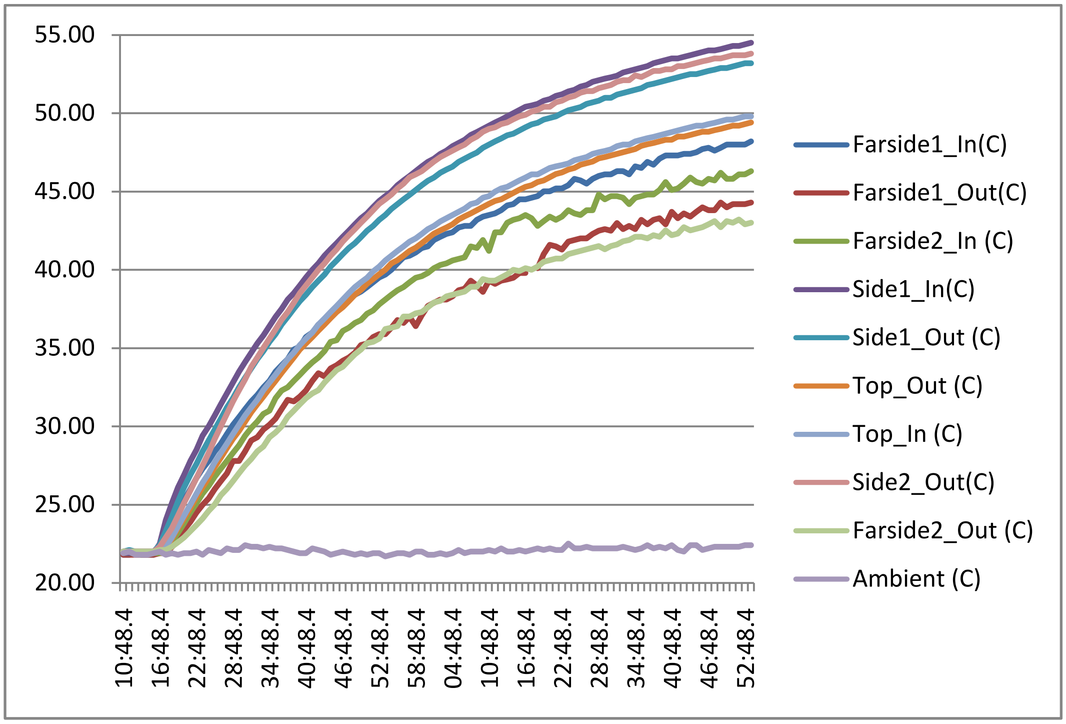


Figure 13: Thermal Data from Extended Use Test

It is assumed the maximum heat dissipation will occur in a small area of the enclosure. It is assumed this radiation area will be approximately an inch extended from either side of the power supply. The radiation area of the bottom is about 148 cm^2 (3.25 inches by 7 inches = 23 $inches^2$). This gives a thermal resistance of 12.4 K/W. The area of the two sides is about 72.3 cm^2 (1.6 inches by 7 inches = 11.2 $inches^2$). This gives a thermal resistance of 25.5 K/W.

Along with this radiated heat dissipation, there is also convection. The convection thermal resistance through air is given as (Bergman et al, 2007)

$$R_{conv} = 1/hA \qquad \textbf{eq (9)}$$

where h is the convection coefficient and A is the area. The value for h is 10 W/m^2K (0.0065 $W/inch^2{*}K$). The same areas are assumed. This gives a thermal resistance of 6.69 K/W for the bottom of the enclosure, and a thermal resistance of 13.7 K/W for the sides.

The rest of the power will be dissipated through the air inside the enclosure, through the aluminum, and then through the air outside the enclosure. So, air will provide thermal resistance to the sides. Instead of assuming one area of the box, this heat dissipation will occur through the entire box, minus the area already accounted for in the previous calculations. The top the enclosure will not be accounted for. This is because the top will be attached to the patient monitor, and it is not desired to rely on conduction through the patient monitor. The remaining area of the bottom is 64.5 cm^2 (3.25 inches by 10.25 inches – 23 inches2 = 10 inches^2). This gives a convection thermal resistance of 15.38 K/W. The area of the two sides is about 33.5 cm^2 (1.6 inches by 10.25 inches - 11.2 inches2 = 5.2 inches^2). This gives a convection thermal resistance of 14.79 K/W. The radiation thermal resistances are 28.6 K/W for the bottom, and 27.5 K/W for the sides. The conduction thermal resistances for the entire enclosure are 0.0073L K/W on the bottom/top and 0.018*L K/W on the sides. The far sides will have an area of approximately 23.2 cm^2 (3.6 inches^2). This gives a conduction thermal resistance of 0.061L K/W, a convection thermal resistance of 42.7 K/W, and a radiation thermal resistance of 79.4 K/W.

Now, we model the thermal dissipation as a current source connected to resistors and a voltage source. The current source represents power being dissipated by the power supply. There are four parallel paths for this power to escape, each corresponding to a side of the aluminum enclosure. The voltage source represents the ambient temperature. The input power to the SL MINT1110A was found to be 108.7 Watts at the maximum 90 Watt load. Assuming all other power is dissipated thermally, we obtain the power dissipated thermally. This value is 18.7 Watts. Assuming that the power supply will be within an ambient temperature of 296K (the temperature operated at in Figure 13), the expected bracket temperature can be obtained. The circuit equivalent of the thermal analysis is shown below.

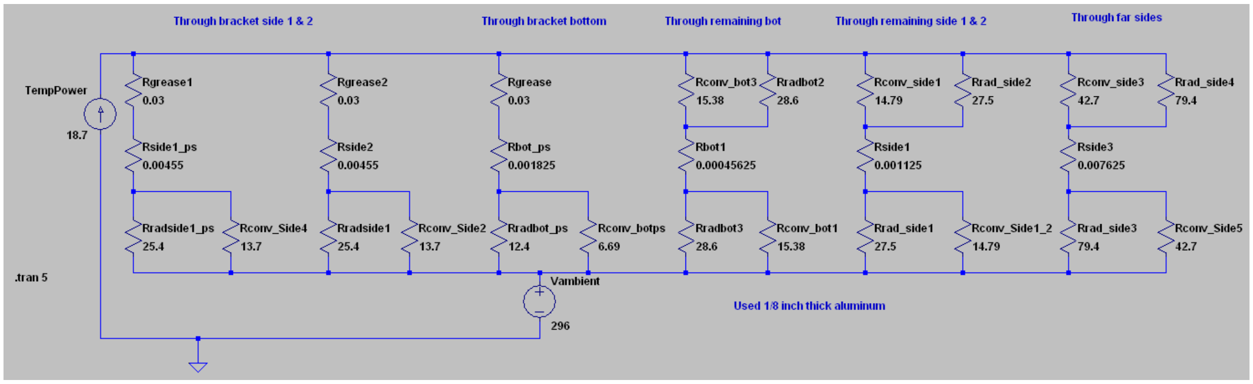


Figure 14: Thermal Circuit Model

According to this analysis, at 296 K ambient temperature the inside bracket can be expected around 329 K. This is 33 K rise from inside to outside temperature. The first enclosure was tested, and a temperature rise of approximately 30 K was seen. The first enclosure's value was expected to be higher, as there was no thermal grease in the initial prototype. The higher resistance would be the cause of the additional heat. However, the model expects a rise that is slightly higher. This is due to the ignoring of thermal conduction through the top of the enclosure.

If the power supply would provide 90 Watts at 40°C, operating on the upper limit may damage the power supply over time. The expected temperature rise puts the power supply at that limit. Because the SL power supply is only rated for 70°C, fins will be needed to ensure the lifetime of the power supply. Unfortunately, due to the special constraints underneath the patient monitor, there is only one space to place the fins. This space is the side of the enclosure with both the IEC320 and XLR connectors used for the input and output.

In order to model the effect of fins, the following equation is used (Bergman et al, 2007)

$$R_{fin} = 1/\eta_0 h A_t \qquad \textbf{eq (7)}$$

where η_0, h, and A_t are the fin array efficiency, convection coefficient, and total area of the fin array. Without going into much detail, the values for fin array efficiency and total area of the fin area will depend on the type of fins used. In this case, it is assumed that rectangular fins are used. The fin resistance then replaces the convection and radiation resistances for one side of the power supply. Using a fin width, length, and thickness of 1’’, 1’’, and 1/10’’, the following graph can be created to show the fin resistance according to the number of fins in the array.

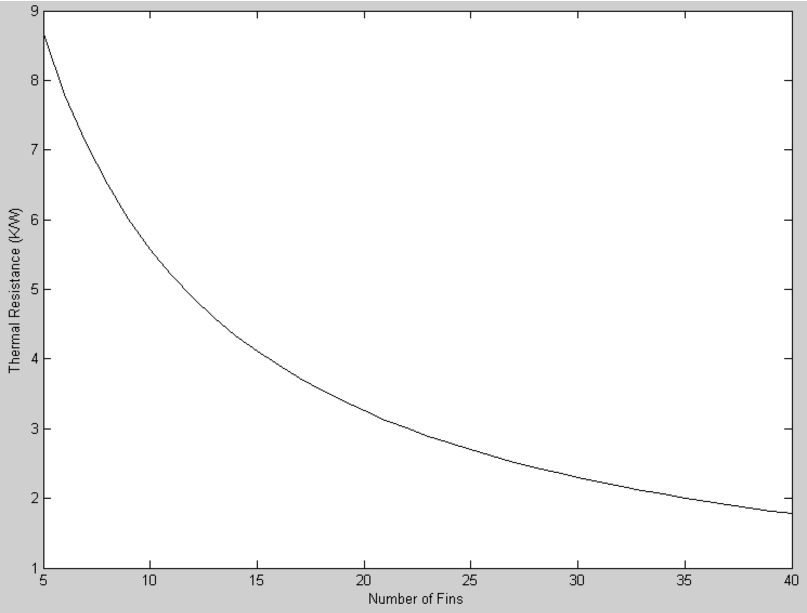


Figure 15: Thermal Resistance of Fin Area

One note is that thickness will not have too much of an effect on the thermal resistance if the thickness is significantly less than the width and length. The greatest factors are the fin length, fin width, and number of fins. At maximum load at 40°C, 60°C was deemed a reasonable inside temperature of the enclosure. In order to obtain this result, approximately 22 fins would be needed. The values for h and k where again assumed to be the worst case. However, this ensures that the power supply will operate to the desired specification.

One final concern is that the power supply will not be able to contact all three sides as this analysis assumed. This is due to imprecision in the enclosure making process. A thermal pad will be used to conduct through the third side. This will cause a slight increase in resistance. The most important aspect in the thermal dissipation is the contact from the power supply to the aluminum enclosure. The thermal resistance of the aluminum enclosure is insignificant compared to the thermal resistance of the thermal grease or air.

7.4 Enclosure Design

Two initial shielded enclosures were constructed with a wall thickness of 0.003175 meters (0.125’’) and a length of 0.3048 meters (12’’). One consists of aluminum, which will provide the best heat transfer and noise attenuation. The other shielded enclosure consists of steel. Steel is a good material for shielding against magnetic fields. Because little was known about the effectiveness of DC shields, this enclosure would be used to experimentally measure the magnetic field attenuation. Calculations are shown later for some of these aspects, and investigate different wall thicknesses. Both shielded enclosures employ the same design. Schematics and pictures are provided below of the shielded enclosure.

Figure 16: Steel Enclosure Top-Side View with SL Power Supply and AC Line Filter Inside

Figure 17: Steel Enclosure Side view, with cutouts for the AC and DC connectors

Figure 18: Enclosure Cover from Bottom. Mesh can be seen on the top cover.

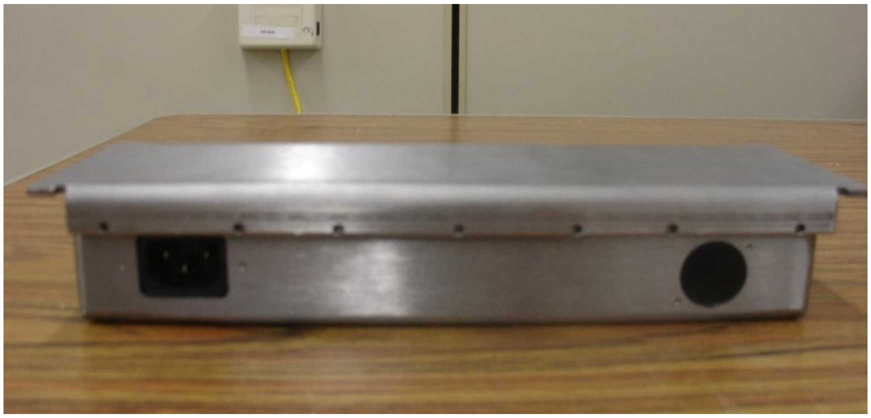


Figure 19: Closed Enclosure Side View. DC and AC connector holes can be seen, as well as screw holes for the lid.

1/8’’ walls were chosen due to restrictions on the enclosure dimensions. With only a height of about 1.6’’ available and a power supply height of approximately 1.2’’, 1/8’’ walls were the maximum thickness. The thickness could be greater on the sides, but it was determined that thicker walls would only increase absorption loses through the shield slightly. Therefore, it was not worth the extra thickness. If a ferromagnetic material were to be used later on for shielding purposes, it would provide greater absorption than the aluminum. This could be an option. Also, if costs can be drastically decreased by decreasing shield thickness, there would be an obvious decision to thin the aluminum.

7.5 Magnetic Applications

The steel shielded enclosure was used in the electromagnetic testing previously mentioned. Orienting the magnetic field along the vertical axis of the enclosure, a gauss probe was used to measure the magnetic field inside and outside the enclosure. Depending on orientation the gauss probe horizontally or vertically, measurements of 1.0 kilogauss and 1.8 kilogauss were measured outside the shielded enclosure. No matter the orientation, the maximum field measured inside the shielded enclosure was 0.02 kilogauss. This is a 17 dB minimum attenuation of the electric field. This does not seem important for the shielding of the power supply, as both the Elpac and SL supplies seem like they can survive the MRI magnetic field with minimal shielding. However, it does allow the possibility for magnetic core inductors for filtering purposes. Previously, only non magnetic inductors were considered. Non magnetic inductors can be expensive and sizable components.

To determine whether or not magnetic shielding was required, a magnetic susceptibility test was performed. The SL MINT1110A and Elpac MVA100 were both tested without any additional hardware. These power supplies are the primary candidates to be used in the power supply prototype. Both the SL MINT1110A and Elpac MVA100 were attached to a piece of wood as seen below in Figure 20. This allowed for someone to hold the supplies so that they were not pulled into the bore of the MRI magnet. A resistive load was added to the supplies to simulate an 18 Watt load from the patient monitor. An LED indicator was added to show whether or not the supplies were performing properly.

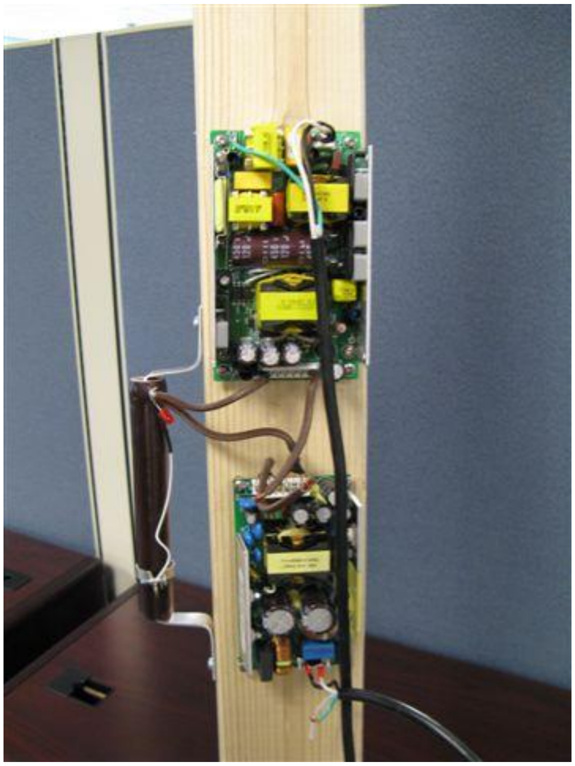


Figure 20: The SL MINT1110A and Elpac MVA100 Test Fixture

The magnetic susceptibility test was performed using the test fixture seen in Figure 20. With both supplies un-energized, the test fixture was stepped towards the MRI’s bore. The supplies were turned in all six possible orientations. Both supplies were subjected to a 30 kGauss field for all axis. When the supplies were energized, they functioned normally.

The next step was to test the supplies energized with no load and full load. Again, all possible axis were tested, and the power supplies were gradually stepped closer to the MRI’s bore. The Elpac MVA100 was able to function properly when oriented on any axis up until the 2 kGauss maximum of the test. The SL MINT1110A was not functional in all axis. When oriented with its vertical axis facing the MRI bore, the SL MINT1110A was only able to function to a maximum of 440 Gauss. This is not a cause for concern however, as the supply will only see a 250 Gauss magnetic field on its orientation underneath either the 3160 or 3160P. The SL MINT1110A also did not function properly when oriented with the AC connector facing the MRI’s bore with a field intensity of 1.7 kGauss or greater. The SL MINT1110A was not damaged during failure. However, the output did turn on and off periodically. Table 7 shows the results of the magnetic susceptibility testing.

Table 7: Results of Magnetic Susceptibility Test

Axis	**Max Level**	**SL Max Level**	**Elpac Max Level**
Parallel to MRI Bed	**1.2 kGauss**	**2 kGauss**	**2 kGauss**
Perpendicular to MRI bed	**0.55 kGauss**	**2 kGauss**	**2 kGauss**
Vertical	**0.25 kGauss**	**0.44 kGauss**	**2 kGauss**

From these tests, it can be concluded that magnetic shielding will not be needed for the power supply. Even with the increasing field strength that is seen in future generations of MRI technology, the increasing shielding is keeping field levels outside the bore relatively close to older generations. This is encouraging, because it will increase the longevity of the product that will result from this project.

As an addition to the susceptibility test, a magnetic pull test was performed. This test measures the force of the MRI on a patient monitor with or without the power supply. For this test, a prototype was used. This prototype contained filtering and connectors to be discussed later. A patient was tested without the prototype first outside the magnetic field and then inside the field, which was next to the bore of the MRI. Measuring outside the magnetic field measured the force of gravity, while the measurements taken near the bore provided both the force of gravity and magnetic pull. This was again repeated with the prototype. The goal was to have the pull on the patient monitor and power supply to be much less than the pull of gravity. Without going into proprietary information, this goal was accomplished. In fact, the prototype that was used did not add much more magnetic pull than the current supply that is used. This pull force can be lessened by the use of non-magnetic materials.

8.0 Radiated Emissions Testing

Radiated emissions testing is an important part of the design process. This testing would give an idea of the interference the power supply could have on the MRI image. First, a baseline comparison needs to be made. For this, a single power supply was connected without any additional components other than connectors for wiring. This provided a baseline test used for comparison. When modifications are made, the effectiveness of the modifications can be tested by looking for improvements in the noise levels. This would then give an idea as to what modifications are successful.

The patient monitor will not be a perfect resistor, but draws current at a nearly constant rate. Therefore, any reactance was ignored for initial tests, which were performed with a load resistor. These tests resulted in measurement error, because the resistor was a noisy source when compared to a patient monitor. For those reasons, results with a load resistor aren’t believed to be as reliable as tests done with an actual patient monitor for a load.

Radiated emissions tests were done in a Philips test area built to measure and record emissions from products. This test area contains a shielded RF enclosure big enough to contain the patient monitor, power supply, and antenna. The antenna sweeps the frequencies ranges that are of concern for MRI interference. Measurements were recorded in dBm at each frequency that was swept. Below are pictures of the test setup used. The patient monitor and power supply are placed on the wooden area, and the antenna measures the radiated noise.

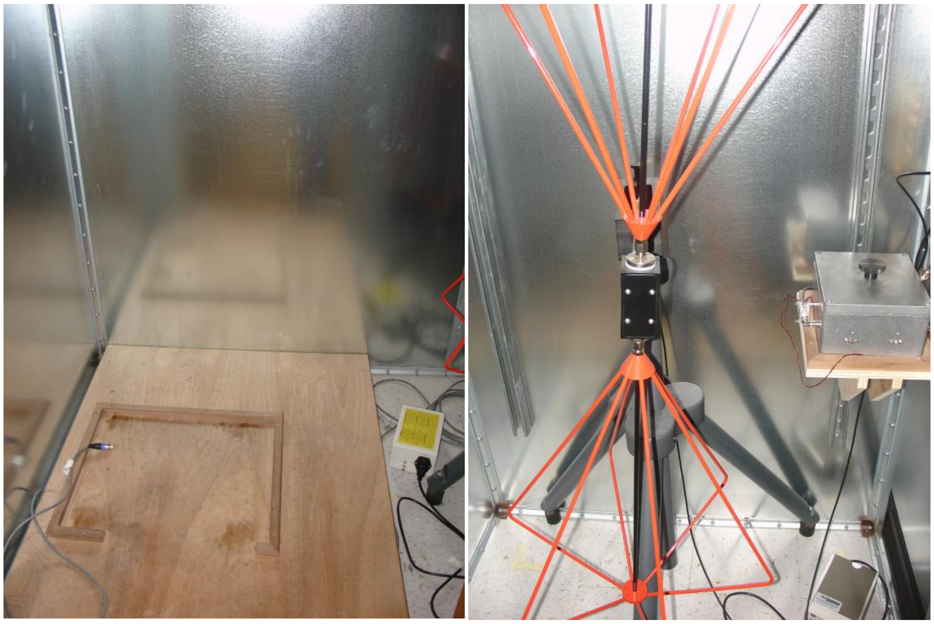


Figure 21 & 22: Radiated Emissions Setup

Figure 23 shows the results of the baseline test. The x axis shows the measurement frequencies, which are in Megahertz. The y axis is the emissions level in dBm. In red one can see the maximum noise threshold. These are thresholds established through Philips. Any noise above threshold would cause a faulty MRI image. In orange you can see the baseline's emissions level. Again, this base test is nothing but the power supply and wiring to power it. The patient monitor is the device at the load side of the power supply.

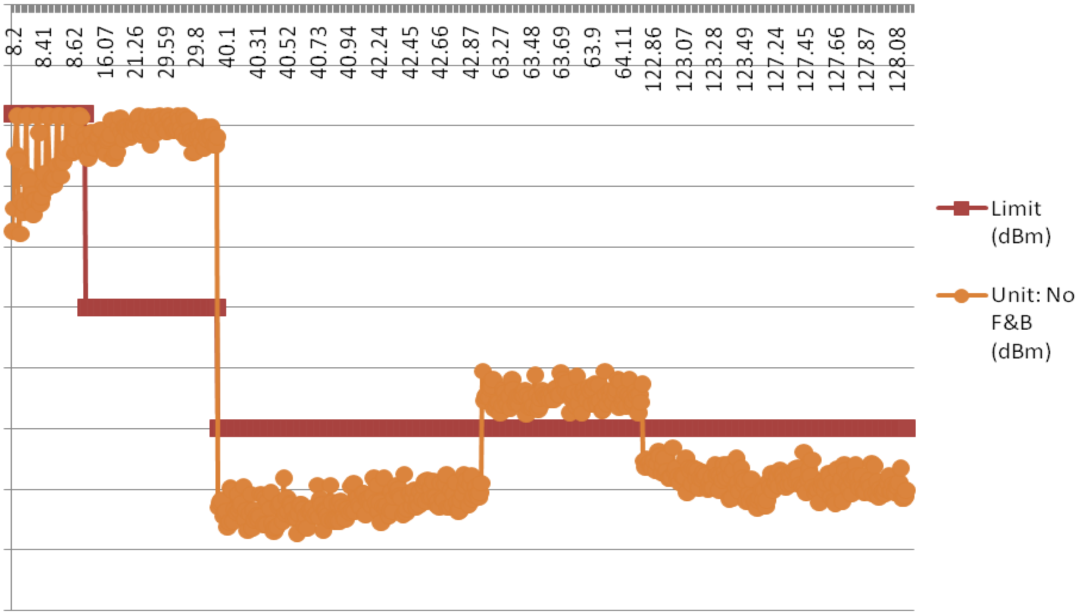


Figure 23: Baseline Emissions Test

Frequencies in the range of 16 to 30 MHz were observed to be approximately 15 dB above the threshold. Frequencies in the range of 63 to 65 MHz were observed to be approximately 3 dB above the threshold. Also, frequencies around 8 MHz are very close to the threshold. These will be frequencies of concern for later design in section 11, which is where input and output filters are implemented.

9.0 Input Connector Selection

The input connector of the power supply requires certain specifications to be met. The input connector needs to be an IEC320 Type C14, 3 pin male recessed receptacle. This power supply will be rated at voltages of 110 Volts for the US, 220 Volts for Europe, 100 Volts for Japan, and 220 Volts for Universal. Any connector will also need to be medical standard. Because of the magnetic field intensity present, any filter on the input connector should not include inductors. These inductors could saturate and malfunction in the present of the MRI magnetic field. If inductors are needed, air core inductors can be made for an additional filter.

Two input connectors were found that matched these specifications. They are the Schurter 5150 Series and the Corcom SRB series. Two tests were done to determine which IEC320 connector would be used. First, a ground leakage test was performed. Per regulations, the leakage current of the power supply cannot exceed 500 μA. If one connector provides less leakage current than the other, then it can allow for more capacitance to ground. This would allow for more filtering of the AC input. The Schurter 5150 Series was measured to have a leakage current of 150 μA at 250 Volts AC. At the same 250 Volts AC, the Corcom SRB Series was measured to have a leakage current of 150 μA. The Schurter 5150 can allow for more capacitance to ground than the Corcom SRB.

The second test of the input connectors was to test their emissions levels. Each connector was connected to the SL MINT1110A. In order to ensure that the connectors were the only variable, the same power supply was used. No shielding or additional hardware was included. Using the screen test previously mentioned in section 8, it can be determined which input connector performs the best. Figure 24 is a graph of the results.

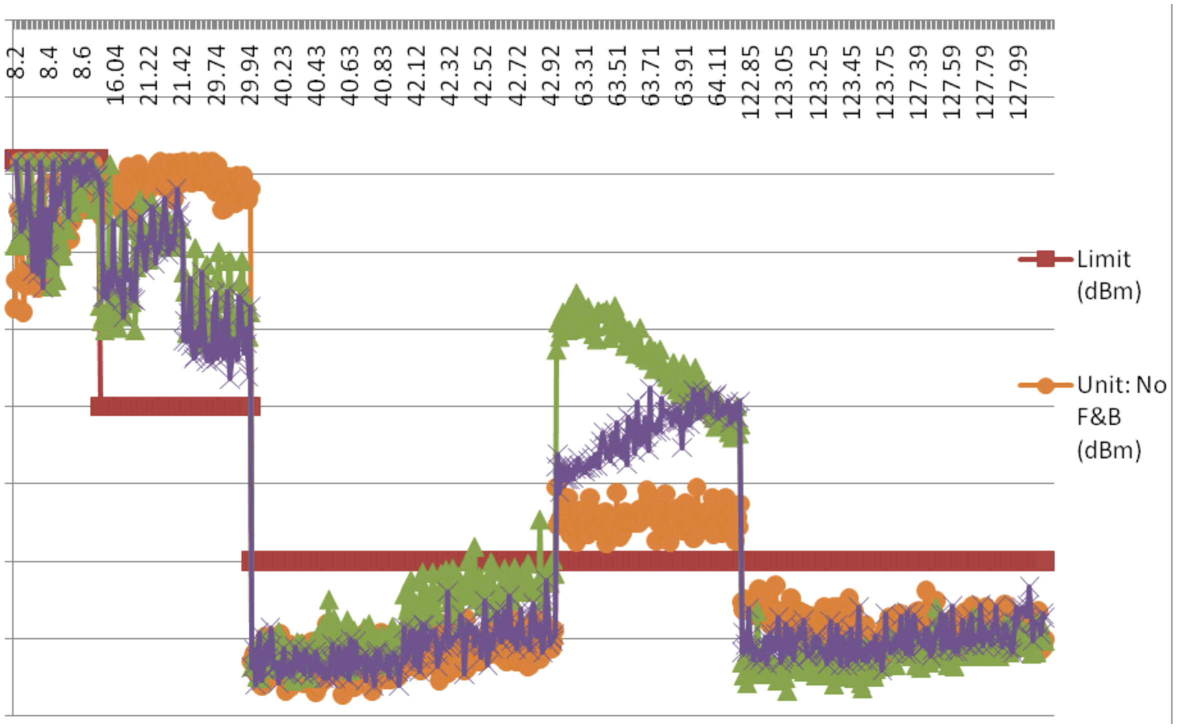


Figure 24: IEC320 Input Connector Emissions Test for SL MINT1110A

The Corcom line filter simply has a 2200 pF capacitance to ground on both the line and neutral inputs. The filtering had the most effect at frequencies in the range of 16 to 30 MHz. However, it actually made noise worse at frequencies in the range of 63 to 65 MHz. The Schurter line filter has a 2250 pF capacitance to ground on both the line and neutral inputs, a 4500 pF capacitance between the line and neutral inputs, and a 1 MΩ bleed resistance. Like the Corcom line filter, the filtering had the most effect at frequencies in the range of 16 to 30 MHz. It actually made noise worse at frequencies in the range of 63 to 65 MHz. However, the Schurter connector would seem to be the best choice. It performed as well as the Corcom connector at most frequencies, and outperformed it in the 63 to 65 MHz. It also has the benefit of less leakage current. In actually, the Schurter connector was not the chosen IEC320 connector, due to its price. The Corcom connector was about one fortieth of the Schurter connector’s cost. For this reason, the performance drop, which is slight, can be taken for the sake of cost.

10.0 Radiation Estimations for Input and Output Wires

One large part of radiated emissions comes from the input and output wires of the power supply. Two modes of current, which are differential and common mode, can cause emissions from cabling. Differential mode current results from the difference in current between two wires. Common mode current is current that travels along both wires in the same direction.

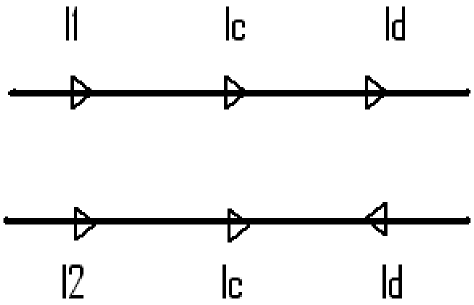


Figure 25: Currents along Two Wires

Figure 25 shows currents along two wires. I_c represents common mode current, while I_d represents the differential mode current. I_1 and I_2 are the individual currents in each wire. Since one wire with differential mode current has an opposing direction than the other, it will help cancel some of the emissions. However, it still plays a significant part in high frequency emissions on cables. Common mode current does not cancel out. In both cases, a filter can be introduced to attenuate these EMI generators by returning them back to the source. In order to understand how much attenuation is needed, there needs to be a way to determine the differential and common mode currents. They are related by the following equations (Paul, 2006)

$$I_d = 0.5*(I_1-I_2) \quad \textbf{eq (7)}$$

$$I_c = 0.5*(I_1+I_2) \quad \textbf{eq (8)}$$

By measuring the currents along each wire, the differential mode and common mode currents can be calculated. A current probe was connected to an oscilloscope. Using the Fast Fourier Transform setting of the oscilloscope, the currents measured by the probe was given according to frequency. In order to measure the differential and common mode current, I_1 and I_2 needed to be measured. To do this, the current probe simply needed to be aligned on the corresponding wire in the correction direction. The test setup is shown in Figure 26, and the results are shown for certain frequencies in Tables 8 through 10. The probe is not as reliable at frequencies above 100 MHz. However, it can give a relative measure.

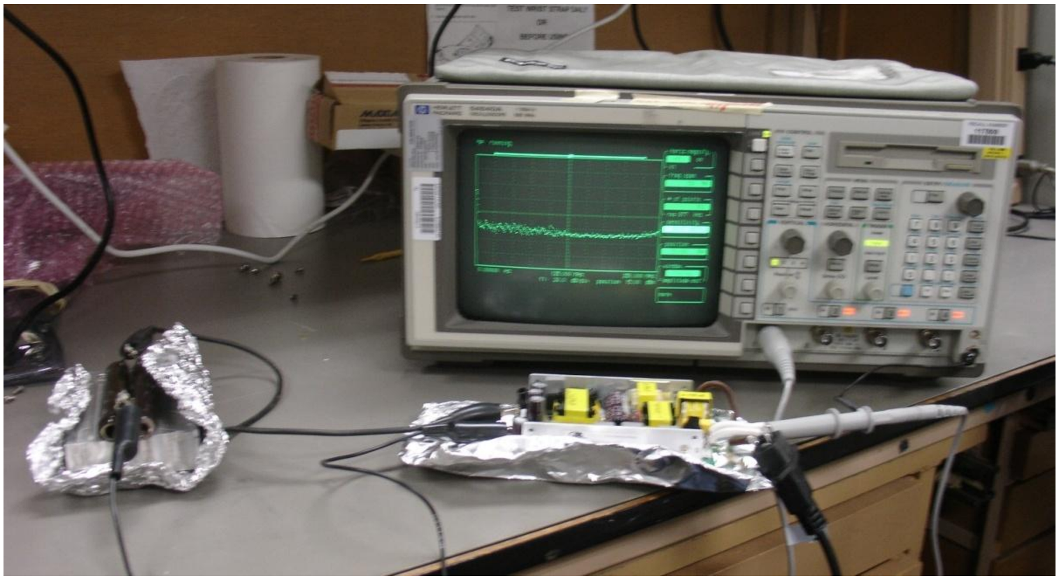


Figure 26: Current Measurement Test Setup

The next step is to determine the emission levels. The following equations give estimates emissions in the far field. This means that radiation is the predominant factor for emissions. In this case, emissions measurements are not in the far field. However, these equations can be helpful for obtaining information on what mode will be the predominant emissions factor, and how much so. To calculate the differential mode emissions (Paul, 2006):

$$\text{(differential mode) } E_{max} = (1.316 \text{ x } 10^{-14} |I_d| f^2 L s) / d \qquad \textbf{eq (9)}$$

where I_d is the differential mode current, f is frequency, L is line length, s is line separation, and d is distance from the wires. To calculate the common mode emissions (Paul, 2006):

$$\text{(common mode) } E_{max} = (1.257 \text{ x } 10^{-6} |I_c| f L) / d \qquad \textbf{eq (10)}$$

where I_c is the common mode current, f is frequency, L is line length, and d is distance from the wires.

Table 8: Current Measurements with 18 Watt Resistor

			18V Positive Side		18V Negative Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	5.000	3.283	-32.910	4.645	-33.570	4.305	4.475	5.740	-164.822	0.170	2602.584	-111.692
16.000	5.000	3.283	-33.550	4.315	-34.650	3.802	4.058	20.823	-153.629	0.257	7860.845	-102.091
21.000	5.000	3.283	-34.750	3.758	-34.320	3.949	3.853	34.061	-149.355	-0.095	3833.968	-108.327
29.000	5.000	3.283	-35.520	3.439	-35.700	3.369	3.404	57.379	-144.825	0.035	1958.144	-114.163
40.000	5.000	3.283	-35.770	3.342	-34.990	3.656	3.499	112.199	-139.000	-0.157	12021.728	-98.401
42.000	5.000	3.283	-35.330	3.515	-36.120	3.210	3.363	118.885	-138.497	0.153	12286.903	-98.211
63.000	5.000	3.283	-35.990	3.258	-36.090	3.221	3.239	257.703	-131.778	0.019	2249.103	-112.960
123.000	5.000	3.283	-36.210	3.177	-36.640	3.023	3.100	939.993	-120.538	0.077	18064.847	-94.863
127.000	5.000	3.283	-36.900	2.934	-37.080	2.874	2.904	938.776	-120.549	0.030	7315.607	-102.715

			AC Line Side		AC Nuetral Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	7.660	3.283	-31.060	5.747	-32.640	4.791	5.269	10.355	-159.697	0.478	11214.265	-99.005
16.000	7.660	3.283	-32.770	4.720	-34.330	3.944	4.332	34.055	-149.356	0.388	18207.624	-94.795
21.000	7.660	3.283	-34.120	4.041	-33.890	4.149	4.095	55.452	-145.122	-0.054	3339.143	-109.527
29.000	7.660	3.283	-34.000	4.097	-34.400	3.913	4.005	103.419	-139.708	0.092	7841.904	-102.112
40.000	7.660	3.283	-34.490	3.872	-35.970	3.266	3.569	175.341	-135.122	0.303	35585.419	-88.975
42.000	7.660	3.283	-36.000	3.254	-36.160	3.195	3.225	174.665	-135.156	0.030	3658.479	-108.734
63.000	7.660	3.283	-35.270	3.540	-35.770	3.342	3.441	419.325	-127.549	0.099	18293.451	-94.754
123.000	7.660	3.283	-35.410	3.483	-35.040	3.635	3.559	1653.289	-115.633	-0.076	27341.026	-91.264
127.000	7.660	3.283	-34.460	3.886	-35.420	3.479	3.682	1823.729	-114.781	0.203	75721.833	-82.416

Table 9: Current Measurements with 90 Watt Resistor

			18V Positive Side		18V Negative Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	5.000	3.283	-28.800	7.455	-28.710	7.533	7.494	9.613	-160.343	-0.039	594.635	-124.515
16.000	5.000	3.283	-31.690	5.345	-32.580	4.825	5.085	26.091	-151.670	0.260	7972.900	-101.968
21.000	5.000	3.283	-33.180	4.503	-33.550	4.315	4.409	38.969	-148.186	0.094	3774.594	-108.463
29.000	5.000	3.283	-35.260	3.544	-34.750	3.758	3.651	61.541	-144.217	-0.107	5949.041	-104.511
40.000	5.000	3.283	-35.380	3.495	-34.860	3.711	3.603	115.544	-138.745	-0.108	8256.473	-101.664
42.000	5.000	3.283	-35.450	3.467	-34.590	3.828	3.648	128.962	-137.791	-0.180	14507.464	-96.768
63.000	5.000	3.283	-34.950	3.673	-35.850	3.311	3.492	277.776	-131.126	0.181	21799.357	-93.231
123.000	5.000	3.283	-36.880	2.941	-37.790	2.648	2.795	847.397	-121.438	0.146	34439.868	-89.259
127.000	5.000	3.283	-35.970	3.266	-35.200	3.568	3.417	1104.626	-119.136	-0.151	36800.440	-88.683

			AC Line Side		AC Nuetral Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	7.660	3.283	-31.380	5.539	-31.030	5.767	5.653	11.110	-159.086	-0.114	2672.161	-111.463
16.000	7.660	3.283	-33.190	4.497	-33.820	4.183	4.340	34.117	-149.341	0.157	7382.966	-102.635
21.000	7.660	3.283	-33.660	4.261	-35.080	3.618	3.939	53.343	-145.458	0.321	19788.656	-94.072
29.000	7.660	3.283	-36.150	3.199	-34.600	3.824	3.511	90.670	-140.851	-0.312	26575.468	-91.510
40.000	7.660	3.283	-36.340	3.129	-34.950	3.673	3.401	167.089	-135.541	-0.272	31857.614	-89.936
42.000	7.660	3.283	-36.010	3.251	-36.060	3.232	3.241	175.566	-135.111	0.009	1149.198	-118.792
63.000	7.660	3.283	-35.450	3.467	-34.520	3.859	3.663	446.420	-127.005	-0.196	36199.791	-88.826
123.000	7.660	3.283	-34.640	3.806	-36.060	3.232	3.519	1634.743	-115.731	0.287	103538.561	-79.698
127.000	7.660	3.283	-36.730	2.992	-36.290	3.148	3.070	1520.326	-116.361	-0.078	28955.293	-90.765

Table 10: Current Measurements with Open Output

			AC Line Side		AC Nuetral Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	7.660	3.283	-31.710	5.333	-31.660	5.364	5.348	10.510	-159.568	-0.015	361.190	-128.845
16.000	7.660	3.283	-33.220	4.482	-34.580	3.832	4.157	32.678	-149.715	0.325	15241.495	-96.339
21.000	7.660	3.283	-34.680	3.789	-35.300	3.528	3.658	49.534	-146.102	0.130	8037.636	-101.897
29.000	7.660	3.283	-35.560	3.423	-35.540	3.431	3.427	88.509	-141.060	-0.004	335.624	-129.483
40.000	7.660	3.283	-34.250	3.981	-36.380	3.115	3.548	174.308	-135.174	0.433	50781.132	-85.886
42.000	7.660	3.283	-35.920	3.285	-35.700	3.369	3.327	180.187	-134.886	-0.042	5189.299	-105.698
63.000	7.660	3.283	-36.340	3.129	-36.080	3.225	3.177	387.186	-128.242	-0.048	8785.273	-101.125
123.000	7.660	3.283	-35.670	3.380	-36.390	3.112	3.246	1507.902	-116.433	0.134	48505.063	-86.284
127.000	7.660	3.283	-36.330	3.133	-35.080	3.618	3.376	1671.748	-115.537	-0.242	90315.767	-80.885

Table 11: Current Measurements with Patient Monitor

			18V Positive Side		18V Negative Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	5.000	3.283	-32.200	5.040	-30.790	5.929	5.485	7.035	-163.054	-0.444	6803.027	-103.346
16.000	5.000	3.283	-34.550	3.846	-33.120	4.534	4.190	21.498	-153.352	-0.344	10540.537	-99.543
21.000	5.000	3.283	-34.480	3.877	-34.710	3.775	3.826	33.819	-149.417	0.051	2036.461	-113.822
29.000	5.000	3.283	-35.440	3.471	-35.320	3.519	3.495	58.917	-144.595	-0.024	1340.445	-117.455
40.000	5.000	3.283	-35.880	3.300	-35.890	3.296	3.298	105.755	-139.514	0.002	145.371	-136.750
42.000	5.000	3.283	-37.000	2.900	-37.020	2.894	2.897	102.431	-139.791	0.003	268.192	-131.431
63.000	5.000	3.283	-36.570	3.048	-36.210	3.177	3.112	247.574	-132.126	-0.064	7777.509	-102.183
123.000	5.000	3.283	-34.440	3.895	-36.460	3.087	3.491	1058.452	-119.507	0.404	95148.316	-80.432
125.000	5.000	3.283	-28.130	8.053	-28.130	8.053	8.053	2522.036	-111.965	0.000	0.000	unkown
127.000	5.000	3.283	-34.840	3.719	-35.930	3.281	3.500	1131.470	-118.927	0.219	53325.081	-85.461

			AC Line Side		AC Nuetral Side		Differential Mode			Common Mode		
Frequency (MHz)	Line length (ft)	Distance (ft)	Current (dBm)	Current (mA)	Current (dBm)	Current (mA)	Current (mA)	Emissions (µV)	Emissions (dBm)	Current (mA)	Emissions (µV)	Emissions (dBm)
8.000	7.660	3.283	-29.910	6.561	-30.620	6.046	6.304	12.387	-158.140	0.257	6041.494	-104.377
16.000	7.660	3.283	-32.310	4.977	-33.190	4.497	4.737	37.238	-148.580	0.240	11251.580	-98.976
21.000	7.660	3.283	-34.040	4.078	-33.740	4.222	4.150	56.194	-145.006	-0.072	4413.542	-107.104
29.000	7.660	3.283	-35.000	3.651	-33.420	4.380	4.016	103.700	-139.684	-0.364	30979.815	-90.178
40.000	7.660	3.283	-36.340	3.129	-35.550	3.427	3.278	161.068	-135.860	-0.149	17478.812	-95.150
42.000	7.660	3.283	-35.540	3.431	-35.100	3.610	3.521	190.690	-134.393	-0.089	10981.800	-99.187
63.000	7.660	3.283	-35.830	3.319	-36.510	3.069	3.194	389.228	-128.196	0.125	23087.957	-92.732
123.000	7.660	3.283	-36.260	3.158	-36.170	3.191	3.175	1474.878	-116.625	-0.016	5933.688	-104.534
125.000	7.660	3.283	-27.270	8.891	-27.810	8.355	8.623	4137.327	-107.666	0.268	98242.374	-80.154
127.000	7.660	3.283	-36.600	3.037	-37.740	2.664	2.850	1411.666	-117.005	0.187	69573.744	-83.151

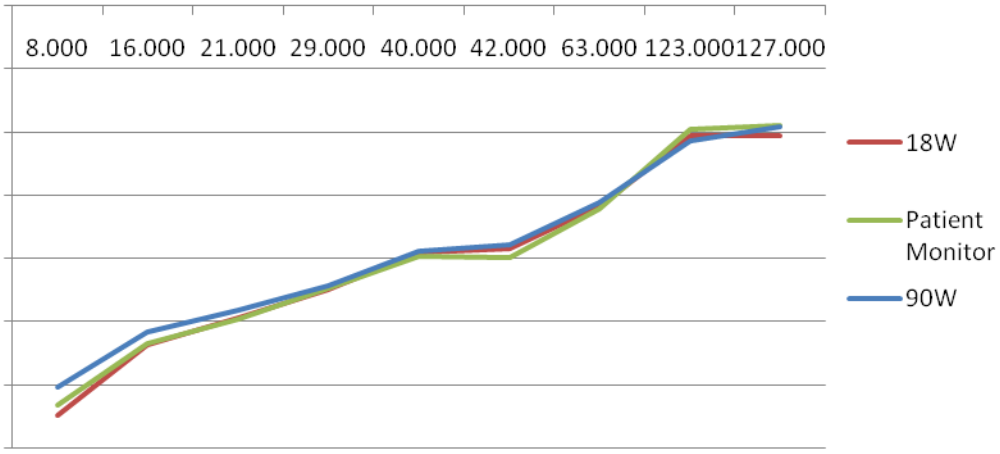


Figure 27: Differential Mode Emissions on 18V line (dBm vs. Frequency)

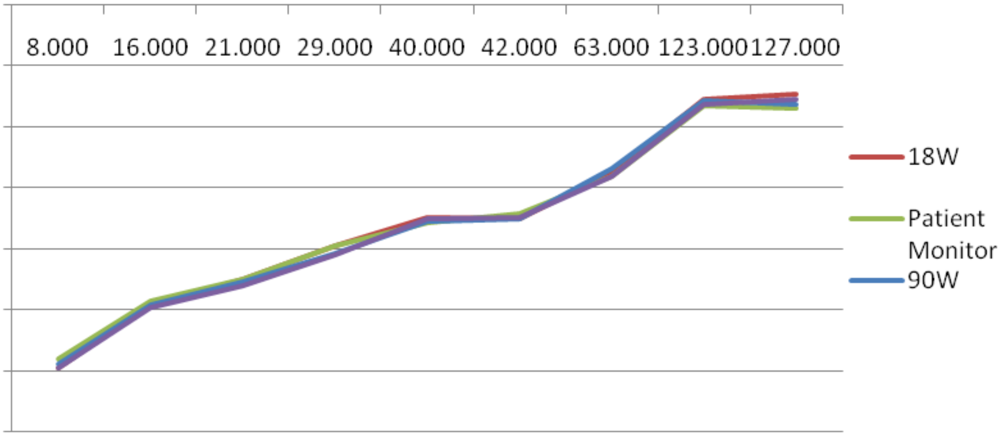


Figure 28: Differential Mode Emissions on AC line (dBm vs. Frequency)

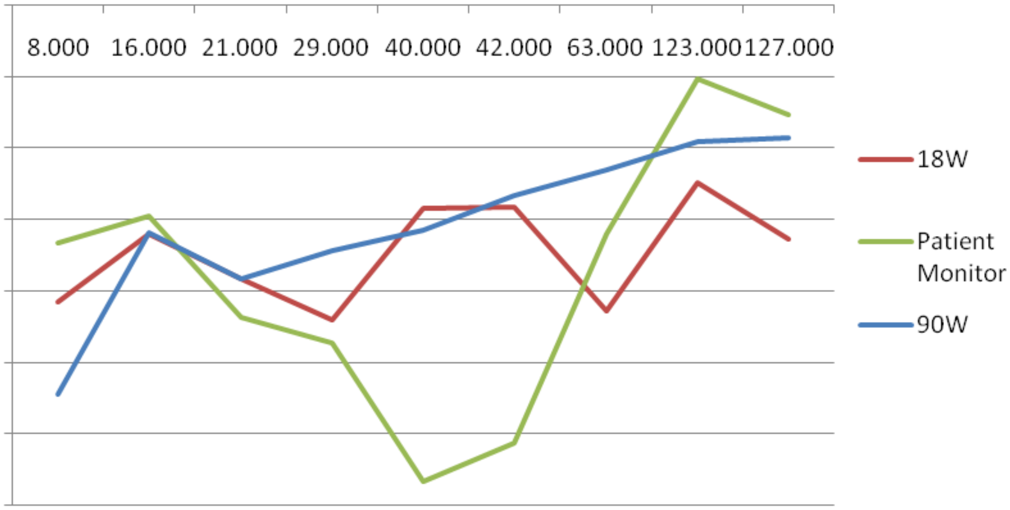


Figure 29: Common Mode Emissions on 18V line (dBm vs. Frequency)

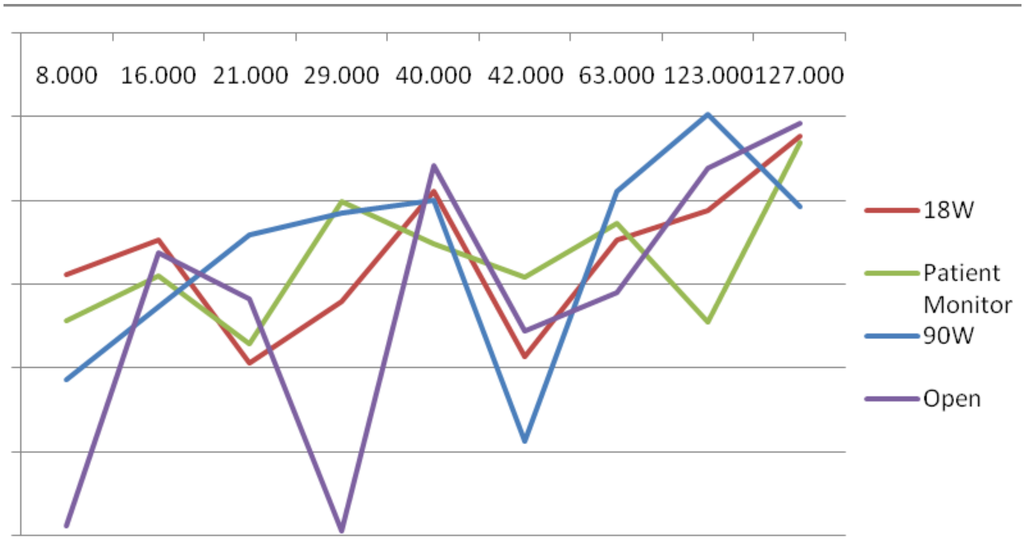


Figure 30: Common Mode Emissions on AC line (dBm vs. Frequency)

All frequencies shown in Figure 27 through 30 were in Megahertz. The results for differential mode emissions are reasonable given the baseline emissions tests. This is not the case for common mode emissions, as they are too high given the baseline emissions tests. These results do show, however, that common mode current will be the predominant emissions generator. According to the results, at least 60 dB of attenuation will be needed on the AC input, but that is uncertain given the overestimate of the results, which is a result of the assumption the radiation occurs in the far field. The extra attenuation can be used to ensure that the power supply will not interfere with the MRI. As restrictions on interference in the MRI environment increase, this will allow for the power supply to continue being used.

11.0 Filtering of Conducted Emissions

As stated in section 7.2 Attenuation Models, EMI from the power supply can be separated into conducted and radiated emissions. Conducted emissions relates to the emissions generated by cabling of the power supply. Two solutions to this problem are shielding the cabling or filtering.

In order to lessen emissions on the input and output cables, filters need to be designed. These filters will lower the high frequencies currents that lead to radiated emission. In filter design, it is important to look at the flow of current as opposed to voltages. The impedance of a capacitor is given by the equation $1/j\omega C$, where ω is the frequency and C is the capacitor value. The impedance of an inductor is given by the equation $j\omega L$, where ω is the frequency and L is the inductor value. With increasing frequency, the impedance of a capacitor decreases while the impedance of an inductor increases. Current will travel through the path with the least impedance. The objective of the low pass filter is to block high frequency currents from traveling through the filter, and instead divert them through the capacitors back to the source. When radiated emissions testing is conducted with the output line filter, it should show significant improvement.

Before finding values for the capacitors, inductors, or common mode chokes to be used, derated values are calculated for each component. Derating is a practice of ensuring component lifetime. Instead of operating components to their limits, there is a margin that ensures the components are not being stressed. Below is a table of derating factors, and what maximum ratings each component selected should have. All derating factors were used from the book Handbook of Reliability Engineering and Management.

Table 11: Filter Component Values and Derating

Component Aspect	Maximum Value from Supply	Derating Factor	Component Value
Capacitor Voltage	18 Volts	0.6	30 Volts
Capacitor Temperature	0 °C, 50 °C	40 °C to extremes	-40 °C, 90 °C
Inductor Voltage	18 Volts	0.7	26 Volts
Inductor Current	5 Amps	0.7	7.14 Amps

The next step is to determine the filter shape and component value. A three pole low pass filter was decided on. This would provide 60 dB/decade of attenuation (until parasitic effects arise). Two capacitor and one common mode choke would be used. The next step is to create a model for the filter circuit shown below.

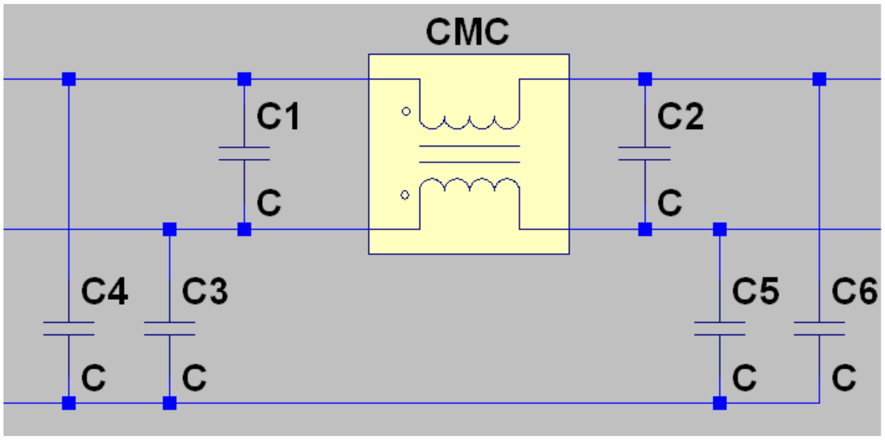


Figure 31: Filter Circuit

The next step is to create the equivalent circuits for both common mode and differential mode filtering. Figures 32 and 33 are these circuits. (Paul, 2006) C_{c1} and C_{c2} both represent capacitors connected from the line to ground. These capacitors will become short circuits at high frequencies, and will be help attenuate common mode current. C_{d1} and C_{d2} both represent capacitors connected from the line to line. Like C_{c1} and C_{c2}, they will act as short circuits across both lines, and will only attenuate differential mode current. L_{choke} is the representation of the choke's inductance for each mode. Ideally, the choke will block the common mode current, and pass all differential mode current. However, this is not actually the case. The inductance of the choke for the common mode is equal to the sum of the inductance of the separate windings and their mutual inductance. The inductance of the choke for the differential mode, which is called the leakage inductance, is equal to the inductance of the separate windings minus their mutual inductance.

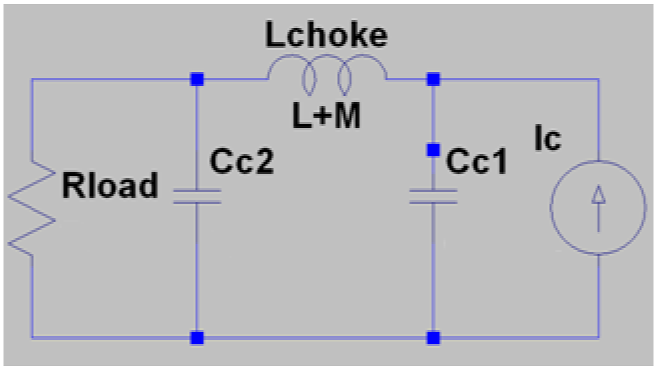


Figure 32: Circuit model for Common Mode Current

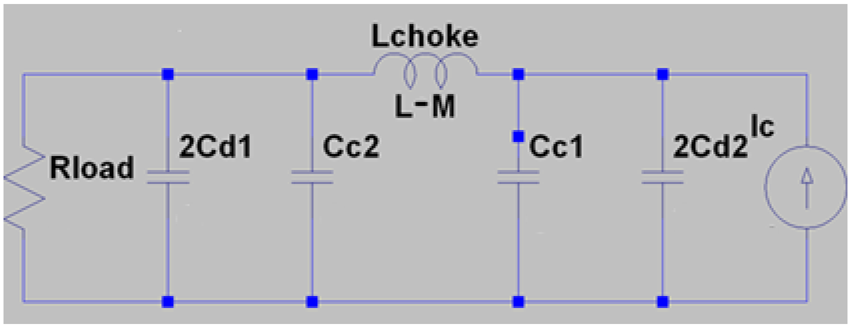


Figure 33: Circuit model for Differential Mode Current

The filter approach was looked at as simple Butterworth filter for the common mode current. From the results of the radiation estimations, it is assumed that this is the most important aspect. This was due to the fact that common mode currents are usually the largest contributors in radiated emissions. With the three components (two capacitors and the choke) of the common mode filter, there is a third order Butterworth filter. The next step is to obtain coefficients for this filter. Using RF Circuit Design Theory and Applications by Reinhold Ludwig and Gene Bogdanov, the coefficients are g1 = g3 = 1 and g2 = 2. The next step is to determine the amount of attenuation needed. Looking back the radiation estimates for each cable, at least 25 dB of attenuation is needed at 123 MHz on the 18V output. For 25 dB at 123 MHz, the cutoff frequency will be about 40 MHz. For the most part, the rest of the 18V output is under the limit of radiation emissions. To find component values for the inductors and capacitors, we use the following equations

$$L = g/(\omega_c R_g) \qquad \textbf{eq (11)}$$

$$C = (gR_g)/\omega_c \qquad \textbf{eq(12)}$$

where R_g, ω_c, and g are the output resistance, the cutoff frequency, and the coefficient. R_g was set equal to 10 Ω. Since the resistance of the output can change between 3.6 Ω and 18 Ω based on the load, a midpoint was chosen. With this information, the value of the capacitors was equal to approximately 40 nF and the value of the inductors was equal to approximately 0.8 nH. Looking at the AC side, there needs to be approximately 60 dB at 40 MHz. For 60 dB at 40MHz, the cutoff frequency will be about 3.6 MHz. Using the same steps as before, the value of the capacitors was equal to approximately 442 nF and the value of the inductors was equal to approximately 8.8 nH.

From the circuits in figure 32 and 33, the expected attenuation can be found. First, the circuit below is the starting point.

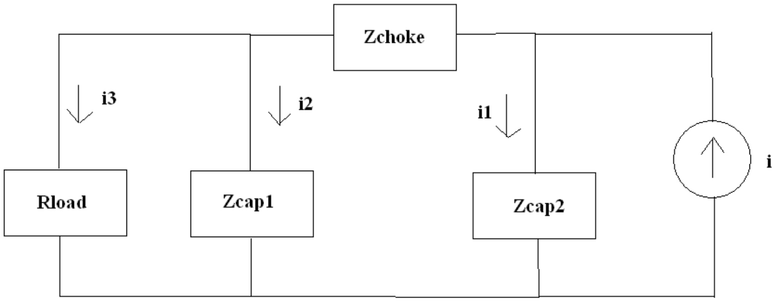


Figure 34: General Filter Circuit model

Now solve for the attenuation (i_3/i):

$i = i_1 + i_2 + i_3$

$R_{load}i_3 = i_2Z_{cap1} \quad => \quad i2 = (R_{load}/ Z_{cap1})i_3$

$i - i_1 = i_3(R_{load}/ Z_{cap1} +1)$

$i_1Z_{cap2} = Z_{choke}(i-i_1) + R_{load}i_3 = Z_{choke}\ i_3(R_{load}/ Z_{cap1} +1)+ R_{load}i_3$

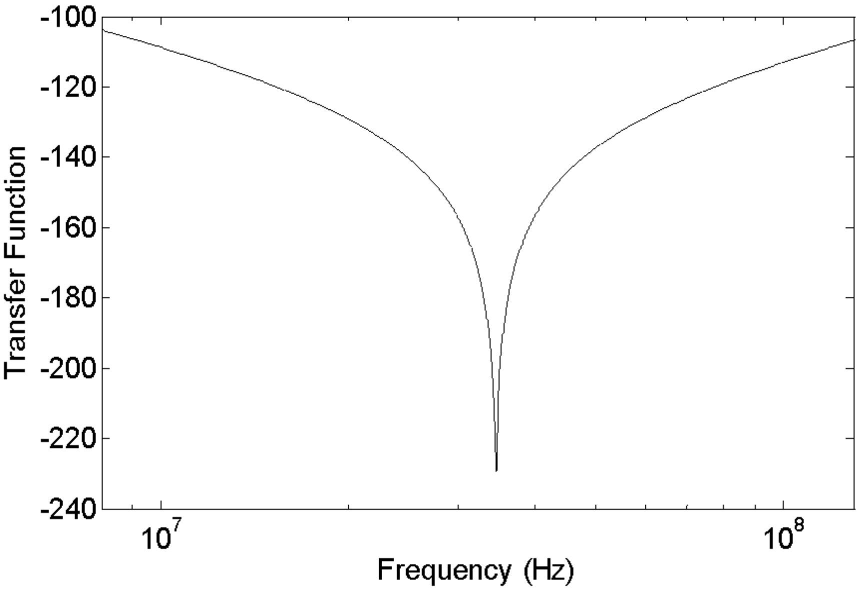
$i_1 = (i_3/Z_{cap2})\ [Z_{choke}\ (R_{load}/ Z_{cap1} +1)+ R_{load}]$

$i - i_2 - i_3 = i - i_3(R_{load}/ Z_{cap1} +1) = (i_3/Z_{cap2})\ [Z_{choke}\ (R_{load}/ Z_{cap1} +1)+ R_{load}]$

$i = i_3[(1/Z_{cap2})\ [Z_{choke}\ (R_{load}/ Z_{cap1} +1)+ R_{load}] + (R_{load}/ Z_{cap1} +1)]$ **eq (13)**

There are multiple issues with the values of the components found with the Butterworth coefficients. First, the common mode choke that needs to be used is an air core. The reason for this is that an air core inductor will lessen the chance of any failures in the magnetic field of the MRI. The minimum air core choke for the 18V side was 100 μH (Gowanda CMF4-1003H). The capacitor values will also need to be changed because of parasitic properties. For the 18V output, a 0.1 μF capacitor (AVX Corp 22255A104FAT2A) will become a short circuit around the 10 to 100 MHz range.

Using equation 13, a model both the common mode and differential mode attenuation can be found. This was simply the ratio of output to input current in dB. Figures 35 and 36 show this expected attenuation. You’ll see that in both graphs that the noise is attenuated well beyond the needs of current MRI technology. However, to extend the longevity of this product, additional attenuation will actually be desirable.



35: Differential Mode Attenuation on 18V Line

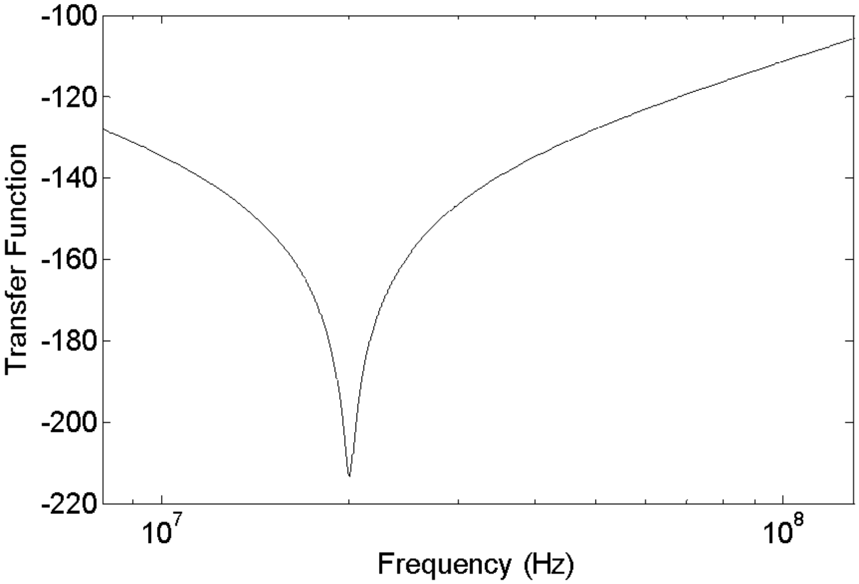


Figure 36: Common Mode Attenuation on 18V Line

Even though the 18 Volt output filter somewhat followed the Butterworth design, the AC input filter will not. The first reason is the inductor. Again, air core common mode chokes are preferable for the MRI environment. However, air core common mode chokes rated for the AC line were not found. So, a common mode choke was not included in the input filter. Another limitation of the input filter are in capacitor values. In order to follow regulations, the power supply cannot generate more than 500 μA of leakage current to the ground. Original datasheets of the SL MINT1110A showed the supply to generate less than 50 μA. An updated datasheet showed this to be less than 300 μA. With the maximum 130 μA generated by the IEC320 connector, that leaves less than 70 μA for filtering. In order to determine the maximum capacitance to ground, we use the following equation, which is simply derived from Ohm’s Law

$$V_{cap} * Z_{cap} = I_{cap}$$

$$V_{ac} * 1/(2\pi f_{ac} C) = I_{leakage} \qquad \textbf{eq (14)}$$

where V_{ac}, $f_{ac,}$ C, and $I_{leakage}$ are the AC voltage, AC frequency, capacitance to ground, and leakage current. Using maximum values of 250 VAC and 60 Hz, the maximum capacitance to ground for 70 μA is approximately 743 pF. Again trying to use the same format as the 18 V output, instead of the same capacitance value for both poles we have two values of 220 pF and 100 pF. Figure 37 and 38 show the expected attenuation for this input filter. It does not provide as much attenuation as needed according to the emission calculation in section 10, but those numbers are believed higher than the actual values. The only concern is the spike that is seen in both graphs. However, because of the limitation on capacitor values, this cannot be helped.

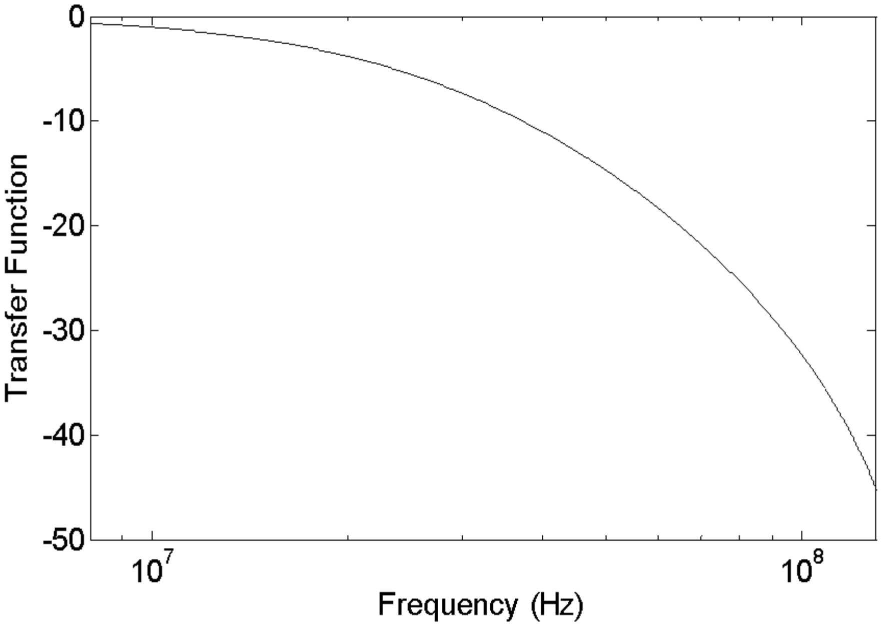


Figure 37: Differential Mode Attenuation on AC Line

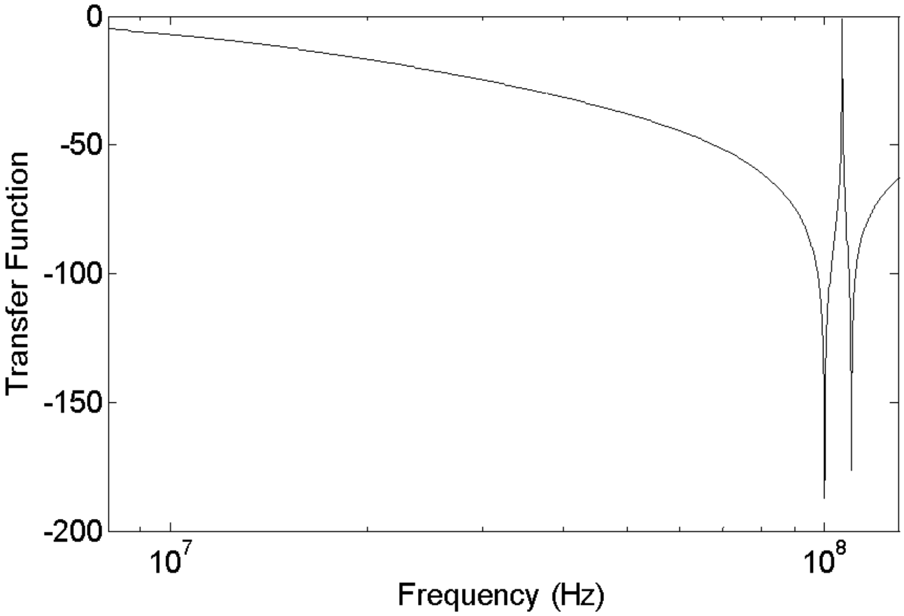


Figure 38: Common Mode Attenuation on AC Line

12.0 Conclusion

With the addition of filtering to the input connector and enclosure, one such prototype was made and tested. First, a scan in the RF chamber used in sections 8 and 9 was performed. The results of the test are shown in Figure 39. It can be seen that the prototype is indeed below the necessary emissions level. In fact, there is almost 5dB of margin from the absolute limit.

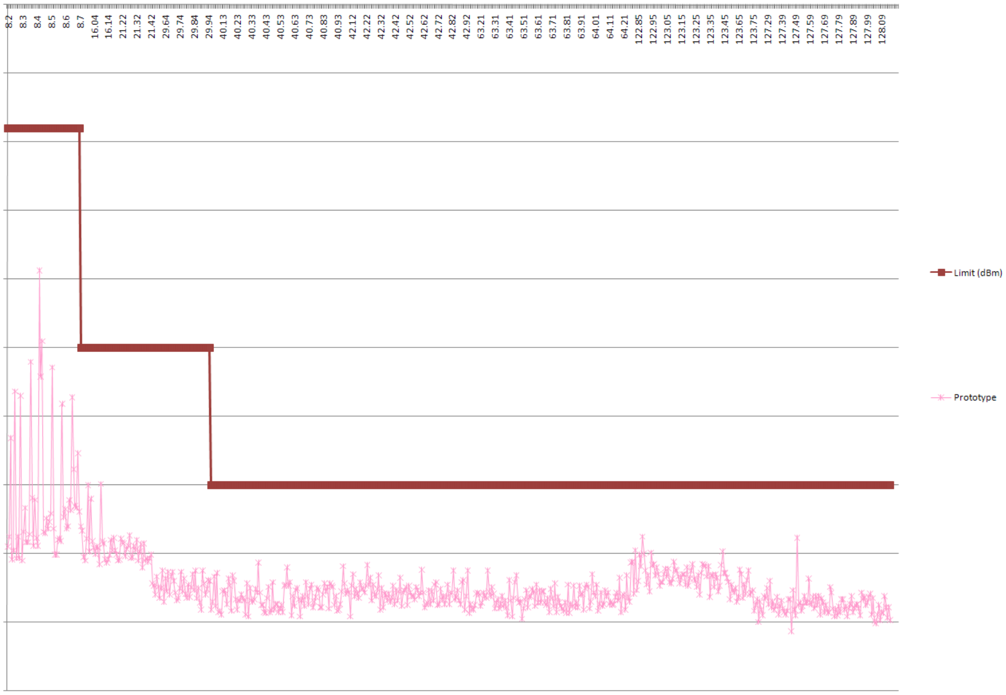


Figure 39: Emissions Test of Prototype

Next the prototype was tested in Gainesville, Florida at a Philips MRI facility. Both 1.5 Tesla and 3 Tesla MRIs were used for testing. These tests were performed with a 3160 patient monitor being powered by the Mr. Fusion prototype power supply. Two scans with 180 Hz and 35 Hz as resolution were used to ensure that the power supply would not cause interference with the MRI imaging. These scans were "service mode" scans, meaning that the MRI was acting as a very sensitive spectrum analyzer. Any noise received from the power supply would result in bright spots or lines on the MRI image. As seen from Figure 40, the MRI image did not contain either of these artifacts. The result was that the Mr. Fusion prototype did not cause sufficient noise to interfere with MRI imaging. A second set of scans were performed using a 3 Tesla MRI. Again, two scans with 180 Hz and 35 Hz were used. The Mr. Fusions prototype again did not cause sufficient noise to interfere with MRI imaging.

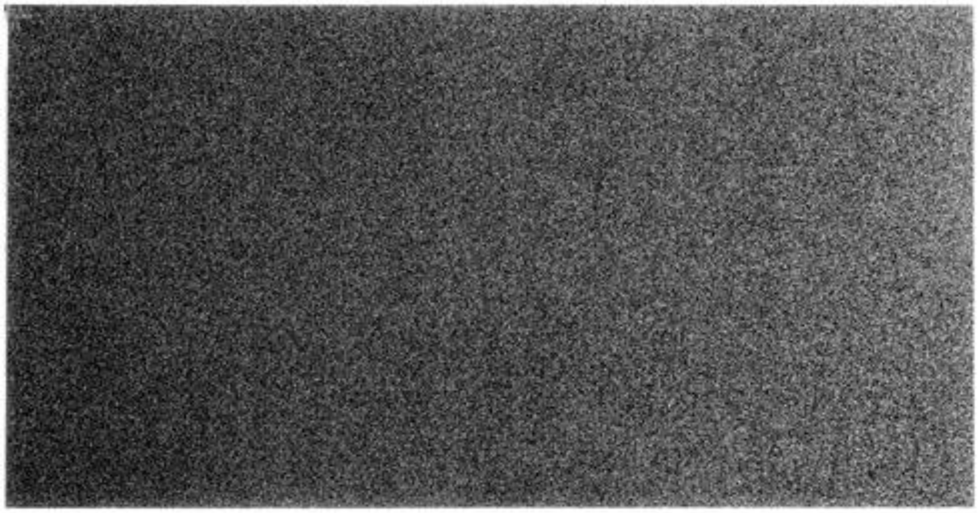


Figure 40: MRI Scan Result

These results are encouraging. However, due to a change in the SL MINT1110A's datasheet, the input filtering used more capacitance to ground. Because of the limited amount of time left, this was not completed before the end of D term. However, there will be a prototype made at some point, and the same testing will be repeated. Additional testing from section 5 will be performed to ensure that this product will be safe for consumers, and will be compliant with all regulations. With this complete, this project may result in a product that will be used for MRI patient monitoring.

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Appendix A

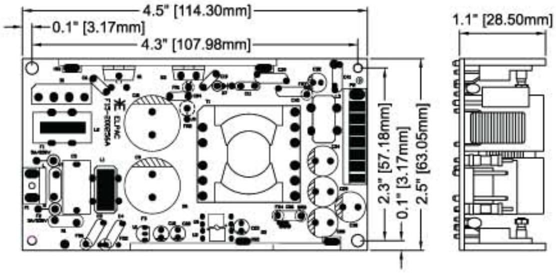
Elpac Power Systems™
A Subsidiary of International Components Corporation

Higher Efficiency, Higher Power Density, Uncompromised Reliability

MVA 100 Series

100 Watt Medical Grade Power Supply

- Wide Range AC Input
- Fully Regulated DC Output
- High Efficiency
- Output Floating
- Medical Grade Approval
- Dimensions Meet 1U Applications
- RoHS Compliant
- 5 Year Warranty



SPECIFICATIONS

INPUT

Voltage	100 - 240 VAC		
Current	3.0 Amp @ 100 VAC		
Frequency	50 - 60 Hz		
Max. Earth	Test Voltage	Normal	Single
Leakage current	132 VAC 60 Hz	80 uA	160 uA
	264 VAC 60 Hz	100 uA	200 uA

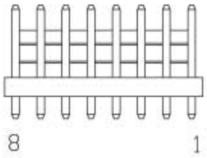
OUTPUT

Total regulation	< +/- 5%
Set point accuracy	< +/- 3% at 60% load
Hold up time	>20 ms min at full load, 115 VAC
Over voltage protection	Built-in
Over current protection	Built-in
Short circuit protection	Pulsing mode, auto recovery
Ripple/noise (Vp-p)	<1% (20 MHz bandwidth)

PINOUT	1	2	3	4	5	6	7	8
Input P1	AC Line	-	AC Neut	N/A	N/A	N/A	N/A	N/A
Output P2	V1	V1	V1	V1	COM	COM	COM	COM

Input and Output Connections

Input connector (P1) =
AMP p/n 640445-3 or equivalent
Output connector (P2) =
AMP p/n 640445-8 or equivalent



ENVIRONMENTAL

Operating temperature	0º C to 40º C
Storage temperature	-40º C to 85º C
Weight	0.50 lbs

SAFETY

cTUVus
UL 60601-1
CSA C22.2 No.60601.1-M90
CB per IEC 60601-1
CE marked to LVD

EMI/EMC

Emissions	CISPR11 and FCC Part 15, Class B
	EN61000-3-2, -3
Immunity	EN61000-4-2, -3, -4, -5, -6, -8, -11

Model No.	Voltage	Power	Current	Eff @ 115VAC (Typ)
MVA100012A	12V	100W	8.3A	90%
MVA100015A	15V	100W	6.7A	90%
MVA100018A	18V	100W	5.6A	91%
MVA100024A	24V	100W	4.2A	91%

Rev 0408

NFS110 Medical Series

Single and quad output

Total Power:	80 - 110 W
Input Voltage:	90 - 253 Vac 127 - 357 Vdc
# of Outputs:	Single, quad

Special Features

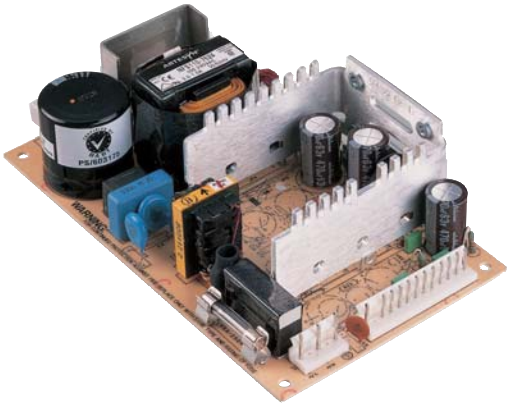
- 7.0 x 4.25 x 1.8 inch package
- Medical, dental and laboratory applications
- Overvoltage and short circuit protection
- 110 W with 20 CFM
- UL, VDE and CSA safety approvals
- EN60601-1 and UL2601 medical approvals
- Available RoHS compliant
- 2 year warranty

Safety

VDE0805/EN60601-1/
IEC601/IEC1010
File No. 10401-3336-1049
Licence No. 2874

UL2601 File No. E147937

CSA C22.2 No. 125
File No. LR41062C



RoHS
2002/95/EC

Electrical Specifications

Output		
Voltage adjustability	+5.1 V o/p on multi's	±3.0%
	5.1 V single output	±3.0%
	12 V single output	12-14 V
	15 V single output	15-18 V
	24 V single output	24-30 V
Line regulation	LL to HL, FL All outputs on all units	±0.1% max.
Overshoot/undershoot	At turn-on no lead	0%
Temperature coefficient	All outputs	±0.02%/°C
Overvoltage protection	Multi o/p 5.1 V only	6.25 V ±0.75 V
	5.1 V single	6.25 V ±0.75 V
	12 V single	15.75 V ±1.0 V
	15 V single	22 V ±1.5 V
	24 V single	33 V ±2.5 V
Output power limit	Primary power limited	Pin max. 160 W Pout min. 110 W
Short circuit protection		Burst mode operation
Input		
Input voltage range		90-253 Vac 127-357 Vdc
Input frequency range		47-440 Hz
Input surge current	110 Vac. 50 Hz	17 A
	230 Vac. 50 Hz	35 A
Safety ground leakage current	132 Vac	50 µA
	264 Vac	100 µA

All specifications are typical at nominal input, full load at 25°C unless otherwise stated

EMC Characteristics

Conducted emissions	EN55022, FCC part 15	Level A
Radiated emissions	EN55022, FCC part 15	Level A
ESD air	EN61000-4-2, level 3	Perf. criteria 1
ESD contact	EN61000-4-2, level 4	Perf. criteria 1
Surge	EN61000-4-3, level 3	Perf. criteria 1
Fast transients	EN61000-4-4, level 3	Perf. criteria 1
Radiated immunity	EN61000-4-5, level 3	Perf. criteria 2
Conducted immunity	EN61000-4-6, level 3	Perf. criteria 2

General Specifications

Hold-up time	110 Vac @ 80 W	35 ms
	110 Vac @ 110 W	17 ms
	230 Vac @ 80 W	140 ms
	230 Vac @ 110 W	100 ms
Efficiency	Multiple outputs	70% typical
	+5.1 V single	70% typical
	12 V and 15 V singles	72% typical
	24 V single	75% typical
Isolation voltage	Input/output	4000 Vac
	Input/chassis	1500 Vac
Approvals and standards (see note 12)		VDE0750, IEC60601, IEC1010, UL2601 CSA C22.2 No. 125
Weight	Singles	550 g (19.4 oz)
	Multiple outputs	600 g (21.2 oz)
MTBF (@25° C)	MIL-HDBK-217E	125,000 hours min.

Environmental Specifications

Thermal performance	Operating, see curve	0° C to +70 °C
(See notes 9, 10)	Non-operating	-40 °C to +85 °C
	0 °C to 50 °C amb. convection cooled	80 W
	+50 °C to +70 °C, amb. convection cooled	Derate 2 W/°C
	0 °C to +50 °C, 20 CFM forced air	110 W
	+50 °C to +70 °C, 20CFM forced air	Derate 2.75 W/°C
	Peak, 0 °C to +50 °C, max. 60 seconds	110W
Relative humidity	Non-condensing	5% to 95% RH
Altitude	Operating	10,000 feet max.
	Non-operating	40,000 feet max.
Vibration (See Note 11)	5-500 Hz	2.4 G rms peak

Ordering Information

Output Voltage	Output Currents			Ripple (4)	Total Regulation (5)	Model Numbers (13, 14, F)
	Max (1)	Peak (2)	Fan (3)			
+5.1 V	8 A	20 A	10 A	50 mV	±2.0%	NFS110-7901PJ
+12 V	4.5 A	9 A	5 A	120 mV	±3.0%	
–12 V	0.5 A	1.5 A	1 A	120 mV	±3.0%	
–5 V	0.5 A	1.5 A	1 A	50 mV	±3.0%	
+5.1 V (I_A)	8 A	20 A	10 A	50 mV	±2.0%	NFS110-7902PJ
+24 V (I_B) (6)	3.5 A	4.5 A	4.5 A	240 mV	+10/–5.0%	
+12 V	4.5 A	9 A	5 A	120 mV	±3.0%	
–12 V	0.5 A	1.5 A	1 A	120 mV	±3.0%	
+5.1 V	8 A	20 A	10 A	50 mV	±2.0%	NFS110-7904PJ
+15 V	4 A	7.5 A	5 A	150 mV	±4.0%	
–15 V	0.5 A	1.5 A	1 A	150 mV	±3.0%	
–5 V	0.5 A	1.5 A	1 A	50 mV	±3.0%	
12 V	7 A	9 A	9 A	120 mV	±2.0%	NFS110-7912J (7,8)
15 V	5 A	7.3 A	7.3 A	150 mV	±2.0%	NFS110-7915J (7,8)
24 V	3.5 A	4.5 A	4.5 A	240 mV	±2.0%	NFS110-7924J (7,8)

Notes

1. Convection cooled, 80 W maximum.
2. Peak outputs lasting less than 60 seconds with duty cycle less than 10%. Total peak power must not exceed 110 W.
3. Forced air, 20 CFM at 1 atmosphere, 110 W maximum.
4. Figure is peak-to-peak. Output ripple is measured across a 50 MHz bandwidth using a 12 inch twisted pair terminated with a 47 μF capacitor.
5. Total regulation is defined at the static output regulation at 25 °C, including initial tolerance, line voltage within stated limits and output voltages adjusted to their factory settings. Also for NFS110-7902PJ, for 24 V output stated regulation $I_A / I_B {}^2 5$. This output will maintain ±5.0% regulation if $I_A {}^2 5$ A, where I_A = +5.1 V output current and I_B = +24 V output current.
6. Single output models have floating outputs which may be referenced as either positive or negative. Higher voltage supplies, may be adjusted over a wide output voltage range, as long as the total output power does not exceed 80 Watts (natural convection) or 110 Watts (forced air).
7. Power fail detect not available on single output models.
8. Derating curve is application specific for ambient temperatures > 50 °C, for optimum reliability no part of the heatsink should exceed 90 °C and no semiconductor case temperature should exceed 100 °C.
9. Caution: Allow a minimum of 1 second after disconnecting the power when making thermal measurements.
10. The user should read the PSU installation instructions in conjunction with the relevant national safety regulations in order to ensure compliance.
11. Three orthogonal axes, random vibration, 10 minute test for each axis.
12. This product is only for inclusion by professional installers within other equipment and must not be operated as a stand alone product.
13. The 'J' suffix indicates that these parts are Pb-free (RoHS 6/6) compliant. TSE RoHS 5/6 (non Pb-free) compliant versions may be available on special request, please contact your local sales representative for details.
14. NOTICE: Some models do not support all options. Please contact your local Emerson Network Power representative or use the on-line model number search tool at http://www.powerconversion.com to find a suitable alternative.

TRANSIENT RESPONSE

NFS110-7901PJ	+5.1 V (7.5-10 A)	150 mV peak, 1 ms recovery
	+12 V (2.5-5 A)	100 mV peak, 0.5 ms recovery
	-12 V (0.5-1 A)	100 mV peak, 0.5 ms recovery
	-5 V (0.5-1 A)	100 mV peak, 0.5 ms recovery
NFS110-7902PJ	+5.1 V (7.5-10 A)	150 mV peak, 1 ms recovery
	+12 V (2.5-5 A)	100 mV peak, 0.5 ms recovery
	-12 V (0.5-1 A)	100 mV peak, 0.5 ms recovery
	24 V (1.5-3 A)	300 mV peak, 1 ms recovery
NFS110-7904PJ	+5.1 V (7.5-10 A)	150 mV peak, 1 ms recovery
	+15 V (2.5-5 A)	100 mV peak, 0.5 ms recovery
	-15 V (0.5-1 A)	100 mV peak, 0.5 ms recovery
	-5 V (0.5-1 A)	100 mV peak, 0.5 ms recovery
NFS110-7905J	+5.1 V (10-20 A)	250 mV peak, 1 ms recovery
NFS110-7912J	+12 V (4.5-9 A)	360 mV peak, 1 ms recovery
NFS110-7915J	+15 V (3.65-7.3 A)	450 mV peak, 1 ms recovery
NFS110-7924J	+24 V (2.25-4.5 A)	720 mV peak,

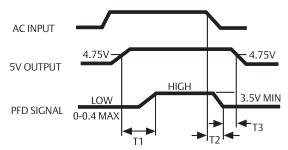
AC (J1) mating connector

Molex 09-50-3051 or Molex 09-91-0500 mating connector with 2478 or equivalent crimp terminals.

DC (J2) mating connector

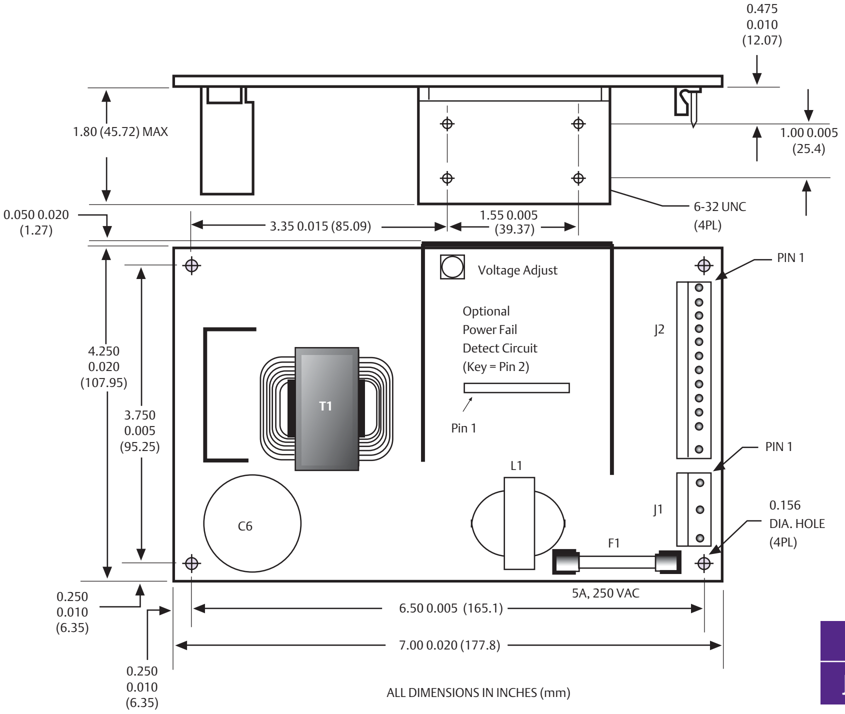
Molex 09-50-3131 or Molex 09-91-1300 mating connector with 2478 or equivalent crimp terminals.

OPTIONAL POWER FAIL DETECT TIMING DIAGRAM

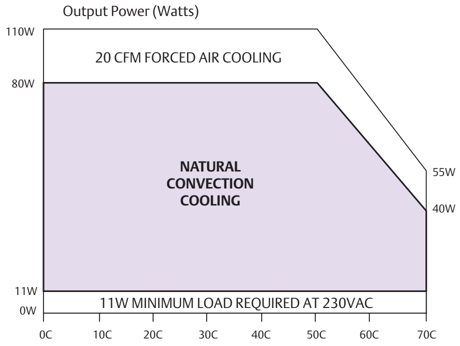


Power fail detect signal (Note 8)

50ms ≤ T1 ≤ 200ms
T2 will vary with line and load
T3 ≥ 3ms
Pout: 110W
PFD output is an open collector which will sink ≤ 40mA in the low state.



DERATING CURVE (See Notes 9, 10)



Mechanical Notes

- **A** Metallic or non-metallic stand-offs (maximum diameter 5.4mm) can be used in all four mounting holes without effecting safety approval.
- **B** The ground pad of the mounting hole near J1, allows system grounding through a metal stand-off to the system chassis.
- **C** The heat sink is grounded, and allows system grounding by mechanical connection to the system chassis.
- **D** The supply must be mechanically supported using the PCB mounting holes and may be additionally supported by the heatsink mounting holes.
- **E** It is always advisable to attach the power supply heat sink to another thermal dissipator (such as a chassis or finned heatsink etc). The resulting decrease in heat sink mounted component temperatures will improve power supply lifetime.
- **F** A standard L-bracket and cover is available for mounting which contains all screws, connectors and necessary mounting hardware. The kit is available, order part number “NFS110CJ”.

Pin Connections

J1	-7901PJ	-7902PJ	-7904PJ	SINGLES
Pin 1	AC Ground	AC Ground	AC Ground	AC Ground
Pin 2	AC Neutral	AC Neutral	AC Neutral	AC Neutral
Pin 3	AC Line	AC Line	AC Line	AC Line
J2				
Pin 1	+5.1 V	+5.1 V	+5.1 V	V_{out}
Pin 2	+5.1 V	+5.1 V	+5.1 V	V_{out}
Pin 3	+5.1 V	+5.1 V	+5.1 V	V_{out}
Pin 4	Return	Return	Return	Return
Pin 5	Return	Return	Return	Return
Pin 6	Return	Return	Return	Return
Pin 7	Return	Return	Return	Return
Pin 8	+12 V	+12 V	+15 V	V_{out}
Pin 9	+12 V	+12 V	+15 V	V_{out}
Pin 10	PFD	PFD	PFD	N/C
Pin 11	-12 V	-12 V	-15 V	N/C
Pin 12	Removed for Key			
Pin 13	-5 V	+24 V	-5 V	N/C

N/C = no connection.

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LPS170-M Series

Medical
175 Watts

Total Power:	**100 - 175 Watts**
Input Voltage:	**85-264 VAC** **120-300 VDC**
# of Outputs:	**Single**

Special Features

- Medical safety approvals
- Active power factor correction
- IEC EN61000-3-2 compliance
- Wide Range Adjustable output
  Remote sense on main output
- Single wire current sharing
- Power fail and remote inhibit
- Built-in EMI filter
- Low output ripple
- Overvoltage protection
- Overload protection
- Thermal overload protection
- DC power good
- 5 V standby output
- 12 V Aux output
- Optional cover (-C suffix)

Safety

VDE	0750/EN60601-1 (IEC601)
UL	UL2601
CSA	CSA 22.2 No. 601.1
CE	Mark (LVD)

Electrical Specifications

Input	
Input range	85-264 VAC; 120-300 VDC
Frequency	47-67 Hz
Inrush current	38 A max, cold start @ 25°C
Efficiency	75% typical at full load
EMI filter	FCC Class B conducted CISPR 22 Class B conducted EN55022 Class B conducted VDE 0878 PT3 Class B conducted
Power Factor	0.99 typical
Safety ground leakage current	<250 µA @ 50/60 Hz, 264 VAC inputS
Output	
Maximum power	110 W convection (75 W with cover) 175 W with 30 CFM forced air (130 W with cover)
Adjustment range	2:1 wide ratio minimum
Standby outputs	5 V @ 2 A regulated ±5%
Hold-up time	20 ms @175 W load at nominal line
Overload protection	Short circuit protection on all outputs. Case overload protected @ 110-145% above peak rating
Overvoltage protection	10% to 40% above nominal output
Aux output	12 V @ 1 A -5 %, +10%

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Logic Control

Power failure	TTL logic signal goes high 100 - 500 msec after V1 output; It goes low at least 4 msec before loss of regulation
Remote inhibit	Requires contact closure to inhibit outputs
Remote sense	Compensates for 0.5 V lead drop min. Will operate without remote sense connected. Reverse connection protected.
DC - OK	TTL logic signal goes high after main output is in regulation. It goes low when there is a loss of regulation

Environmental Specifications

Operating temperature:	0° to 50°C ambient; derate each output at 2.5% per degree from 50° to 70°C
Storage temperature:	-40°C to +85°C
Temperature coefficient:	±0.4% per °C
Storage temperature:	-40° to 85°C
Electromagnetic susceptibility:	Designed to meet IEC EN61000-4, -2, -3, -4, -5, -6, -8, -11 Level 3
Humidity:	Operating; non-condensing 5% to 95%
Vibration:	Three orthogonal axes, sweep at 1 oct/min, 5 min. dwell at four major resonances 0.75G peak 5Hz to 500Hz, operational
MTBF demonstrated:	>550,000 hours at full load and 25°C ambient conditions

Ordering Information

Model Number	Output Voltage	Minimum Load	Maximum Load with Convection Cooling	Maximum Load with 30CFM forced Air	Peak Load [1]	Regulation [2]	Ripple P/P (PARD)[3]
LPS172-M	5 V (2.5 - 6 V)	0 A	22 A	35 A	38 A	±2%	50 mV
LPS173-M	12 V (6 - 12 V)	0 A	9.1 A	15 A	16.5 A	±2%	120 mV
LPS174-M	15 V (12 - 24 V)	0A	7.3 A	12 A	13.2 A	±2%	<1%
LPS175-M	24 V (24 - 54 V)	0A	4.5 A	7.5 A	8.2 A	±2%	<1%

1. Peak current lasting <30 seconds with a maximum 10% duty cycle.
2. At 25°C including initial tolerance, line voltage, load currents and output voltages adjusted to factory settings.
3. Peak-to-peak with 20 MHz bandwidth and 10 µF in parallel with a 0.1 µF capacitor at rated line voltage and load ranges.
4. Remote inhibit resets OVP latch.

Note: -C suffix added to the model number indicates cover option.

Notes:
1. Specifications subject to change without notice.
2. All dimensions in inches (mm), tolerance is ±0.02”.
3. Specifications are for convection rating at factory settings unless otherwise stated.
4. Mounting screw maximum insertion depth is 0.12”.
5. Warranty: 2 year
6. Weight: 1.8 lb / 0.85 kg

Pin Assignments

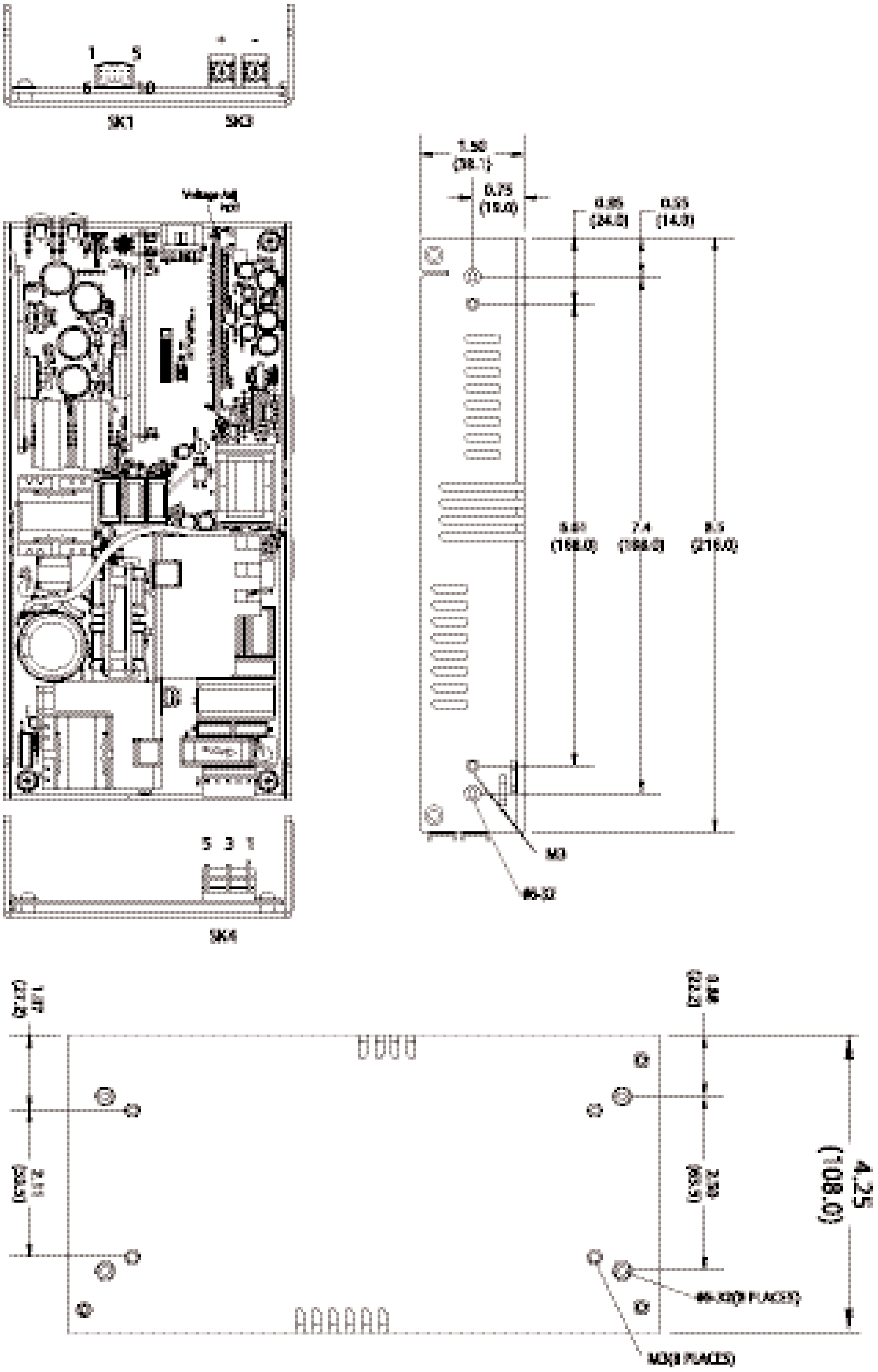
Connector	**LPS17x**	
SK1	PIN 1	+12 V
	PIN 2	5 V Standby
	Pin 3	Common
	Pin 4	V1 SWP
	PIN 5	Common
	PIN 6	+V1 sense
	PIN 7	Sense common
	PIN 8	Remote inhibit
	PIN 9	DC poer good
	PIN 10	POK
SK2	TB-1	COMMON
	TB-2	Main output
SK3	PIN 1	GROUND
	PIN 2	LINE
	Pin 5	NEUTRAL

Mating Connectors

(SK4) AC Input:	Molex 09-50-8051 (USA) Molex 09-91-0500 (UK) PINS: 08-58-0111
(SK3) DC Output:	Molex 19141-0058
(SK1) Control Signals:	Molex 90142-0010 (USA) PINS: 90119-2110 or Amp: 87977-3 PINS: 87309-8

Astec connector kit #70-841-016

Mechanical Drawing



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Engineering Specification – 110W, MINT1110A Medical Family

- **Typical 85% efficiency**
- **Less than 1.27" height**
- **EN60601-1 Medical approval**
- **Rugged, EMC compliant design**

Model	Output Voltage	Output Current 50°C	Output Current 60°C (1)	Total Regulation	Initial Set point Tolerance	OVP Limit	Ripple or Noise Pk-Pk(max)
MINT1110A1208K01	12V	7.5A	8,3A	2%	1%	15±1V	1%
MINT1110A1508K01	15V	6.5A	7.2A	2%	1%	18±1V	1%
MINT1110A1808K01	18V	5.8A	6.3A	2%	1%	23±1V	1%
MINT1110A2408K01	24V	4.6A	4.8A	2%	1%	28±1V	1%

OUTPUT SPECIFICATIONS

Total regulation (Line and load): +/- 2%

Turn-on time: < 2S

Hold up time: 16mS minimum from loss of AC input at full load, nominal line (120Vac/60 Hz)

Ripple & noise: p-p max

Transient response: 0.5 msec. for 50% load change typical

Input connector: 2 Pin LANDWIN P/N 3361P03E3TSN02

Output connector: 4 Pin LANDWIN P/N 3361P04E3T

Earth Ground connection to be via 0.187" faston tab P/N 3201T122R LANDWIN

INPUT SPECIFICATIONS

Input voltage: 100-240 VAC, +/-10%

Input frequency: 47-63Hz

Input current: 1.4A max. at 115 VAC input

Input surge current: 264Vac (Cold start)	30A max
Input fuse: UL/IEC127	T3.15A, 250Vac
Power factor:	IEC61000-3-2
Leakage current: 115Vac@60Hz	<50uA
Input configuration:	

GENERAL SPECIFICATIONS

Efficiency: up to 90% typically

Isolation voltage:	Input/output	4000Vac
	Input/Earth	1800Vac
	Output/Earth	500Vac

Safety approval: UL2601, CSA 22.2 No. 601.1-M90,
IEC 601-1 (1988), EN 60601-1(1999):

EMC SPECIFICATIONS

Conducted emissions:
FCC Part 18 Subpart B / EN55011 Class B

Radiated emissions:
FCC Part 18 Subpart B / EN55011 Class B

ESD air:	IEC 61000-4-2, 15kV
ESD contact:	IEC 61000-4-2, 8kV
Conducted immunity:	IEC61000-4-6, 3Vrms
Radiated immunity:	IEC 61000-4-3, 10V/m
Fast transients:	IEC 61000-4-4, 2kV/5kHz
Surge:	IEC 61000-4-5, 1kV Differential, 2kV Common
Power freq. Mag. Field:	IEC61000-4-8, 3A/m
Voltage dip immunity:	IEC61000-4-11 240Vac, 0%/0.5 cycle, 40%/5cycles, 70%/25 cycles

PROTECTION SPECIFICATIONS

Over current protection:	Hiccup mode
Short circuit protection:	Hiccup mode.
Over voltage protection:	Built-in, latch off
Over temperature protection:	Option

MECHANICAL SPECIFICATIONS

Dimensions: W 3.0"X L5.0"x H 1.2"

See Figure 1

Weight: TBD gm

ENVIROMENT SPECIFICATIONS

Operating temp.:		0-70°C
Storage temp.:		-40-+85°C
Relative humidity:		0%-95%
Altitude:	Operating:	-500 to 10,000 ft. MSL
	Non-Operating:	-500 to 40,000 ft .MSL

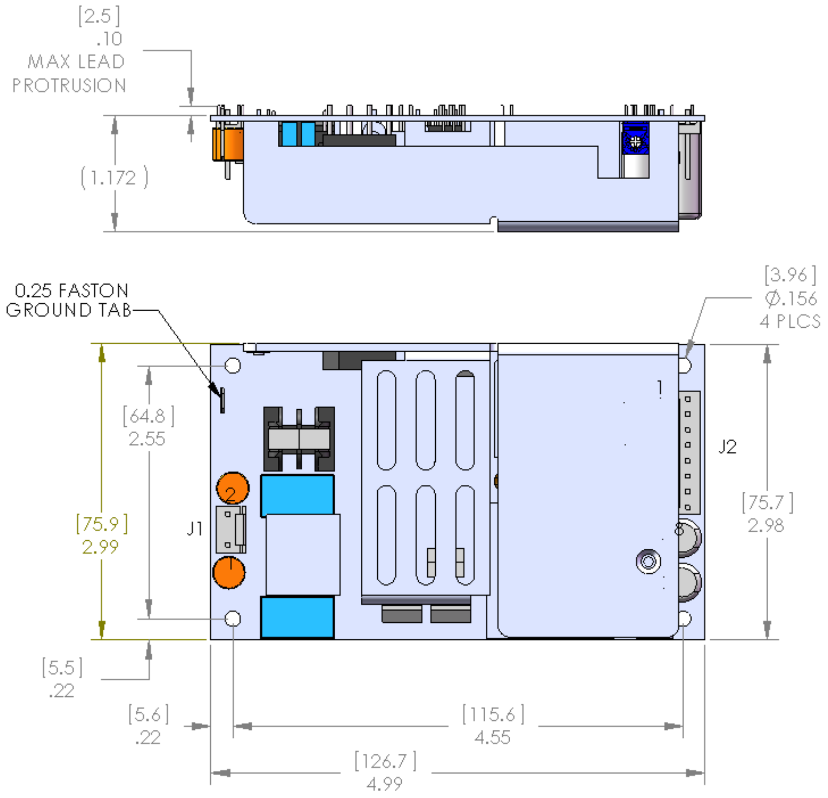


Fig. 1

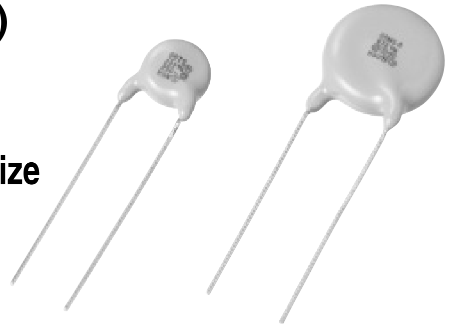
Input Connector – J1	
Pin 1	AC Line
Pin 2	AC Neutral

Output Connector – J2	
Pin	Single
1	+V1
2	+V1
3	+V1
4	+V1
5	RTN
6	RTN
7	RTN
8	RTN

J1 Mates with AMP MTA-156 3P connector (Middle Pin Removed)
J2 Mates with AMP MTA-156 8P Connector

Ceramic Disc Capacitors (Safety Regulations)

Type NS-A IEC60384-14 Sub-class Y1/X1, UL, CSA
Type TS IEC60384-14 Sub-class Y2/X1, UL, CSA
Type VS IEC60384-14 Sub-class Y2/X1, UL, CSA Smaller size



■ Features

- ● Related by IEC60384-14 2nd Ed. and approved by European Safety Regulations (Types NS-A, TS and VS)
- ● Reinforced Body Insulation /0.4mm min. approved by BSI, VDE (Type NS-A, Y1, Reinforced Insulation)
- ● Flame-retardant insulated coating
- ● Easy mounting through kinked leads and radial taping

■ Recommended Applications

- ● Interference suppressors for IT equipment (for eg. Modem)
- ● Interference suppressors for AC Primary Line of electronic equipment (Switching power supplies, Inverter type lighting apparatus etc.)
- ● Other electronic equipment for AC primary Line.

■ Explanation of Part Numbers

1	2	3	4	5	6	7	8	9	10	11	12
E	C	K	N	T	S	1	0	2	M	E	

Product Code

Code	Class
ECC	Class 1
ECK	Class 2

Lead Style

Code	Style
A	Kinked Lead Bulk
N	Kinked Lead Taped

Type Name

Code	Type
NA	Type NS-A
TS	Type TS
VS	Type VS

Nominal Capacitance

Ex.	Cap.
101	100 pF
102	1000 pF
222	2200 pF
472	4700 pF
103	10000 pF

Cap. Tolerance

Code	Cap. Tol.
J	±5 %
K	±10 %
M	±20 %
Z	+80, –20 %

Temp. Char

Code	Char.
G	SL/GP
B	B/Y5P
E	E/Y5U
F	F/Y5V

Suffix

■ Specifications

Characteristics	Type NS-A	Type TS	Type VS
Related Standards	IEC 60384-14(Y1/,X1) BSI, VDE, SEV, SEMKO FIMKO, NEMKO, DEMKO UL,CSA, KTL	IEC 60384-14(Y2/,X1) BSI, VDE, SEV, SEMKO FIMKO, NEMKO, DEMKO UL,CSA, KTL	IEC 60384-14(Y2/, X1) VDE, SEMKO, FIMKO NEMKO, DEMKO UL, KTL
Operating Temperature Range	–25 to 125 °C		
Rated Voltage	250 VAC/440 VAC		
Dielectric Withstanding Voltage	4000 VAC for 1 minute	2600 VAC for 1 minute	1500 VAC for 1 minute
Capacitance	Within the tolerance, when measured at 1 kHz ± 20 %, 1 Vrms, and 20 °C		
Q (Temp. Char. SL)	30 pF or under Q > 400+20C (C : Cap. pF) over 30 pF Q > 1000 at 1 MHz ±20 % 1 to 5 Vrms. and 20 °C		
Dissipation Factor (tanδ)	tan δ < 0.025, when measured at 1 kHz ±20 %, 1 Vrms, and 20 °C		
Insulation Resistance	10000 MΩ min at 500 VDC 1 minute electrification.		
Temperature Characteristics	see below		

Temperature Characteristics

Char.	max. Cap. Change	Temperature Range
SL/GP	+350 to –1000 ppm/°C	20 to 85 °C
B/Y5P	±10 %	–25 to 85 °C
E/Y5U	+20, –55 %	–25 to 85 °C
F/Y5V	+30, –80 %	–25 to 85 °C

■ Related Standards and Certificate Numbers

● Type NS-A

Certifying Body	Related Standard	Certificate Number	Sub-class	Rated Voltage	Dielectric Withstanding Voltage	Operating Temperature Range
BSI (UK)	EN 132 400:1994 Sub-class Y2 (IEC 60384-14 2nd Ed.)	226319	Y1, X1	Y1:250 VAC X1:440 VAC	Y1:4000 VAC X1:1892 VDC	–25 to 125 °C
VDE (Germany)		087472				
SEV (Switzerland)		05.0123				
SEMKO (Sweden)		9918234/01-02				
FIMKO (Finland)		F1 13556				
NEMKO (Norway)		P99101676				
DEMKO (Denmark)		DK99-02495				
KTL (Korea)	K60384-14 (IEC 60384-14 2nd Ed.)	SU03012-3002				
UL (USA)	UL1414	E62674	—	250 VAC	1500 VAC	–25 to 85 °C
CSA (Canada)	CSA C22.2 No.1	LR58064				

Note:Certification Number sometimes changes with the change of the approval contents and so on. CQC and KTL marks are indicated on the label.

● Type TS

Certifying Body	Related Standard	Certificate Number		Sub-class	Rated Voltage	Dielectric Withstanding Voltage	Operating Temperature Range
		Plant Code H	Plant Code M				
BSI (UK)	EN132 400:1994 Sub-class Y2 (IEC 60384-14 2nd Ed.)	228035		Y2, X1	Y2:250 VAC X1:440 VAC	Y2:1500 VAC X1:1892 VDC	–25 to 125 °C
VDE (Germany)		1220129	118911				
SEV (Switzerland)		05.0122					
SEMKO (Sweden)		9618031/01(Y2) 9909191/01(X1)	9909196/01-02				
FIMKO (Finland)		FI13324A1					
NEMKO (Norway)		P96102354(Y2) P99101084(X1)	P99101190				
DEMKO (Denmark)		305880(Y2) DK99-01676(X1)	DK99-01749				
KTL (Korea)	K60384-14(IEC 60384-14 2nd Ed.)	SU03012-3001	SU03013-3002				
UL (USA)	UL 1414	E62674		—	250 VAC	1500 VAC	–25 to 85 °C
CSA (Canada)	CSA C22.2 No.1	LR58064	LR31605				

Note:Certification Number sometimes changes with the change of the approval contents and so on. KTL marks are indicated on the label.

● Type VS

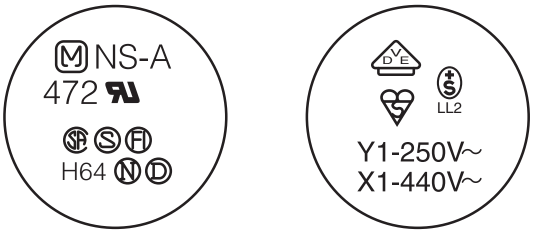
Certifying Body	Related Standard	Certificate Number	Sub-class	Rated Voltage	Dielectric Withstanding Voltage	Operating Temperature Range
VDE (Germany)	EN 132 400:1994 Sub-class Y2 (IEC 60384-14 2nd Ed.)	123139	Y2, X1	Y2:250 VAC X1:440 VAC	Y2:1500 VAC X1:1892 VDC	–25 to 125 °C
SEMKO (Sweden)		0042075/01-02				
FIMKO (Finland)		FI16196				
NEMKO (Norway)		P00102412				
DEMKO (Denmark)		310308-01				
KTL (Korea)	K60384-14 (IEC 60384-14 2nd Ed.)	SU03013-3003				
UL (USA)	UL1414* CSA C22.2 No.1*	E62674	—	–250 VAC	1500 VAC	–25 to 85 °C

Note:✻ is for Line-by-pass capacitors. Certification Number sometimes changes with the change of the approval contents and so on. KTL marks is indicated on the label. Certification contents are subject to differ in capacitance values.

■ Marking Examples (Ex. Type NS-A, 4700 pF)

Marking Items		
Manufacturer's Identification		Ⓜ
Type Designation		NS-A
sub-class and Rated Voltage		Y1-250V ~ X1-440V~
Capacitance		472
Recognized Marking (Logo or Monogram)	BSI	♡
	VDE	DVE
	SEV	S LL2
	SEMKO	Ⓢ
	FIMKO	FI
	NEMKO	Ⓝ
	DEMKO	Ⓓ
	UL	ЯU
	CSA	SP
Plant Code		H
Date Code (Ex. Apr. 2006)		64

Examples* (Marking of the face and the reverse)



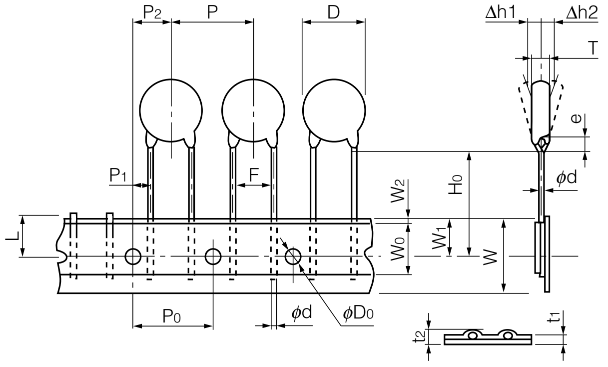
Note: ✻ The actual marking is sometimes different from the above example with the change of the safety approval contents and so on.

■ Dimensions in mm (not to scale)

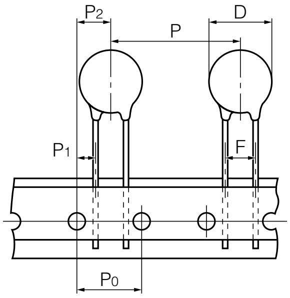
Standard lead styles are available in Kinked Lead and Kinked Lead Taping shown below.

- Kinked Lead Taping

Type N0, N1

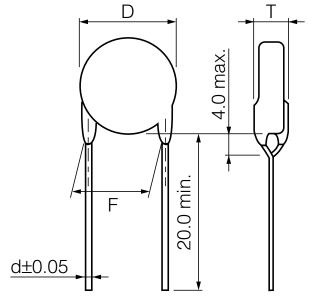


Type N2 *



* Same dimensions as Type N0, N1 except for special dimensions.

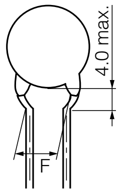
- Kinked Lead Type



Note:Tolerance of Lead Space

Dim. F(Nominal)	Tolerance of Dim. F
5.0	±1.0
7.5	±1.5
10.0	±1.5 ($^{+1.5}_{-1.0}$ for Type NS–A)

Under kinked lead style are applied to only 3300 pF and over have a lead space (F) 7.5 mm of Type TS



Unit (mm)

Taping Type Symbol	N0	N1	N2
P	12.7±1.0	15.0±2.0	30.0±2.0
P_0	12.7±0.3	15.0±0.3	15.0±0.3
F	5.0±0.8	7.5±1.0	7.5±1.0
P_1	3.85±0.70	3.75±0.80	3.75±0.80
P_2	6.35±1.30	7.5±1.5	7.5±1.5
D	To comply with each individual specification		
W	$18.0^{+1.0}_{-0.5}$		
W_0	10.0 min.		
W_1	9.0±0.5		
W_2	3.0 max.		
H_0	$18.0^{+2.0}_{-0}$		
e	4.0 max.		
ϕD_0	4.0±0.2		
ϕd	0.60±0.05	0.65±0.05	0.65±0.05
t_1	0.6±0.3		
t_2	1.5 max.		
T	To comply with each individual specification		
Δh_1, Δh_2	2.0 max.		
L	11.0 max.		

■ Minimum Quantity/Packing Unit

Type		Part Number		Minimum Packing Quantity	Packing Quantity in Carton	Carton L×W×H (mm)
Type NS-A	Kinked Lead Bulk	ECKANA□□□□□	100 to 2200 pF	200	3000	365×197×126
			3300, 4700 pF	200	2000	
Type TS	Kinked Lead Bulk	ECKATS□□□□□	100 to 2200 pF	200	3000	365×197×126
			3300, 4700 pF	200	2000	
			10000 pF	200	1000	
	Kinked Lead Taped Type	ECKNTS□□□□□	100 to 10000 pF	500	2500	358×232×305
Type VS	Kinked Lead Bulk	ECCAVS□□□□□	5 to 68 pF	200	4000	365×197×126
		ECKAVS□□□□□	100 to 3300 pF	200	4000	
		ECKAVS472MF	4700 pF	200	4000	
		ECKAVS472ME	4700 pF	200	3000	
		ECKAVS103MF	10000 pF	200	3000	
	Kinked Lead Taped Type	ECCNVS□□□□□	5 to 68 pF	1000	5000	358×232×305
		ECKNVS□□□□□	100 to 4700 pF	1000	5000	
		ECKNVS103MF	10000 pF	500	2500	

■ Ratings and Characteristics

● Type NS-A (IEC60384-14 Sub-class Y1, X1) Ratings and Characteristics

Cap. in pF	Capacitance Tolerance (%)	Temp. Char.	Dimensions in mm		Kinked Lead Type (Bulk)		
			D max.	T max.	Part Number	Dim. in mm	
						F	d
100	±10, ±20	B/Y5P	11.0	8.0	ECKANA101□B	10.0	0.65
150	±10, ±20	B/Y5P	11.0	8.0	ECKANA151□B	10.0	0.65
220	±10, ±20	B/Y5P	11.0	8.0	ECKANA221□B	10.0	0.65
330	±10, ±20	B/Y5P	11.0	8.0	ECKANA331□B	10.0	0.65
470	±10, ±20	B/Y5P	11.0	8.0	ECKANA471□B	10.0	0.65
680	±10, ±20	B/Y5P	11.0	8.0	ECKANA681□B	10.0	0.65
1000	±10, ±20	B/Y5P	11.0	8.0	ECKANA102□B	10.0	0.65
1000	±20	E/Y5U	10.0	8.0	ECKANA102ME	10.0	0.65
1500	±20	E/Y5U	11.0	8.0	ECKANA152ME	10.0	0.65
2200	±20	E/Y5U	11.0	8.0	ECKANA222ME	10.0	0.65
3300	±20	E/Y5U	13.0	8.0	ECKANA332ME	10.0	0.65
4700	±20	E/Y5U	16.0	8.0	ECKANA472ME	10.0	0.65

Remark
·Type NS-A is approved by BSI and VDE for Reinforced Body Insulation (0.4 mm min.)

CB certification No.

BSI (UK)	GB386W

Certification No.

VDE (Germay)	087469 087472

·Redial Taped version is available.
(Lead space is available only in 10 mm)

·□:Capacitance Tolerance Code
K:(±10 %) or M(±20 %)

● Type TS (IEC60384-14 Sub-class Y2, X1) Ratings and Characteristics

Cap. in pF	Capacitance Tolerance (%)	Temp. Char.	Dimensions in mm		Kinked Lead Type (Bulk)			Kinked Lead Taped Type			
			D max. (Tol.)	T max.	Part Number	Dim. in mm		Part Number	Taped Type	Dim. in mm	
						F	d			F	d
100	±10, ±20	B/Y5P	8.0(7.0±1.0)	7.0	ECKATS101□B	7.5	0.65	ECKNTS101□B	N1	7.5	0.65
150	±10, ±20	B/Y5P	8.0(7.0±1.0)	7.0	ECKATS151□B	7.5	0.65	ECKNTS151□B	N1	7.5	0.65
220	±10, ±20	B/Y5P	8.0(7.0±1.0)	7.0	ECKATS221□B	7.5	0.65	ECKNTS221□B	N1	7.5	0.65
330	±10, ±20	B/Y5P	8.0(7.0±1.0)	7.0	ECKATS331□B	7.5	0.65	ECKNTS331□B	N1	7.5	0.65
470	±10, ±20	B/Y5P	8.0(7.0±1.0)	7.0	ECKATS471□B	7.5	0.65	ECKNTS471□B	N1	7.5	0.65
680	±10, ±20	B/Y5P	9.0(8.0±1.0)	7.0	ECKATS681□B	7.5	0.65	ECKNTS681□B	N1	7.5	0.65
1000	±10, ±20	B/Y5P	10.5(9.5±1.0)	7.0	ECKATS102□B	7.5	0.65	ECKNTS102□B	N1	7.5	0.65
1000	±20	E/Y5U	8.0(7.0±1.0)	7.0	ECKATS102ME	7.5	0.65	ECKNTS102ME	N1	7.5	0.65
1500	±20	E/Y5U	9.0(8.0±1.0)	7.0	ECKATS152ME	7.5	0.65	ECKNTS152ME	N1	7.5	0.65
2200	±20	E/Y5U	9.5(9.0±1.0)	7.0	ECKATS222ME	7.5	0.65	ECKNTS222ME	N1	7.5	0.65
3300	±20	E/Y5U	12.5(11.5±1.0)	7.0	ECKATS332ME	7.5	0.65	ECKNTS332ME	N1	7.5	0.65
4700	±20	E/Y5U	15.0(14.0±1.0)	7.0	ECKATS472ME	10.0	0.65	ECKNTS472ME	N2	7.5	0.65
4700	±20	F/Y5V	12.5(11.5±1.0)	7.0	ECKATS472MF	7.5	0.65	ECKNTS472MF	N1	7.5	0.65
10000	±20	F/Y5V	17.0(16.0±1.5)	7.0	ECKATS103MF	10.0	0.65	ECKNTS103MF	N2	7.5	0.65

Note : □-- Capacitance Tolerance Code K (±10 %) or M (±20 %)

● Type VS (IEC60384-14 Sub-class Y2, X1 Smaller type) Ratings and Characteristics

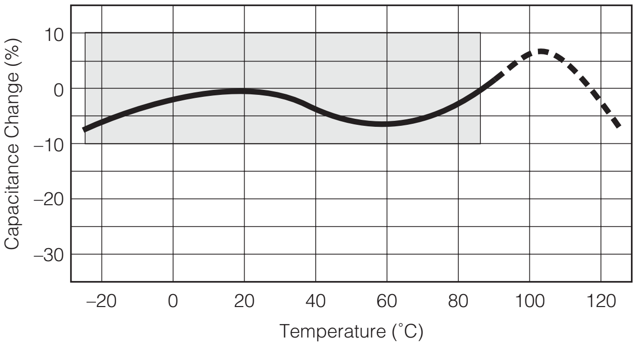
Cap. in pF	Capacitance Tolerance (%)	Temp. Char.	Dimensions in mm		Kinked Lead Type (Bulk)			Kinked Lead Taped Type			
			D max.	T max.	Part Number	Dim. in mm		Part Number	Taped Type	Dim. in mm	
						F	d			F	d
10	±0.5pF, ±1pF	SL/GP	8.0	6.0	ECCAVS100□G*	5.0	0.60	ECCNVS100□G*	N0	5.0	0.60
15	±5, ±10	SL/GP	8.0	6.0	ECCAVS150□G*	5.0	0.60	ECCNVS150□G*	N0	5.0	0.60
22	±5, ±10	SL/GP	8.0	6.0	ECCAVS220□G*	5.0	0.60	ECCNVS220□G*	N0	5.0	0.60
33	±5, ±10	SL/GP	8.0	6.0	ECCAVS330□G	5.0	0.60	ECCNVS330□G	N0	5.0	0.60
47	±5, ±10	SL/GP	8.0	6.0	ECCAVS470□G	5.0	0.60	ECCNVS470□G	N0	5.0	0.60
68	±5, ±10	SL/GP	8.0	6.0	ECCAVS680□G	5.0	0.60	ECCNVS680□G	N0	5.0	0.60
100	±10, ±20	B/Y5P	8.0	6.0	ECKAVS101□B	5.0	0.60	ECKNVS101□B	N0	5.0	0.60
150	±10, ±20	B/Y5P	8.0	6.0	ECKAVS151□B	5.0	0.60	ECKNVS151□B	N0	5.0	0.60
220	±10, ±20	B/Y5P	8.0	6.0	ECKAVS221□B	5.0	0.60	ECKNVS221□B	N0	5.0	0.60
330	±10, ±20	B/Y5P	8.0	6.0	ECKAVS331□B	5.0	0.60	ECKNVS331□B	N0	5.0	0.60
470	±10, ±20	B/Y5P	8.0	6.0	ECKAVS471□B	5.0	0.60	ECKNVS471□B	N0	5.0	0.60
680	±10, ±20	B/Y5P	8.0	6.0	ECKAVS681□B	5.0	0.60	ECKNVS681□B	N0	5.0	0.60
1000	±20	E/Y5U	8.0	6.0	ECKAVS102ME	5.0	0.60	ECKNVS102ME	N0	5.0	0.60
1500	±20	E/Y5U	8.0	6.0	ECKAVS152ME	5.0	0.60	ECKNVS152ME	N0	5.0	0.60
2200	±20	E/Y5U	9.0	6.0	ECKAVS222ME	5.0	0.60	ECKNVS222ME	N0	5.0	0.60
3300	±20	E/Y5U	10.0	6.0	ECKAVS332ME	5.0	0.60	ECKNVS332ME	N0	5.0	0.60
4700	±20	E/Y5U	11.0	6.0	ECKAVS472ME	5.0	0.60	ECKNVS472ME	N0	5.0	0.60
4700	±20	F/Y5V	10.0	6.0	ECKAVS472MF	5.0	0.60	ECKNVS472MF	N0	5.0	0.60
10000	±20	F/Y5V	14.0	6.0	ECKAVS103MF	7.5	0.65	ECKNVS103MF	N1	7.5	0.65

Note 1 : □--Capacitance Tolerance Code D (±0.5 pF) or F (±1 pF) or J (±5 %) or K(±10 %) or M(±20 %)
2 : ✻ --except for VDE and KTL.

■ Typical Temperature Characteristics (Type TS, and Type NS-A)

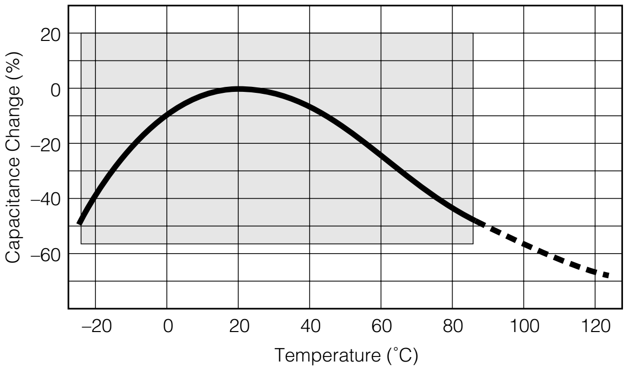
Char. B/Y5P

(Temp. Range : –25 to 85 °
max.Cap.Change : +10 %)



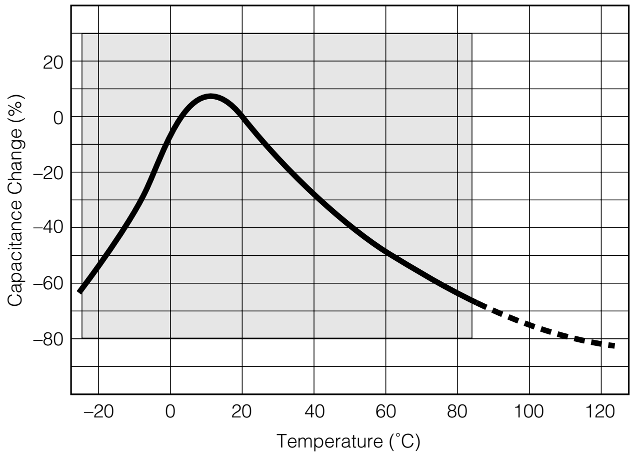
Char. E/Y5U

(Temp. Range : –25 to 85 °
max.Cap.Change : +20, –55 %)



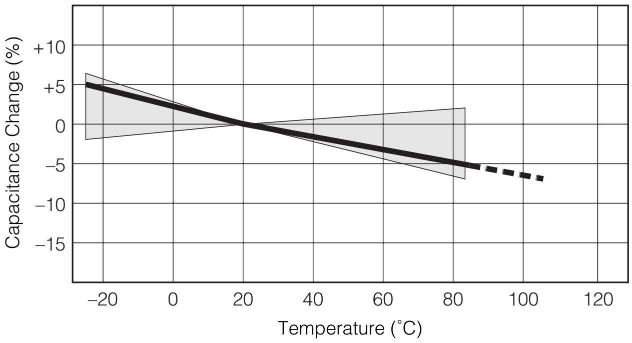
Char. F/Y5V

(Temp. Range : –25 to 85 °
max.Cap.Change : +30, –80 %)



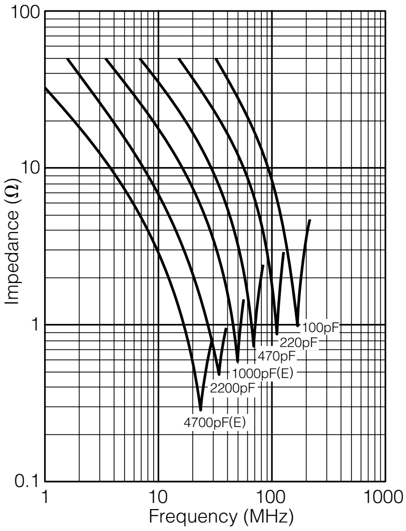
Char. SL/GP

(Temp. Coeff. : +350 to –1000 ppm/°C)

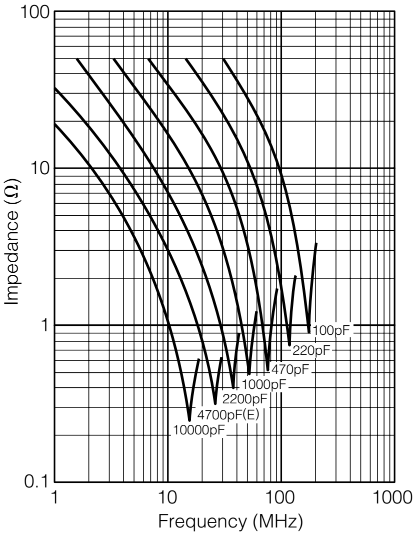


■ Impedance vs. Frequency Characteristics

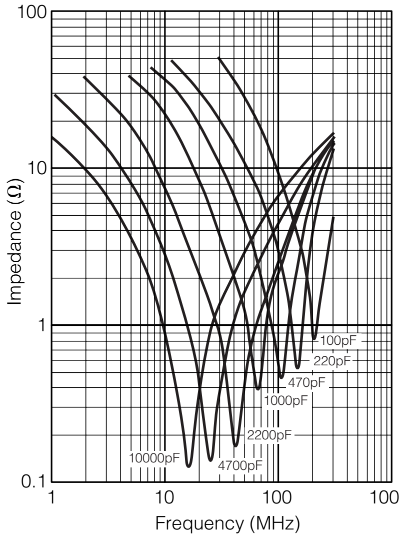
Type NS-A



Type TS



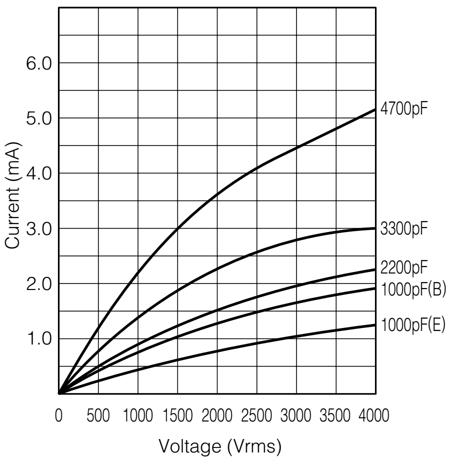
Type VS

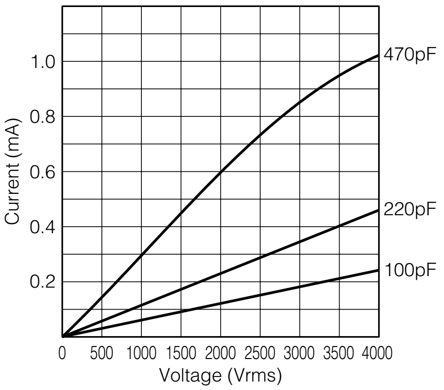


■ Current vs. Voltage (Leakage Current Characteristics)

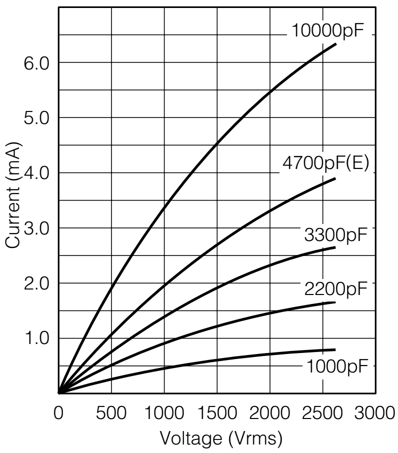
Conditions Temperature: 20 °C, Applied Voltage: Sine Wave 60 Hz

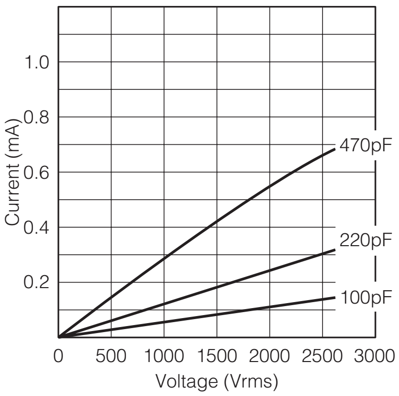
Type NS-A



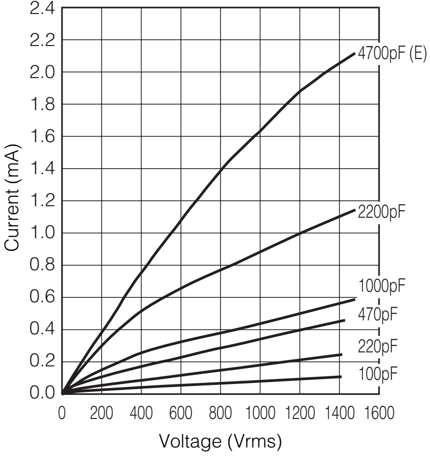


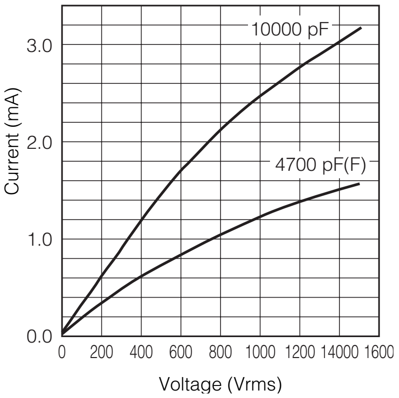
Type TS





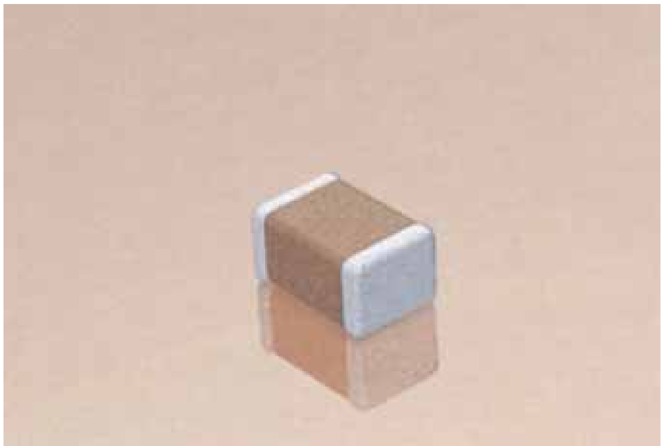
Type VS





X7R Dielectric

General Specifications



X7R formulations are called “temperature stable” ceramics and fall into EIA Class II materials. X7R is the most popular of these intermediate dielectric constant materials. Its temperature variation of capacitance is within ±15% from -55°C to +125°C. This capacitance change is non-linear.

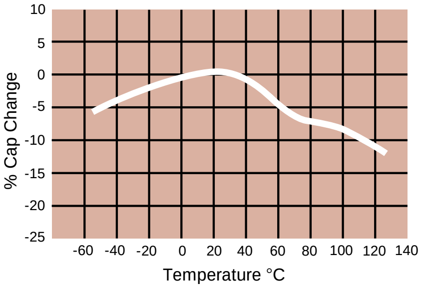
Capacitance for X7R varies under the influence of electrical operating conditions such as voltage and frequency.

X7R dielectric chip usage covers the broad spectrum of industrial applications where known changes in capacitance due to applied voltages are acceptable.

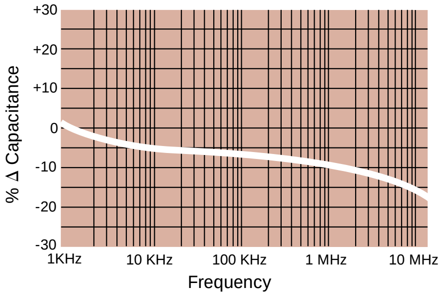
PART NUMBER (see page 2 for complete part number explanation)

0805	5	C	103	M	A	T	2	A
Size (L" x W")	**Voltage** 4V = 4 6.3V = 6 10V = Z 16V = Y 25V = 3 50V = 5 100V = 1 200V = 2 500V = 7	**Dielectric** X7R = C	**Capacitance Code (In pF)** 2 Sig. Digits + Number of Zeros	**Capacitance Tolerance** J = ± 5% K = ±10% M = ± 20%	**Failure Rate** A = Not Applicable	**Terminations** T = Plated Ni and Sn 7 = Gold Plated	**Packaging** 2 = 7" Reel 4 = 13" Reel 7 = Bulk Cass. 9 = Bulk **Contact Factory For Multiples**	**Special Code** A = Std. Product

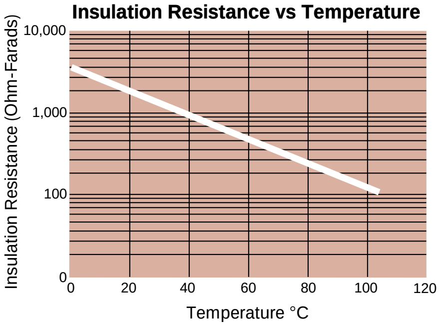
X7R Dielectric
Typical Temperature Coefficient



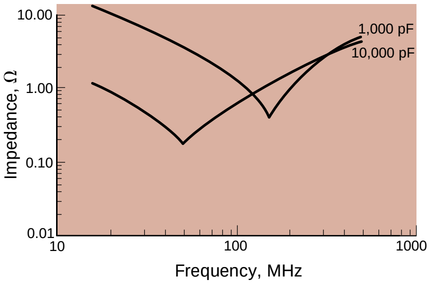
Δ Capacitance vs. Frequency



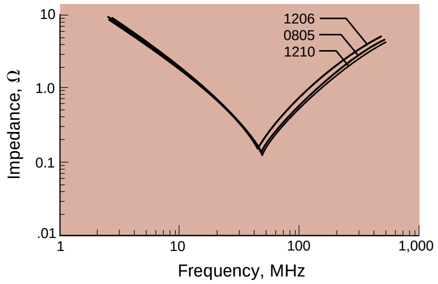
Insulation Resistance vs Temperature



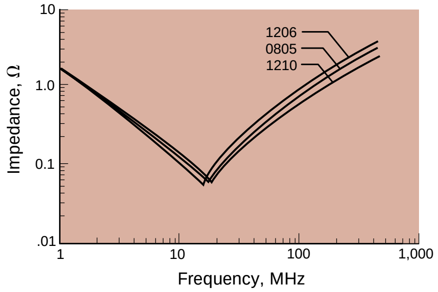
Variation of Impedance with Cap Value
Impedance vs. Frequency
1,000 pF vs. 10,000 pF - X7R
0805



Variation of Impedance with Chip Size
Impedance vs. Frequency
10,000 pF - X7R

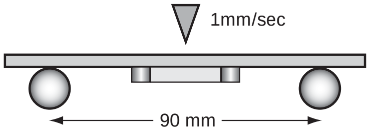


Variation of Impedance with Chip Size
Impedance vs. Frequency
100,000 pF - X7R



X7R Dielectric

Specifications and Test Methods

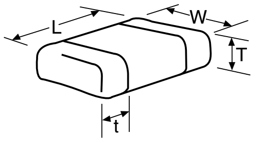
Parameter/Test		X7R Specification Limits	Measuring Conditions	
Operating Temperature Range		-55ºC to +125ºC	Temperature Cycle Chamber	
Capacitance		Within specified tolerance	Freq.: 1.0 kHz ± 10% Voltage: 1.0Vrms ± .2V For Cap > 10 µF, 0.5Vrms @ 120Hz	
Dissipation Factor		≤ 2.5% for ≥ 50V DC rating ≤ 3.0% for 25V DC rating ≤ 3.5% for 16V DC rating ≤ 5.0% for ≤ 10V DC rating		
Insulation Resistance		100,000MΩ or 1000MΩ - µF, whichever is less	Charge device with rated voltage for 120 ± 5 secs @ room temp/humidity	
Dielectric Strength		No breakdown or visual defects	Charge device with 300% of rated voltage for 1-5 seconds, w/charge and discharge current limited to 50 mA (max) Note: Charge device with 150% of rated voltage for 500V devices.	
Resistance to Flexure Stresses	Appearance	No defects	Deflection: 2mm Test Time: 30 seconds  	
	Capacitance Variation	≤ ±12%		
	Dissipation Factor	Meets Initial Values (As Above)		
	Insulation Resistance	≥ Initial Value x 0.3		
Solderability		≥ 95% of each terminal should be covered with fresh solder	Dip device in eutectic solder at 230 ± 5ºC for 5.0 ± 0.5 seconds	
Resistance to Solder Heat	Appearance	No defects, <25% leaching of either end terminal	Dip device in eutectic solder at 260ºC for 60 seconds. Store at room temperature for 24 ± 2 hours before measuring electrical properties.	
	Capacitance Variation	≤ ±7.5%		
	Dissipation Factor	Meets Initial Values (As Above)		
	Insulation Resistance	Meets Initial Values (As Above)		
	Dielectric Strength	Meets Initial Values (As Above)		
Thermal Shock	Appearance	No visual defects	Step 1: -55ºC ± 2º	30 ± 3 minutes
	Capacitance Variation	≤ ±7.5%	Step 2: Room Temp	≤ 3 minutes
	Dissipation Factor	Meets Initial Values (As Above)	Step 3: +125ºC ± 2º	30 ± 3 minutes
	Insulation Resistance	Meets Initial Values (As Above)	Step 4: Room Temp	≤ 3 minutes
	Dielectric Strength	Meets Initial Values (As Above)	Repeat for 5 cycles and measure after 24 ± 2 hours at room temperature	
Load Life	Appearance	No visual defects	Charge device with twice rated voltage in test chamber set at 125ºC ± 2ºC for 1000 hours (+48, -0) Remove from test chamber and stabilize at room temperature for 24 ± 2 hours before measuring.	
	Capacitance Variation	≤ ±12.5%		
	Dissipation Factor	≤ Initial Value x 2.0 (See Above)		
	Insulation Resistance	≥ Initial Value x 0.3 (See Above)		
	Dielectric Strength	Meets Initial Values (As Above)		
Load Humidity	Appearance	No visual defects	Store in a test chamber set at 85ºC ± 2ºC/ 85% ± 5% relative humidity for 1000 hours (+48, -0) with rated voltage applied. Remove from chamber and stabilize at room temperature and humidity for 24 ± 2 hours before measuring.	
	Capacitance Variation	≤ ±12.5%		
	Dissipation Factor	≤ Initial Value x 2.0 (See Above)		
	Insulation Resistance	≥ Initial Value x 0.3 (See Above)		
	Dielectric Strength	Meets Initial Values (As Above)		

X7R Dielectric

Capacitance Range

PREFERRED SIZES ARE SHADED

SIZE		0201	0402			0603					0805						1206						
Soldering		Reflow Only	Reflow Only			Reflow Only					Reflow/Wave						Reflow/Wave						
Packaging		All Paper	All Paper			All Paper					Paper/Embossed						Paper/Embossed						
(L) Length	MM (in.)	0.60 ± 0.03 (0.024 ± 0.001)	1.00 ± 0.10 (0.040 ± 0.004)			1.60 ± 0.15 (0.063 ± 0.006)					2.01 ± 0.20 (0.079 ± 0.008)						3.20 ± 0.20 (0.126 ± 0.008)						
(W) Width	MM (in.)	0.30 ± 0.03 (0.011 ± 0.001)	0.50 ± 0.10 (0.020 ± 0.004)			0.81 ± 0.15 (0.032 ± 0.006)					1.25 ± 0.20 (0.049 ± 0.008)						1.60 ± 0.20 (0.063 ± 0.008)						
(t) Terminal	MM (in.)	0.15 ± 0.05 (0.006 ± 0.002)	0.25 ± 0.15 (0.010 ± 0.006)			0.35 ± 0.15 (0.014 ± 0.006)					0.50 ± 0.25 (0.020 ± 0.010)						0.50 ± 0.25 (0.020 ± 0.010)						
	WVDC	16	16	25	50	10	16	25	50	100	10	16	25	50	100	200	10	16	25	50	100	200	500
Cap	100	A																					
(pF)	150	A																					
	220	A			C																		
	330	A			C				G	G	J	J	J	J	J	J							K
	470	A			C				G	G	J	J	J	J	J	J							K
	680	A			C				G	G	J	J	J	J	J	J							K
	1000	A			C				G	G	J	J	J	J	J	J							K
	1500				C				G	G	J	J	J	J	J	J	J	J	J	J	J	J	M
	2200				C				G	G	J	J	J	J	J	J	J	J	J	J	J	J	M
	3300			C	C				G	G	J	J	J	J	J	J	J	J	J	J	J	J	M
	4700			C					G		J	J	J	J	J	J	J	J	J	J	J	J	M
	6800		C	C					G		J	J	J	J	J	J	J	J	J	J	J	J	P
Cap	0.010		C						G		J	J	J	J	J	J	J	J	J	J	J	J	P
(µF	0.015		C					G	G		J	J	J	J	J	J	J	J	J	J	J	M	
	0.022		C					G			J	J	J	J	J	M	J	J	J	J	J	M	
	0.033							G			J	J	J	J	M		J	J	J	J	J	M	
	0.047						G	G			J	J	J	J	M		J	J	J	J	J	M	
	0.068						G				J	J	J	J			J	J	J	J	J	P	
	0.10					G	G	G			J	J	J	J			J	J	J	J	M		
	0.15					G					J	J	J				J	J	J	J			
	0.22					G					J	J	M				J	J	J	J			
	0.33										M	M					J	J	M	M			
	0.47										N	M					M	M	M				
	0.68										N						M	M					
	1.0										N						M	M	Q				
	1.5																P						
	2.2																Q						
	3.3																						
	4.7																						
	10																						
	22																						
	47																						
	100																						
	WVDC	16	16	25	50	10	16	25	50	100	10	16	25	50	100	200	10	16	25	50	100	200	500
SIZE		0201	0402			0603					0805						1206						



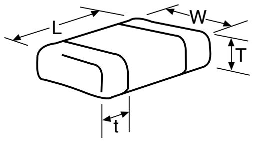
Letter	A	C	E	G	J	K	M	N	P	Q	X	Y	Z
Max. Thickness	0.33 (0.013)	0.56 (0.022)	0.71 (0.028)	0.86 (0.034)	0.94 (0.037)	1.02 (0.040)	1.27 (0.050)	1.40 (0.055)	1.52 (0.060)	1.78 (0.070)	2.29 (0.090)	2.54 (0.100)	2.79 (0.110)
	PAPER					EMBOSSED							

X7R Dielectric

Capacitance Range

PREFERRED SIZES ARE SHADED

SIZE		1210							1812				1825		2220				2225	
Soldering		Reflow Only							Reflow Only				Reflow Only		Reflow Only				Reflow Only	
Packaging		Paper/Embossed							All Embossed				All Embossed		All Embossed				All Embossed	
(L) Length	MM (in.)	3.20 ± 0.20 (0.126 ± 0.008)							4.50 ± 0.30 (0.177 ± 0.012)				4.50 ± 0.30 (0.177 ± 0.012)		5.70 ± 0.40 (0.225 ± 0.016)				5.72 ± 0.25 (0.225 ± 0.010)	
(W) Width	MM (in.)	2.50 ± 0.20 (0.098 ± 0.008)							3.20 ± 0.20 (0.126 ± 0.008)				6.40 ± 0.40 (0.252 ± 0.016)		5.00 ± 0.40 (0.197 ± 0.016)				6.35 ± 0.25 (0.250 ± 0.010)	
(t) Terminal	MM (in.)	0.50 ± 0.25 (0.020 ± 0.010)							0.61 ± 0.36 (0.024 ± 0.014)				0.61 ± 0.36 (0.024 ± 0.014)		0.64 ± 0.39 (0.025 ± 0.015)				0.64 ± 0.39 (0.025 ± 0.015)	
	WVDC	10	16	25	50	100	200	500	50	100	200	500	50	100	6.3	50	100	200	50	100
Cap	100																			
(pF)	150																			
	220																			
	330																			
	470																			
	680																			
	1000																			
	1500	J	J	J	J	J	J	M												
	2200	J	J	J	J	J	J	M												
	3300	J	J	J	J	J	J	M												
	4700	J	J	J	J	J	J	M												
	6800	J	J	J	J	J	J	M												
Cap	0.010	J	J	J	J	J	J	M	K	K	K	K	M	M	X	X	X	X	M	P
(µF	0.015	J	J	J	J	J	J	P	K	K	K	P	M	M	X	X	X	X	M	P
	0.022	J	J	J	J	J	J	Q	K	K	K	P	M	M	X	X	X	X	M	P
	0.033	J	J	J	J	J	J		K	K	K	X	M	M	X	X	X	X	M	P
	0.047	J	J	J	J	J	J		K	K	K	Z	M	M	X	X	X	X	M	P
	0.068	J	J	J	J	J	M		K	K	K		M	M	X	X	X	X	M	P
	0.10	J	J	J	J	J	M		K	K	K		M	M	X	X	X	X	M	P
	0.15	J	J	J	J	M			K	K	P		M	M	X	X	X	X	M	P
	0.22	J	J	J	J	P			K	K	P		M	M	X	X	X		M	P
	0.33	J	J	J	J	Z			K	M			M	M	X	X	X		M	P
	0.47	M	M	M	M	Z			K	P			M	M	X	X	X		M	P
	0.68	M	M	P	X	Z			M	Q			M		X	X	X		M	P
	1.0	N	N	P	X	Z			M	X			M				Z		M	P
	1.5	N	N										M						M	X
	2.2			X					Z										M	
	3.3																			
	4.7	Q	Z																	
	10	Z																		
	22																			
	47																			
	100																			
	WVDC	10	16	25	50	100	200	500	50	100	200	500	50	100	6.3	50	100	200	50	100
SIZE		1210							1812				1825		2220				2225	



Letter	A	C	E	G	J	K	M	N	P	Q	X	Y	Z
Max. Thickness	0.33 (0.013)	0.56 (0.022)	0.71 (0.028)	0.86 (0.034)	0.94 (0.037)	1.02 (0.040)	1.27 (0.050)	1.40 (0.055)	1.52 (0.060)	1.78 (0.070)	2.29 (0.090)	2.54 (0.100)	2.79 (0.110)
	PAPER					EMBOSSED							

Packaging of Chip Components

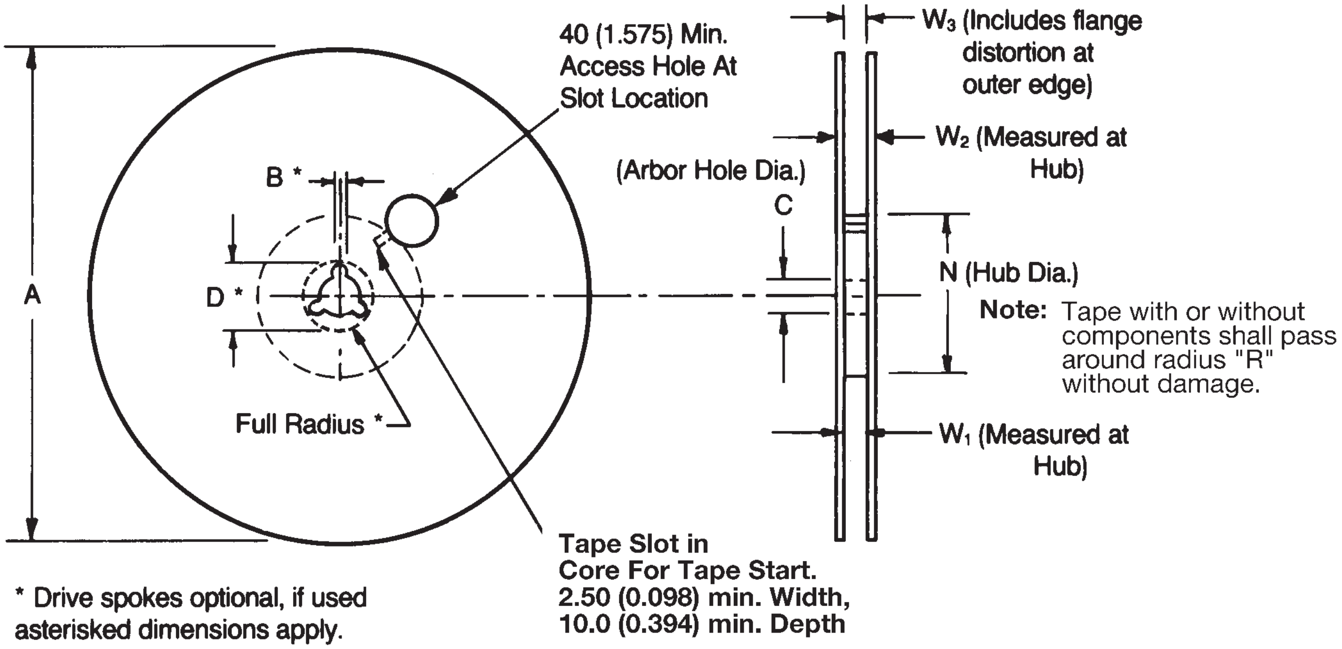
Automatic Insertion Packaging

TAPE & REEL QUANTITIES

All tape and reel specifications are in compliance with RS481.

	8mm	12mm	
Paper or Embossed Carrier	0612, 0508, 0805, 1206, 1210		
Embossed Only		1808	1812, 1825 2220, 2225
Paper Only	0201, 0306, 0402, 0603		
Qty. per Reel/7" Reel	2,000, 3,000 or 4,000, 10,000, 15,000 Contact factory for exact quantity	3,000	500, 1,000 Contact factory for exact quantity
Qty. per Reel/13" Reel	5,000, 10,000, 50,000 Contact factory for exact quantity	10,000	4,000

REEL DIMENSIONS



Note: Tape with or without components shall pass around radius "R" without damage.

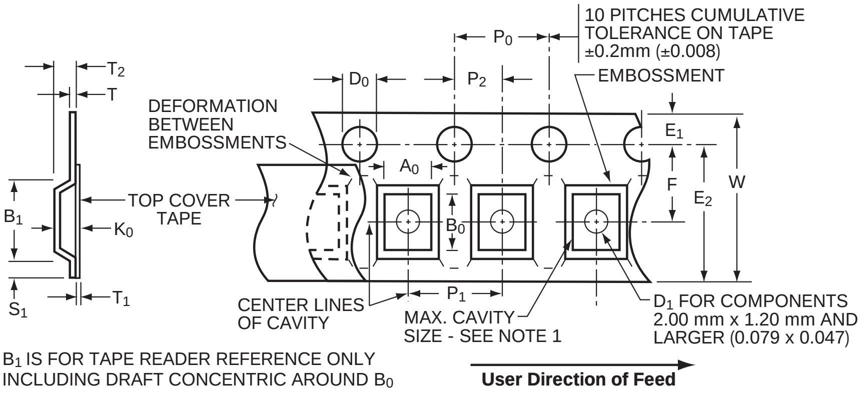
* Drive spokes optional, if used asterisked dimensions apply.

Tape Size[(1)]	A Max.	B* Min.	C	D* Min.	N Min.	W_1	W_2 Max.	W_3
8mm	330 (12.992)	1.5 (0.059)	$13.0^{+0.50}_{-0.20}$ $(0.512^{+0.020}_{-0.008})$	20.2 (0.795)	50.0 (1.969)	$8.40^{+1.5}_{-0.0}$ $(0.331^{+0.059}_{-0.0})$	14.4 (0.567)	7.90 Min. (0.311) 10.9 Max. (0.429)
12mm						$12.4^{+2.0}_{-0.0}$ $(0.488^{+0.079}_{-0.0})$	18.4 (0.724)	11.9 Min. (0.469) 15.4 Max. (0.607)

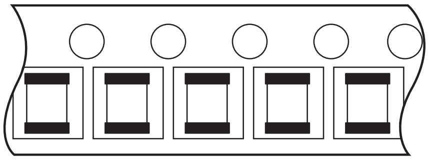
Metric dimensions will govern.
English measurements rounded and for reference only.
(1) For tape sizes 16mm and 24mm (used with chip size 3640) consult EIA RS-481 latest revision.

Embossed Carrier Configuration

8 & 12mm Tape Only



Chip Orientation



8 & 12mm Embossed Tape Metric Dimensions Will Govern

CONSTANT DIMENSIONS

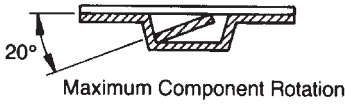
Tape Size	D_0	E	P_0	P_2	S_1 Min.	T Max.	T_1
8mm and 12mm	$1.50^{+0.10}_{-0.0}$ $(0.059^{+0.004}_{-0.0})$	1.75 ± 0.10 (0.069 ± 0.004)	4.0 ± 0.10 (0.157 ± 0.004)	2.0 ± 0.05 (0.079 ± 0.002)	0.60 (0.024)	0.60 (0.024)	0.10 (0.004) Max.

VARIABLE DIMENSIONS

Tape Size	B_1 Max.	D_1 Min.	E_2 Min.	F	P_1 See Note 5	R Min. See Note 2	T_2	W Max.	$A_0 B_0 K_0$
8mm	4.35 (0.171)	1.00 (0.039)	6.25 (0.246)	3.50 ± 0.05 (0.138 ± 0.002)	4.00 ± 0.10 (0.157 ± 0.004)	25.0 (0.984)	2.50 Max. (0.098)	8.30 (0.327)	See Note 1
12mm	8.20 (0.323)	1.50 (0.059)	10.25 (0.404)	5.50 ± 0.05 (0.217 ± 0.002)	4.00 ± 0.10 (0.157 ± 0.004)	30.0 (1.181)	6.50 Max. (0.256)	12.3 (0.484)	See Note 1
8mm 1/2 Pitch	4.35 (0.171)	1.00 (0.039)	6.25 (0.246)	3.50 ± 0.05 (0.138 ± 0.002)	2.00 ± 0.10 (0.079 ± 0.004)	25.0 (0.984)	2.50 Max. (0.098)	8.30 (0.327)	See Note 1
12mm Double Pitch	8.20 (0.323)	1.50 (0.059)	10.25 (0.404)	5.50 ± 0.05 (0.217 ± 0.002)	8.00 ± 0.10 (0.315 ± 0.004)	30.0 (1.181)	6.50 Max. (0.256)	12.3 (0.484)	See Note 1

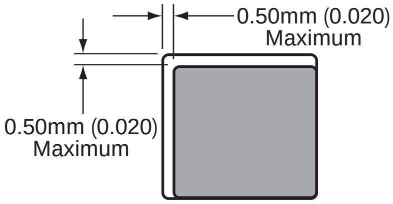
NOTES:

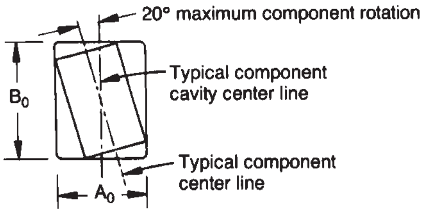
1. The cavity defined by A_0, B_0, and K_0 shall be configured to provide the following:
   Surround the component with sufficient clearance such that:
   - a) the component does not protrude beyond the sealing plane of the cover tape.
   - b) the component can be removed from the cavity in a vertical direction without mechanical restriction, after the cover tape has been removed.
   - c) rotation of the component is limited to 20º maximum (see Sketches D & E).
   - d) lateral movement of the component is restricted to 0.5mm maximum (see Sketch F).
2. Tape with or without components shall pass around radius "R" without damage.
3. Bar code labeling (if required) shall be on the side of the reel opposite the round sprocket holes. Refer to EIA-556.
4. B_1 dimension is a reference dimension for tape feeder clearance only.
5. If P_1 = 2.0mm, the tape may not properly index in all tape feeders.



Side or Front Sectional View
Sketch "C"

Top View, Sketch "F"
Component Lateral Movements

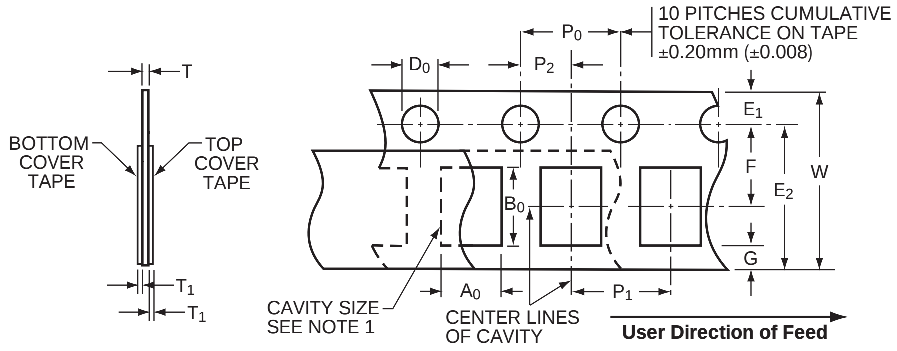




Top View
Sketch "D"

Paper Carrier Configuration

8 & 12mm Tape Only



8 & 12mm Paper Tape
Metric Dimensions Will Govern

CONSTANT DIMENSIONS

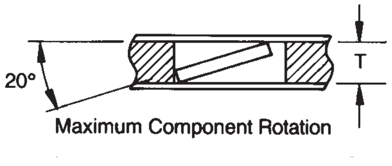
Tape Size	D_0	E	P_0	P_2	T_1	G. Min.	R Min.
8mm and 12mm	$1.50^{+0.10}_{-0.0}$ $(0.059^{+0.004}_{-0.0})$	1.75 ± 0.10 (0.069 ± 0.004)	4.00 ± 0.10 (0.157 ± 0.004)	2.00 ± 0.05 (0.079 ± 0.002)	0.10 (0.004) Max.	0.75 (0.030) Min.	25.0 (0.984) See Note 2 Min.

VARIABLE DIMENSIONS

Tape Size	P_1 See Note 4	E_2 Min.	F	W	A_0 B_0	T
8mm	4.00 ± 0.10 (0.157 ± 0.004)	6.25 (0.246)	3.50 ± 0.05 (0.138 ± 0.002)	$8.00^{+0.30}_{-0.10}$ $(0.315^{+0.012}_{-0.004})$	See Note 1	1.10mm (0.043) Max. for Paper Base Tape and 1.60mm (0.063) Max. for Non-Paper Base Compositions
12mm	4.00 ± 0.010 (0.157 ± 0.004)	10.25 (0.404)	5.50 ± 0.05 (0.217 ± 0.002)	12.0 ± 0.30 (0.472 ± 0.012)		
8mm 1/2 Pitch	2.00 ± 0.05 (0.079 ± 0.002)	6.25 (0.246)	3.50 ± 0.05 (0.138 ± 0.002)	$8.00^{+0.30}_{-0.10}$ $(0.315^{+0.012}_{-0.004})$		
12mm Double Pitch	8.00 ± 0.10 (0.315 ± 0.004)	10.25 (0.404)	5.50 ± 0.05 (0.217 ± 0.002)	12.0 ± 0.30 (0.472 ± 0.012)		

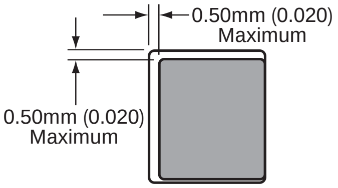
NOTES:

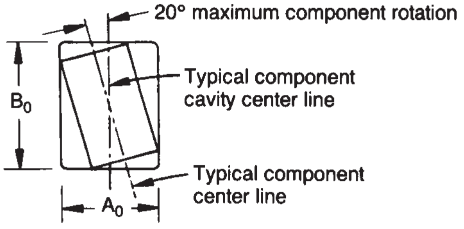
1. The cavity defined by A_0, B_0, and T shall be configured to provide sufficient clearance surrounding the component so that:
   a) the component does not protrude beyond either surface of the carrier tape;
   b) the component can be removed from the cavity in a vertical direction without mechanical restriction after the top cover tape has been removed;
   c) rotation of the component is limited to 20º maximum (see Sketches A & B);
   d) lateral movement of the component is restricted to 0.5mm maximum (see Sketch C).
2. Tape with or without components shall pass around radius “R” without damage.
3. Bar code labeling (if required) shall be on the side of the reel opposite the sprocket holes. Refer to EIA-556.
4. If P_1 = 2.0mm, the tape may not properly index in all tape feeders.



Side or Front Sectional View
Sketch “A”

Top View, Sketch "C"
Component Lateral





Top View
Sketch “B”

Bar Code Labeling Standard

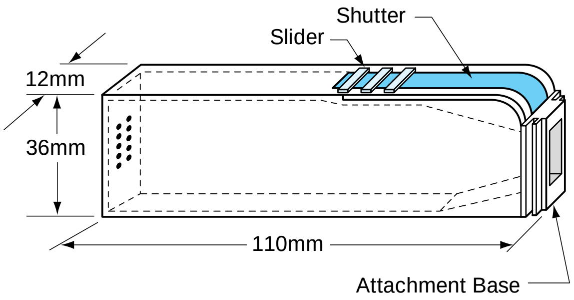
AVX bar code labeling is available and follows latest version of EIA-556

Bulk Case Packaging

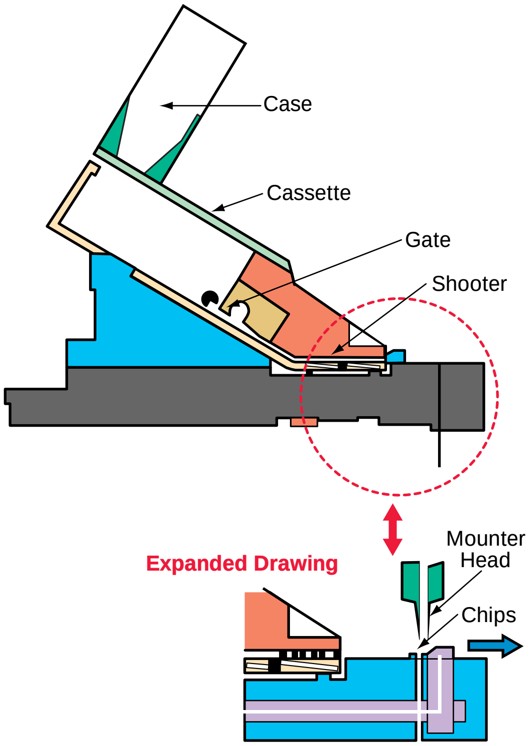
BENEFITS

- Easier handling
- Smaller packaging volume
(1/20 of T/R packaging)
- Easier inventory control
- Flexibility
- Recyclable

CASE DIMENSIONS



BULK FEEDER



CASE QUANTITIES

Part Size	0402	0603	0805	1206
Qty. (pcs / cassette)	80,000	15,000	10,000 (T=.023") 8,000 (T=.031") 6,000 (T=.043")	5,000 (T=.023") 4,000 (T=.032") 3,000 (T=.044")

Basic Capacitor Formulas

I. Capacitance (farads)

English: $C = \frac{.224\,K\,A}{T_D}$

Metric: $C = \frac{.0884\,K\,A}{T_D}$

II. Energy stored in capacitors (Joules, watt - sec)

$E = \frac{1}{2}CV^2$

III. Linear charge of a capacitor (Amperes)

$I = C\,\frac{dV}{dt}$

IV. Total Impedance of a capacitor (ohms)

$Z = \sqrt{R_S^2 + (X_C - X_L)^2}$

V. Capacitive Reactance (ohms)

$x_C = \frac{1}{2\,\pi\,fC}$

VI. Inductive Reactance (ohms)

$x_L = 2\,\pi\,fL$

VII. Phase Angles:

Ideal Capacitors: Current leads voltage 90°
Ideal Inductors: Current lags voltage 90°
Ideal Resistors: Current in phase with voltage

VIII. Dissipation Factor (%)

D.F.= tan δ (loss angle) = $\frac{E.S.R.}{X_C}$ = $(2\,\pi fC)$ (E.S.R.)

IX. Power Factor (%)

P.F. = Sine δ (loss angle) = Cos ϕ (phase angle)
P.F. = (when less than 10%) = DF

X. Quality Factor (dimensionless)

Q = Cotan δ (loss angle) = $\frac{1}{D.F.}$

XI. Equivalent Series Resistance (ohms)

E.S.R. = (D.F.) (Xc) = (D.F.) / $(2\,\pi\,fC)$

XII. Power Loss (watts)

Power Loss = $(2\,\pi\,fCV^2)$ (D.F.)

XIII. KVA (Kilowatts)

$KVA = 2\,\pi\,fCV^2 \times 10^{-3}$

XIV. Temperature Characteristic (ppm/°C)

$T.C. = \frac{Ct - C_{25}}{C_{25}\,(T_t - 25)} \times 10^6$

XV. Cap Drift (%)

$C.D. = \frac{C_1 - C_2}{C_1} \times 100$

XVI. Reliability of Ceramic Capacitors

$\frac{L_0}{L_t} = \left(\frac{V_t}{V_o}\right)^X \left(\frac{T_t}{T_o}\right)^Y$

XVII. Capacitors in Series (current the same)

Any Number: $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} --- \frac{1}{C_N}$

Two: $C_T = \frac{C_1\,C_2}{C_1 + C_2}$

XVIII. Capacitors in Parallel (voltage the same)

$C_T = C_1 + C_2 --- + C_N$

XIX. Aging Rate

A.R. = %Δ C/decade of time

XX. Decibels

$db = 20 \log \frac{V_1}{V_2}$

METRIC PREFIXES

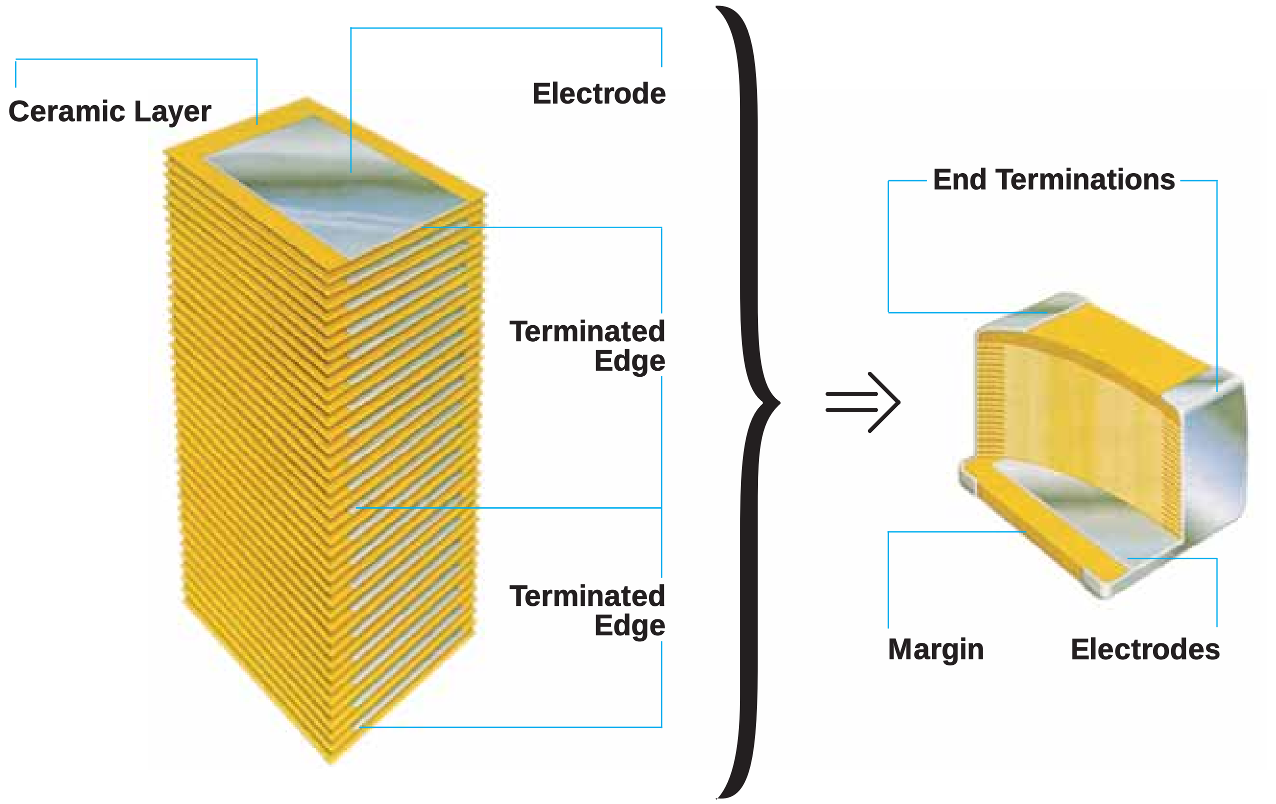
Pico	X 10^{-12}
Nano	X 10^{-9}
Micro	X 10^{-6}
Milli	X 10^{-3}
Deci	X 10^{-1}
Deca	X 10^{+1}
Kilo	X 10^{+3}
Mega	X 10^{+6}
Giga	X 10^{+9}
Tera	X 10^{+12}

SYMBOLS

K	= Dielectric Constant	f	= frequency	L_t	= Test life
A	= Area	L	= Inductance	V_t	= Test voltage
T_D	= Dielectric thickness	δ	= Loss angle	V_o	= Operating voltage
V	= Voltage	ϕ	= Phase angle	T_t	= Test temperature
t	= time	X & Y	= exponent effect of voltage and temp.	T_o	= Operating temperature
R_S	= Series Resistance	L_o	= Operating life		

General Description

Basic Construction – A multilayer ceramic (MLC) capacitor is a monolithic block of ceramic containing two sets of offset, interleaved planar electrodes that extend to two opposite surfaces of the ceramic dielectric. This simple structure requires a considerable amount of sophistication, both in material and manufacture, to produce it in the quality and quantities needed in today's electronic equipment.



Multilayer Ceramic Capacitor

Figure 1

Formulations – Multilayer ceramic capacitors are available in both Class 1 and Class 2 formulations. Temperature compensating formulation are Class 1 and temperature stable and general application formulations are classified as Class 2.

Class 1 – Class 1 capacitors or temperature compensating capacitors are usually made from mixtures of titanates where barium titanate is normally not a major part of the mix. They have predictable temperature coefficients and in general, do not have an aging characteristic. Thus they are the most stable capacitor available. The most popular Class 1 multilayer ceramic capacitors are C0G (NP0) temperature compensating capacitors (negative-positive 0 ppm/°C).

Class 2 – EIA Class 2 capacitors typically are based on the chemistry of barium titanate and provide a wide range of capacitance values and temperature stability. The most commonly used Class 2 dielectrics are X7R and Y5V. The X7R provides intermediate capacitance values which vary only ±15% over the temperature range of -55°C to 125°C. It finds applications where stability over a wide temperature range is required.

The Y5V provides the highest capacitance values and is used in applications where limited temperature changes are expected. The capacitance value for Y5V can vary from 22% to -82% over the -30°C to 85°C temperature range.

All Class 2 capacitors vary in capacitance value under the influence of temperature, operating voltage (both AC and DC), and frequency. For additional information on performance changes with operating conditions, consult AVX's software, SpiCap.

Table 1: EIA and MIL Temperature Stable and General Application Codes

EIA CODE
Percent Capacity Change Over Temperature Range

RS198	**Temperature Range**
X7	-55°C to +125°C
X6	-55°C to +105°C
X5	-55°C to +85°C
Y5	-30°C to +85°C
Z5	+10°C to +85°C
Code	**Percent Capacity Change**
D	±3.3%
E	±4.7%
F	±7.5%
P	±10%
R	±15%
S	±22%
T	+22%, -33%
U	+22%, - 56%
V	+22%, -82%

EXAMPLE – A capacitor is desired with the capacitance value at 25°C to increase no more than 7.5% or decrease no more than 7.5% from -30°C to +85°C. EIA Code will be Y5F.

MIL CODE

Symbol	**Temperature Range**	
A	-55°C to +85°C	
B	-55°C to +125°C	
C	-55°C to +150°C	
Symbol	**Cap. Change Zero Volts**	**Cap. Change Rated Volts**
R	+15%, -15%	+15%, -40%
S	+22%, -22%	+22%, -56%
W	+22%, -56%	+22%, -66%
X	+15%, -15%	+15%, -25%
Y	+30%, -70%	+30%, -80%
Z	+20%, -20%	+20%, -30%

Temperature characteristic is specified by combining range and change symbols, for example BR or AW. Specification slash sheets indicate the characteristic applicable to a given style of capacitor.

In specifying capacitance change with temperature for Class 2 materials, EIA expresses the capacitance change over an operating temperature range by a 3 symbol code. The first symbol represents the cold temperature end of the temperature range, the second represents the upper limit of the operating temperature range and the third symbol represents the capacitance change allowed over the operating temperature range. Table 1 provides a detailed explanation of the EIA system.

Effects of Voltage – Variations in voltage have little effect on Class 1 dielectric but does affect the capacitance and dissipation factor of Class 2 dielectrics. The application of DC voltage reduces both the capacitance and dissipation factor while the application of an AC voltage within a reasonable range tends to increase both capacitance and dissipation factor readings. If a high enough AC voltage is applied, eventually it will reduce capacitance just as a DC voltage will. Figure 2 shows the effects of AC voltage.

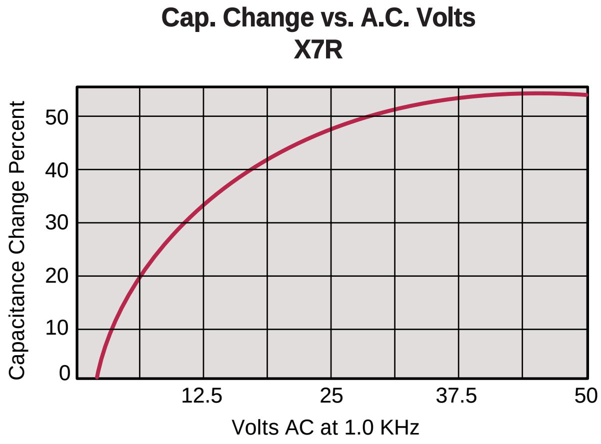


Figure 2

Capacitor specifications specify the AC voltage at which to measure (normally 0.5 or 1 VAC) and application of the wrong voltage can cause spurious readings. Figure 3 gives the voltage coefficient of dissipation factor for various AC voltages at 1 kilohertz. Applications of different frequencies will affect the percentage changes versus voltages.

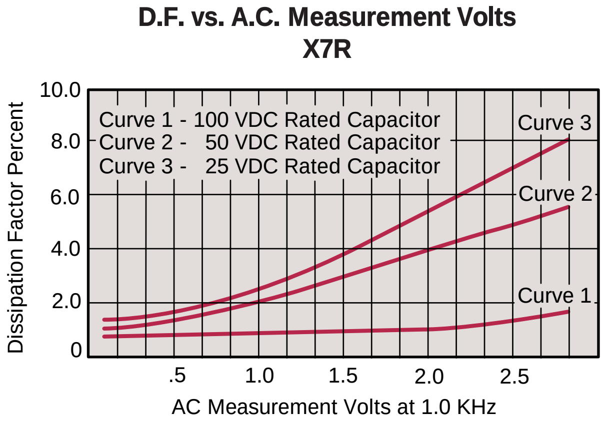


Figure 3

Typical effect of the application of DC voltage is shown in Figure 4. The voltage coefficient is more pronounced for higher K dielectrics. These figures are shown for room temperature conditions. The combination characteristic known as voltage temperature limits which shows the effects of rated voltage over the operating temperature range is shown in Figure 5 for the military BX characteristic.

General Description

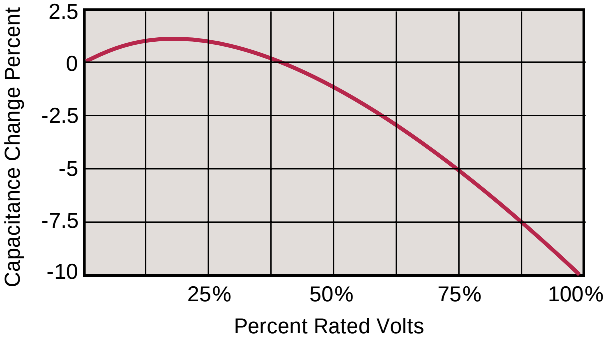

Typical Cap. Change vs. D.C. Volts
X7R

Figure 4

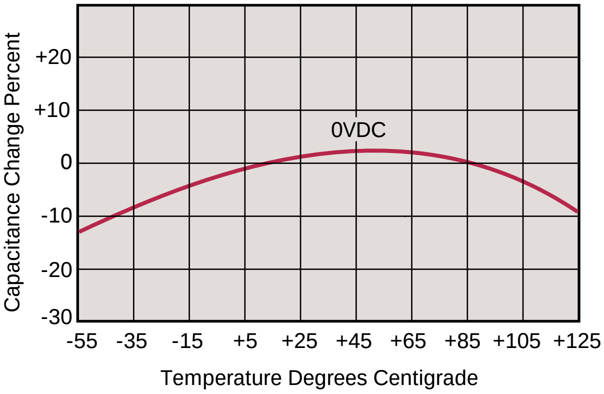
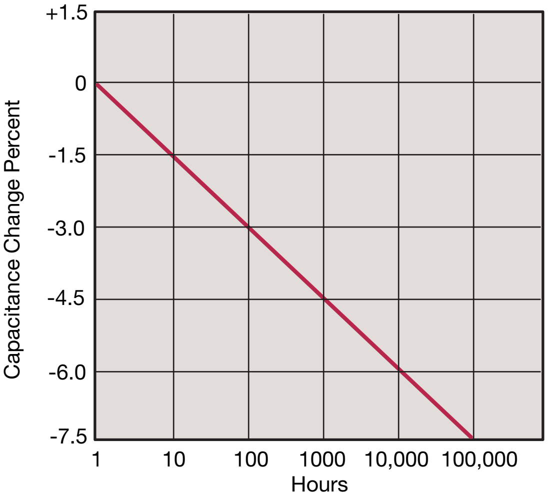

Typical Cap. Change vs. Temperature
X7R

Figure 5

Effects of Time – Class 2 ceramic capacitors change capacitance and dissipation factor with time as well as temperature, voltage and frequency. This change with time is known as aging. Aging is caused by a gradual re-alignment of the crystalline structure of the ceramic and produces an exponential loss in capacitance and decrease in dissipation factor versus time. A typical curve of aging rate for semi-stable ceramics is shown in Figure 6.

If a Class 2 ceramic capacitor that has been sitting on the shelf for a period of time, is heated above its curie point, (125°C for 4 hours or 150°C for ½ hour will suffice) the part will de-age and return to its initial capacitance and dissipation factor readings. Because the capacitance changes rapidly, immediately after de-aging, the basic capacitance measurements are normally referred to a time period sometime after the de-aging process. Various manufacturers use different time bases but the most popular one is one day or twenty-four hours after "last heat." Change in the aging curve can be caused by the application of voltage and other stresses. The possible changes in capacitance due to de-aging by heating the unit explain why capacitance changes are allowed after test, such as temperature cycling, moisture resistance, etc., in MIL specs. The application of high voltages such as dielectric withstanding voltages also tends to de-age capacitors and is why re-reading of capacitance after 12 or 24 hours is allowed in military specifications after dielectric strength tests have been performed.


Typical Curve of Aging Rate
X7R

Characteristic	Max. Aging Rate %/Decade
C0G (NP0)	None
X7R, X5R	2
Y5V	7

Figure 6

Effects of Frequency – Frequency affects capacitance and impedance characteristics of capacitors. This effect is much more pronounced in high dielectric constant ceramic formulation than in low K formulations. AVX's SpiCap software generates impedance, ESR, series inductance, series resonant frequency and capacitance all as functions of frequency, temperature and DC bias for standard chip sizes and styles. It is available free from AVX and can be downloaded for free from AVX website: www.avx.com.

General Description

Effects of Mechanical Stress – High “K” dielectric ceramic capacitors exhibit some low level piezoelectric reactions under mechanical stress. As a general statement, the piezoelectric output is higher, the higher the dielectric constant of the ceramic. It is desirable to investigate this effect before using high “K” dielectrics as coupling capacitors in extremely low level applications.

Reliability – Historically ceramic capacitors have been one of the most reliable types of capacitors in use today. The approximate formula for the reliability of a ceramic capacitor is:

$$\frac{L_o}{L_t} = \left(\frac{V_t}{V_o}\right)^X \left(\frac{T_t}{T_o}\right)^Y$$

where

L_o = operating life
L_t = test life
V_t = test voltage
V_o = operating voltage
T_t = test temperature and
T_o = operating temperature in °C
X,Y = see text

Historically for ceramic capacitors exponent X has been considered as 3. The exponent Y for temperature effects typically tends to run about 8.

A capacitor is a component which is capable of storing electrical energy. It consists of two conductive plates (electrodes) separated by insulating material which is called the dielectric. A typical formula for determining capacitance is:

$$C = \frac{.224\ KA}{t}$$

C = capacitance (picofarads)
K = dielectric constant (Vacuum = 1)
A = area in square inches
t = separation between the plates in inches (thickness of dielectric)
.224 = conversion constant (.0884 for metric system in cm)

Capacitance – The standard unit of capacitance is the farad. A capacitor has a capacitance of 1 farad when 1 coulomb charges it to 1 volt. One farad is a very large unit and most capacitors have values in the micro (10^{-6}), nano (10^{-9}) or pico (10^{-12}) farad level.

Dielectric Constant – In the formula for capacitance given above the dielectric constant of a vacuum is arbitrarily chosen as the number 1. Dielectric constants of other materials are then compared to the dielectric constant of a vacuum.

Dielectric Thickness – Capacitance is indirectly proportional to the separation between electrodes. Lower voltage requirements mean thinner dielectrics and greater capacitance per volume.

Area – Capacitance is directly proportional to the area of the electrodes. Since the other variables in the equation are usually set by the performance desired, area is the easiest parameter to modify to obtain a specific capacitance within a material group.

Energy Stored – The energy which can be stored in a capacitor is given by the formula:

$$E = \tfrac{1}{2}CV^2$$

E = energy in joules (watts-sec)
V = applied voltage
C = capacitance in farads

Potential Change – A capacitor is a reactive component which reacts against a change in potential across it. This is shown by the equation for the linear charge of a capacitor:

$$I_{ideal} = C\frac{dV}{dt}$$

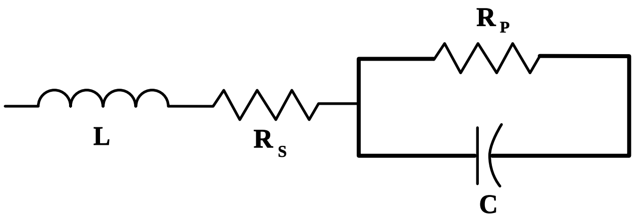
where

I = Current
C = Capacitance
dV/dt = Slope of voltage transition across capacitor

Thus an infinite current would be required to instantly change the potential across a capacitor. The amount of current a capacitor can “sink” is determined by the above equation.

Equivalent Circuit – A capacitor, as a practical device, exhibits not only capacitance but also resistance and inductance. A simplified schematic for the equivalent circuit is:

C = Capacitance
L = Inductance
R_s = Series Resistance
R_p = Parallel Resistance



Reactance – Since the insulation resistance (R_p) is normally very high, the total impedance of a capacitor is:

$$Z = \sqrt{R_S^2 + (X_C - X_L)^2}$$

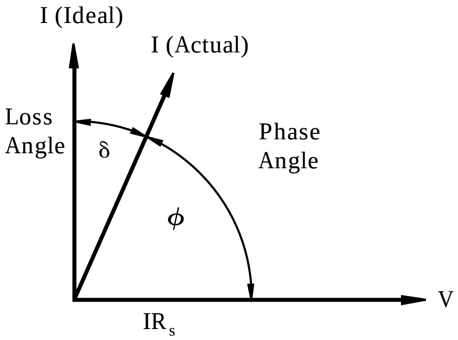
where

Z = Total Impedance
R_s = Series Resistance
X_C = Capacitive Reactance $= \dfrac{1}{2\,\pi\, fC}$
X_L = Inductive Reactance $= 2\,\pi\, fL$

The variation of a capacitor’s impedance with frequency determines its effectiveness in many applications.

Phase Angle – Power Factor and Dissipation Factor are often confused since they are both measures of the loss in a capacitor under AC application and are often almost identical in value. In a “perfect” capacitor the current in the capacitor will lead the voltage by 90°.

General Description

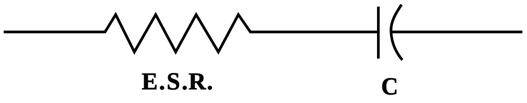


In practice the current leads the voltage by some other phase angle due to the series resistance R_S. The complement of this angle is called the loss angle and:

Power Factor (P.F.) = Cos ϕ or Sine δ
Dissipation Factor (D.F.) = tan δ

for small values of δ the tan and sine are essentially equal which has led to the common interchangeability of the two terms in the industry.

Equivalent Series Resistance – The term E.S.R. or Equivalent Series Resistance combines all losses both series and parallel in a capacitor at a given frequency so that the equivalent circuit is reduced to a simple R-C series connection.



Dissipation Factor – The DF/PF of a capacitor tells what percent of the apparent power input will turn to heat in the capacitor.

$$\textbf{Dissipation Factor} = \frac{\textbf{E.S.R.}}{X_c} = (2\pi fC)(\text{E.S.R.})$$

The watts loss are:

$$\textbf{Watts loss} = (2\pi fCV^2)(\text{D.F.})$$

Very low values of dissipation factor are expressed as their reciprocal for convenience. These are called the “Q” or Quality factor of capacitors.

Parasitic Inductance – The parasitic inductance of capacitors is becoming more and more important in the decoupling of today’s high speed digital systems. The relationship between the inductance and the ripple voltage induced on the DC voltage line can be seen from the simple inductance equation:

$$V = L\frac{di}{dt}$$

The $\frac{di}{dt}$ seen in current microprocessors can be as high as 0.3 A/ns, and up to 10A/ns. At 0.3 A/ns, 100pH of parasitic inductance can cause a voltage spike of 30mV. While this does not sound very drastic, with the Vcc for microprocessors decreasing at the current rate, this can be a fairly large percentage.

Another important, often overlooked, reason for knowing the parasitic inductance is the calculation of the resonant frequency. This can be important for high frequency, bypass capacitors, as the resonant point will give the most signal attenuation. The resonant frequency is calculated from the simple equation:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

Insulation Resistance – Insulation Resistance is the resistance measured across the terminals of a capacitor and consists principally of the parallel resistance R_P shown in the equivalent circuit. As capacitance values and hence the area of dielectric increases, the I.R. decreases and hence the product (C x IR or RC) is often specified in ohm faradsor more commonly megohm-microfarads. Leakage current is determined by dividing the rated voltage by IR (Ohm’s Law).

Dielectric Strength – Dielectric Strength is an expression of the ability of a material to withstand an electrical stress. Although dielectric strength is ordinarily expressed in volts, it is actually dependent on the thickness of the dielectric and thus is also more generically a function of volts/mil.

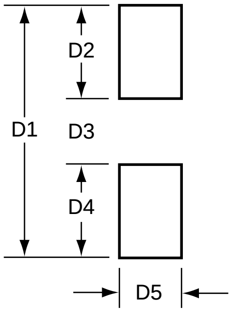
Dielectric Absorption – A capacitor does not discharge instantaneously upon application of a short circuit, but drains gradually after the capacitance proper has been discharged. It is common practice to measure the dielectric absorption by determining the “reappearing voltage” which appears across a capacitor at some point in time after it has been fully discharged under short circuit conditions.

Corona – Corona is the ionization of air or other vapors which causes them to conduct current. It is especially prevalent in high voltage units but can occur with low voltages as well where high voltage gradients occur. The energy discharged degrades the performance of the capacitor and can in time cause catastrophic failures.

Surface Mounting Guide

MLC Chip Capacitors

REFLOW SOLDERING



Dimensions in millimeters (inches)

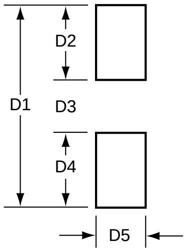
Case Size	D1	D2	D3	D4	D5
0402	1.70 (0.07)	0.60 (0.02)	0.50 (0.02)	0.60 (0.02)	0.50 (0.02)
0603	2.30 (0.09)	0.80 (0.03)	0.70 (0.03)	0.80 (0.03)	0.75 (0.03)
0805	3.00 (0.12)	1.00 (0.04)	1.00 (0.04)	1.00 (0.04)	1.25 (0.05)
1206	4.00 (0.16)	1.00 (0.04)	2.00 (0.09)	1.00 (0.04)	1.60 (0.06)
1210	4.00 (0.16)	1.00 (0.04)	2.00 (0.09)	1.00 (0.04)	2.50 (0.10)
1808	5.60 (0.22)	1.00 (0.04)	3.60 (0.14)	1.00 (0.04)	2.00 (0.08)
1812	5.60 (0.22)	1.00 (0.04))	3.60 (0.14)	1.00 (0.04)	3.00 (0.12)
1825	5.60 (0.22)	1.00 (0.04)	3.60 (0.14)	1.00 (0.04)	6.35 (0.25)
2220	6.60 (0.26)	1.00 (0.04)	4.60 (0.18)	1.00 (0.04)	5.00 (0.20)
2225	6.60 (0.26)	1.00 (0.04)	4.60 (0.18)	1.00 (0.04)	6.35 (0.25)

Component Pad Design

Component pads should be designed to achieve good solder filets and minimize component movement during reflow soldering. Pad designs are given below for the most common sizes of multilayer ceramic capacitors for both wave and reflow soldering. The basis of these designs is:

- Pad width equal to component width. It is permissible to decrease this to as low as 85% of component width but it is not advisable to go below this.
- Pad overlap 0.5mm beneath component.
- Pad extension 0.5mm beyond components for reflow and 1.0mm for wave soldering.

WAVE SOLDERING

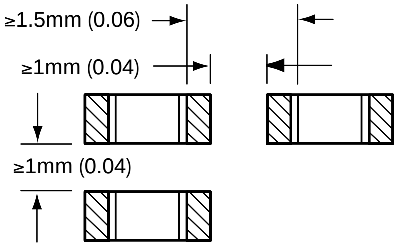


Case Size	D1	D2	D3	D4	D5
0603	3.10 (0.12)	1.20 (0.05)	0.70 (0.03)	1.20 (0.05)	0.75 (0.03)
0805	4.00 (0.15)	1.50 (0.06)	1.00 (0.04)	1.50 (0.06)	1.25 (0.05)
1206	5.00 (0.19)	1.50 (0.06)	2.00 (0.09)	1.50 (0.06)	1.60 (0.06)

Dimensions in millimeters (inches)

Component Spacing

For wave soldering components, must be spaced sufficiently far apart to avoid bridging or shadowing (inability of solder to penetrate properly into small spaces). This is less important for reflow soldering but sufficient space must be allowed to enable rework should it be required.



Preheat & Soldering

The rate of preheat should not exceed 4°C/second to prevent thermal shock. A better maximum figure is about 2°C/second.

For capacitors size 1206 and below, with a maximum thickness of 1.25mm, it is generally permissible to allow a temperature differential from preheat to soldering of 150°C. In all other cases this differential should not exceed 100°C.

For further specific application or process advice, please consult AVX.

Cleaning

Care should be taken to ensure that the capacitors are thoroughly cleaned of flux residues especially the space beneath the capacitor. Such residues may otherwise become conductive and effectively offer a low resistance bypass to the capacitor.

Ultrasonic cleaning is permissible, the recommended conditions being 8 Watts/litre at 20-45 kHz, with a process cycle of 2 minutes vapor rinse, 2 minutes immersion in the ultrasonic solvent bath and finally 2 minutes vapor rinse.

Surface Mounting Guide

MLC Chip Capacitors

APPLICATION NOTES

Storage

Good solderability is maintained for at least twelve months, provided the components are stored in their “as received” packaging at less than 40°C and 70% RH.

Solderability

Terminations to be well soldered after immersion in a 60/40 tin/lead solder bath at 235 ± 5°C for 2 ± 1 seconds.

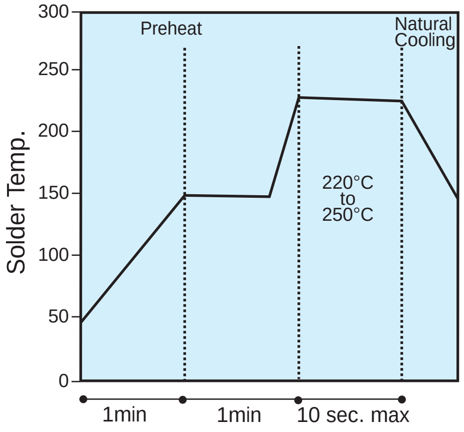
Leaching

Terminations will resist leaching for at least the immersion times and conditions shown below.

Termination Type	Solder Tin/Lead/Silver	Solder Temp. °C	Immersion Time Seconds
Nickel Barrier	60/40/0	260 ± 5	30 ± 1

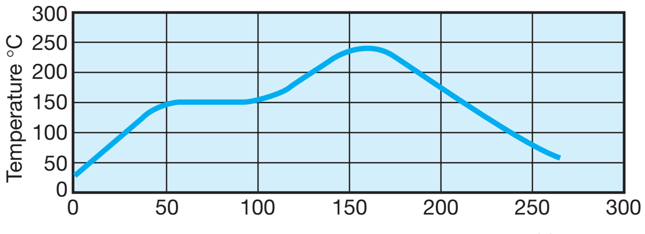
Recommended Soldering Profiles

Reflow



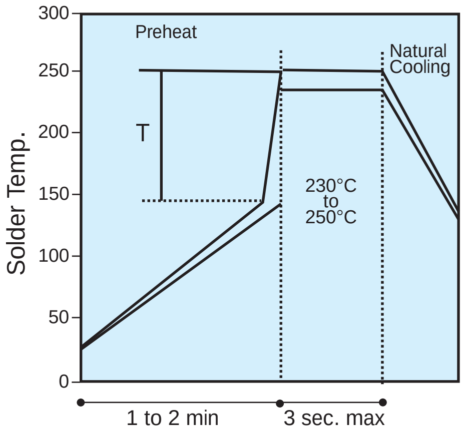
(Minimize soldering time)

Lead-Free Reflow Profile



- Pre-heating: 150°C ±15°C / 60-90s
- Max. Peak Gradient 2.5°C/s
- Peak Temperature: 245°C ±5°C
- Time at >230°C: 40s Max.

Wave



(Preheat chips before soldering)
T/maximum 150°C

Lead-Free Wave Soldering

The recommended peak temperature for lead-free wave soldering is 250°C-260°C for 3-5 seconds. The other parameters of the profile remains the same as above.

The following should be noted by customers changing from lead based systems to the new lead free pastes.

a) The visual standards used for evaluation of solder joints will need to be modified as lead free joints are not as bright as with tin-lead pastes and the fillet may not be as large.

b) Resin color may darken slightly due to the increase in temperature required for the new pastes.

c) Lead-free solder pastes do not allow the same self alignment as lead containing systems. Standard mounting pads are acceptable, but machine set up may need to be modified.

General

Surface mounting chip multilayer ceramic capacitors are designed for soldering to printed circuit boards or other substrates. The construction of the components is such that they will withstand the time/temperature profiles used in both wave and reflow soldering methods.

Handling

Chip multilayer ceramic capacitors should be handled with care to avoid damage or contamination from perspiration and skin oils. The use of tweezers or vacuum pick ups is strongly recommended for individual components. Bulk handling should ensure that abrasion and mechanical shock are minimized. Taped and reeled components provides the ideal medium for direct presentation to the placement machine. Any mechanical shock should be minimized during handling chip multilayer ceramic capacitors.

Preheat

It is important to avoid the possibility of thermal shock during soldering and carefully controlled preheat is therefore required. The rate of preheat should not exceed 4°C/second and a target figure 2°C/second is recommended. Although an 80°C to 120°C temperature differential is preferred, recent developments allow a temperature differential between the component surface and the soldering temperature of 150°C (Maximum) for capacitors of 1210 size and below with a maximum thickness of 1.25mm. The user is cautioned that the risk of thermal shock increases as chip size or temperature differential increases.

Soldering
Mildly activated rosin fluxes are preferred. The minimum amount of solder to give a good joint should be used. Excessive solder can lead to damage from the stresses caused by the difference in coefficients of expansion between solder, chip and substrate. AVX terminations are suitable for all wave and reflow soldering systems. If hand soldering cannot be avoided, the preferred technique is the utilization of hot air soldering tools.

Cooling
Natural cooling in air is preferred, as this minimizes stresses within the soldered joint. When forced air cooling is used, cooling rate should not exceed 4°C/second. Quenching is not recommended but if used, maximum temperature differentials should be observed according to the preheat conditions above.

Cleaning
Flux residues may be hygroscopic or acidic and must be removed. AVX MLC capacitors are acceptable for use with all of the solvents described in the specifications MIL-STD-202 and EIA-RS-198. Alcohol based solvents are acceptable and properly controlled water cleaning systems are also acceptable. Many other solvents have been proven successful, and most solvents that are acceptable to other components on circuit assemblies are equally acceptable for use with ceramic capacitors.

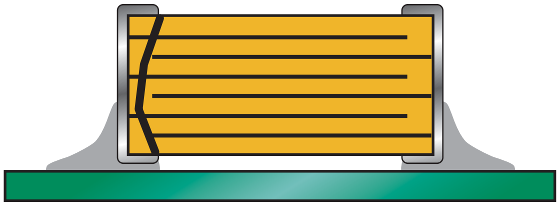
POST SOLDER HANDLING

Once SMP components are soldered to the board, any bending or flexure of the PCB applies stresses to the soldered joints of the components. For leaded devices, the stresses are absorbed by the compliancy of the metal leads and generally don’t result in problems unless the stress is large enough to fracture the soldered connection.

Ceramic capacitors are more susceptible to such stress because they don’t have compliant leads and are brittle in nature. The most frequent failure mode is low DC resistance or short circuit. The second failure mode is significant loss of capacitance due to severing of contact between sets of the internal electrodes.

Cracks caused by mechanical flexure are very easily identified and generally take one of the following two general forms:

Type A:
Angled crack between bottom of device to top of solder joint.



Type B:
Fracture from top of device to bottom of device.

Mechanical cracks are often hidden underneath the termination and are difficult to see externally. However, if one end termination falls off during the removal process from PCB, this is one indication that the cause of failure was excessive mechanical stress due to board warping.

COMMON CAUSES OF MECHANICAL CRACKING

The most common source for mechanical stress is board depanelization equipment, such as manual breakapart, v-cutters and shear presses. Improperly aligned or dull cutters may cause torqueing of the PCB resulting in flex stresses being transmitted to components near the board edge. Another common source of flexural stress is contact during parametric testing when test points are probed. If the PCB is allowed to flex during the test cycle, nearby ceramic capacitors may be broken.

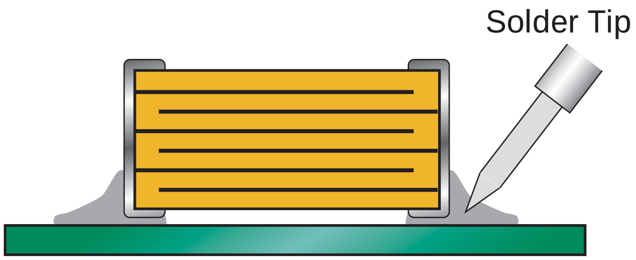
A third common source is board to board connections at vertical connectors where cables or other PCBs are connected to the PCB. If the board is not supported during the plug/unplug cycle, it may flex and cause damage to nearby components.

Special care should also be taken when handling large (>6" on a side) PCBs since they more easily flex or warp than smaller boards.

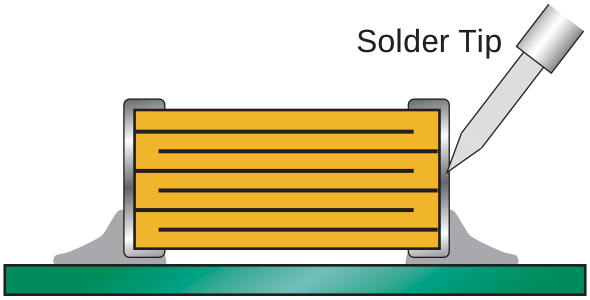
REWORKING OF MLCs

Thermal shock is common in MLCs that are manually attached or reworked with a soldering iron. *AVX strongly recommends that any reworking of MLCs be done with hot air reflow rather than soldering irons.* It is practically impossible to cause any thermal shock in ceramic capacitors when using hot air reflow.

However direct contact by the soldering iron tip often causes thermal cracks that may fail at a later date. If rework by soldering iron is absolutely necessary, it is recommended that the wattage of the iron be less than 30 watts and the tip temperature be <300ºC. *Rework should be performed by applying the solder iron tip to the pad and not directly contacting any part of the ceramic capacitor.*



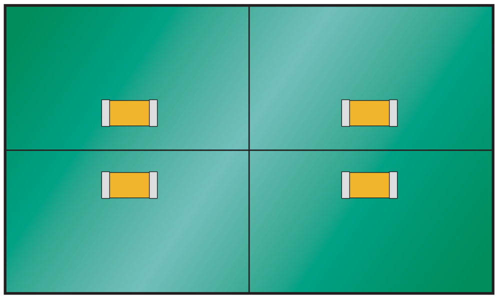
Preferred Method - No Direct Part Contact



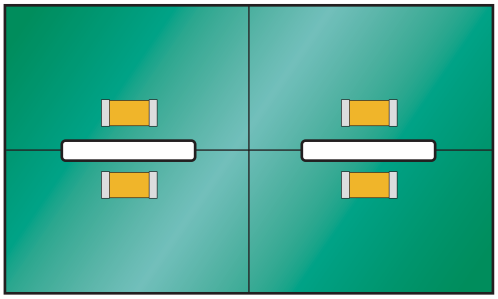
Poor Method - Direct Contact with Part

PCB BOARD DESIGN

To avoid many of the handling problems, AVX recommends that MLCs be located at least .2" away from nearest edge of board. However when this is not possible, AVX recommends that the panel be routed along the cut line, adjacent to where the MLC is located.



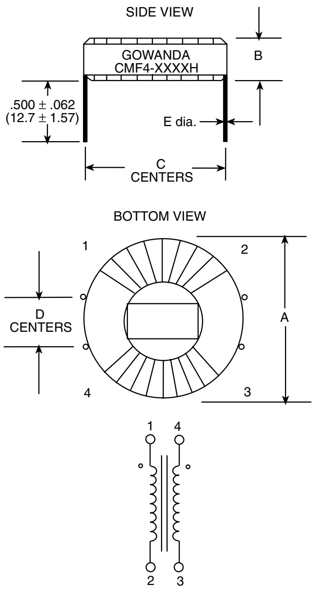
No Stress Relief for MLCs



Routed Cut Line Relieves Stress on MLC

CMF4 HLF *RoHS Horizontal Mount Common Modes*

PART NUMBER	INDUCTANCE @ 10 kHz µH ± 30%*	DCR OHMS MAX.*	CURRENT RATING AMPS	LEAKAGE L µH REF.	INTERWINDING CAPACITANCE pF REF.	A DIM. NOM.	B DIM. NOM.	C DIM. NOM.	D DIM. NOM.	E DIM. NOM.
CMF4-1003HLF	100	.0025	15.0	1.5	4.8	1.04 (26.42)	.440 (11.18)	.800 (20.32)	.300 (7.62)	.051 (1.30)
CMF4-2503HLF	250	.0038	12.0	3.2	8.0	1.04 (26.42)	.440 (11.18)	.800 (20.32)	.300 (7.62)	.051 (1.30)
CMF4-5003HLF	500	.006	10.0	5.8	9.7	1.04 (26.42)	.425 (10.80)	.800 (20.32)	.300 (7.62)	.045 (1.14)
CMF4-7503HLF	750	.013	6.7	8.0	12.0	1.00 (25.40)	.425 (10.80)	.800 (20.32)	.300 (7.62)	.036 (0.91)
CMF4-1004HLF	1000	.018	5.7	11.0	12.0	1.00 (25.40)	.400 (10.16)	.800 (20.32)	.300 (7.62)	.032 (0.81)
CMF4-1704HLF	1700	.060	3.1	22.0	11.0	.950 (24.13)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.020 (0.51)
CMF4-2504HLF	2500	.073	2.8	29.0	15.0	.950 (24.13)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.020 (0.51)
CMF4-3304HLF	3300	.125	2.2	38.0	15.0	.950 (24.13)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.016 (0.41)
CMF4-5004HLF	5000	.150	2.0	48.0	17.0	.950 (24.13)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.016 (0.41)
CMF4-7504HLF	7500	.300	1.4	80.0	20.0	.950 (24.13)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.013 (0.33)
CMF4-1005HLF	10000	.390	1.2	95.0	20.0	.935 (23.75)	.370 (9.40)	.800 (20.32)	.300 (7.62)	.011 (0.28)



in. (mm)

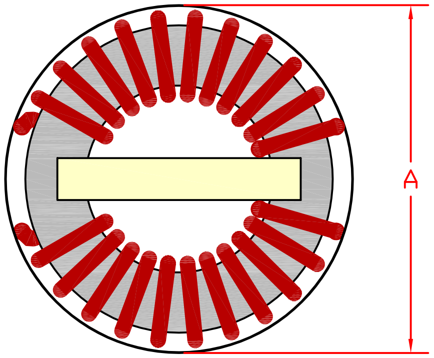
NOTES:

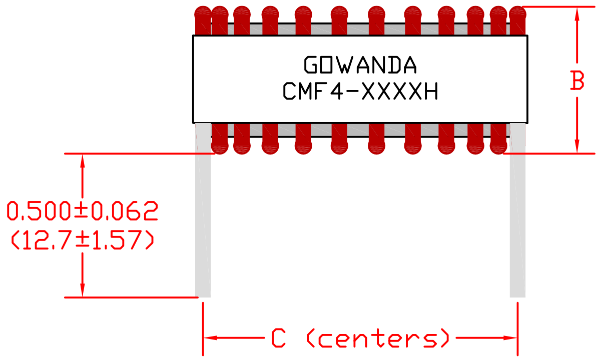
- Inductance and DCR is for each side or single winding
- Operating temperature -55°C to +125°C

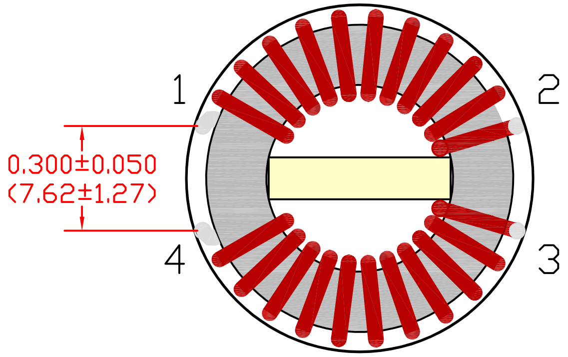
PACKAGING SPECS:

Bulk only.

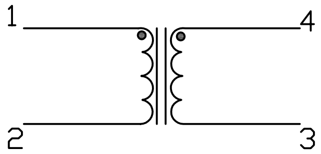
www.gowanda.com







CMF4-Horizontal Mount Common Modes				
Part Number	A Dim. Nom.	B Dim. Nom.	C Dim. ± 0.050	E Dim. Nom.
CMF4-1003H	1.040 (26.51)	0.440 (11.18)	0.900 (22.86)	0.051 (1.30)
CMF4-2503H	1.040 (26.51)	0.440 (11.18)	0.900 (22.86)	0.051 (1.30)
CMF4-5003H	1.040 (26.51)	0.425 (10.80)	0.900 (22.86)	0.045 (1.14)
CMF4-7503H	1.000 (25.40)	0.425 (10.80)	0.880 (22.35)	0.036 (0.91)
CMF4-1004H	1.000 (25.40)	0.400 (10.16)	0.880 (22.35)	0.032 (0.81)
CMF4-1704H	0.950 (24.13)	0.370 (9.40)	0.860 (21.84)	0.020 (0.51)
CMF4-2504H	0.950 (24.13)	0.370 (9.40)	0.860 (21.84)	0.020 (0.51)
CMF4-3304H	0.950 (24.13)	0.370 (9.40)	0.860 (21.84)	0.016 (0.41)
CMF4-5004H	0.950 (24.13)	0.370 (9.40)	0.860 (21.84)	0.016 (0.41)
CMF4-7504H	0.950 (24.13)	0.370 (9.40)	0.860 (21.84)	0.013 (0.33)
CMF4-1005H	0.935 (23.75)	0.370 (9.40)	0.860 (21.84)	0.011 (0.28)



Notes:
Packaging: Bulk only

NEXT ASSEM.	USED ON	LTR.	REVISION	BY	DATE

Part #: **CMF4H-Dimensional Specification**

DRAWN BY	KB	APPROVED BY	ENG KB	QA BM	MFG GG

Unless otherwise specified dimensions are in inches.

in. (mm)

GOWANDA

ONE MAGNETICS PARKWAY
P.O. BOX 111
GOWANDA, NEW YORK 14070

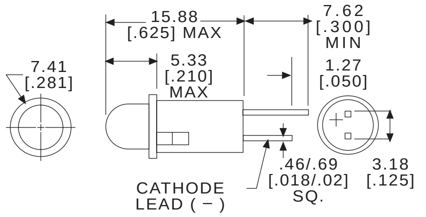
Phone Number: (716)532-2234
Website: www.gowanda.com

5mm
LED Panel Mount Indicator
5V or 12V Integral Resistor
.250” Mounting Hole, Snap In Mounting

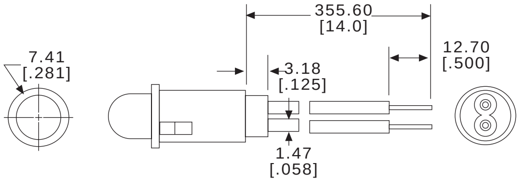
Dialight

559 Series

STRAIGHT TERMINALS – TERMINAL OPTION 1



24 AWG WIRE LEADS – TERMINAL OPTION 3 FOR 6”
TERMINAL OPTION 7 FOR 14”



NOTE: WIRE LEAD COLORS RED (ANODE)
& BLACK (CATHODE)

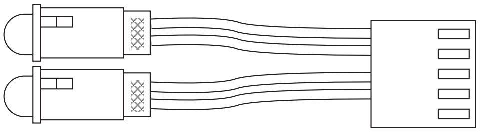
BENEFITS

- Available with a variety of LEDs
- Designed for quick positive insertions in panels from .787mm [.031] through 1.57mm [.062] thick. Recommended hole size from 6.32mm [.249] to 6.40mm [.252].
- Front panel mounting
- Uniform illumination
- Snap-in mounting requires no additional hardware
- IC compatible
- Housing meets UL94V-0
- High reliability - 100,000 hour life
- Black housing enhances LED contrast
- Straight terminals suitable for wire-wrapping

CUSTOM CAPABILITIES

Connectors and terminals can be added to wire leads

Example



Typical Operating Characteristics **(T_A=25°C)**

DIFFUSED LED

Absolute
Maximum Ratings

Part Number	Color	Termination Options	Peak Wavelength (nm)	Iv Typical (mcd)	Vf Volts (V)	If (mA)		Min Reverse Voltage	Viewing Angle 2Θ½	DC Forward Voltage	Temperature °C	
						Typ	Max				Operating	Storage
559-0102-00x	R	1,3,7	655	2	5	13	20	5	60	7.5	-40/+85	-55/+100
559-0103-00x	R	1,3,7	655	2	12	13	20	5	60	15	-40/+85	-55/+100
559-0202-00x	G	1,3,7	565	8	5	12	15	5	60	7.5	-20/+85	-55/+100
559-0203-00x	G	1,3,7	565	4	12	13	20	5	60	15	-20/+85	-55/+100
559-0302-00x	Y	1,3,7	583	8	5	10	15	5	60	7.5	-40/+85	-55/+100
559-0303-00x	Y	1,3,7	583	8	12	13	20	5	60	15	-40/+85	-55/+100

COLOR CODES:

R	Red
G	Green
Y	Yellow

PART NUMBER ORDERING CODE

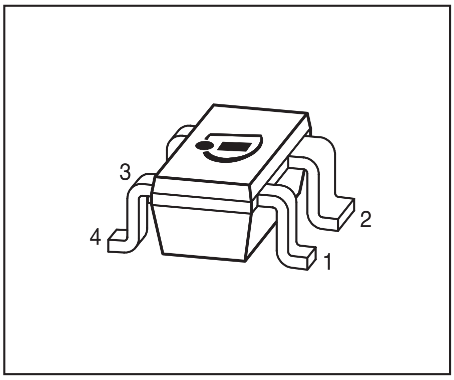
559 – XXXX – 00X

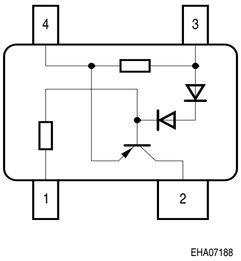
Series

Termination Option
1 = Straight Terminals
3 = 6” Wire Leads
7 = 14” Wire Leads

BCR401R

LED Driver





- Supplies stable bias current even at low battery voltage
- Suitable for PWM control up to 100kHz
- Ideal for stabilizing bias current of LEDs
- Negative temperature coefficient protects LEDs against thermal overload
- Pb-free (RoHS compliant) package[1]
- Qualified according AEC Q101

Type	Marking	Pin Configuration				Package
BCR401R	W5s	1 = GND	2 = I_{out}	3 = V_S	4 = R_{ext}	SOT143R

Maximum Ratings

Parameter	Symbol	Value	Unit
Source voltage	V_S	18	V
Output current	I_{out}	60	mA
Output voltage	V_{out}	16	V
Reverse voltage between all terminals	V_R	0.5	
Total power dissipation, T_S = 75 °C	P_{tot}	330	mW
Junction temperature	T_j	150	°C
Storage temperature	T_{stg}	-65 ... 150	

Thermal Resistance

Parameter	Symbol	Value	Unit
Junction - soldering point[2]	R_{thJS}	225	K/W

---

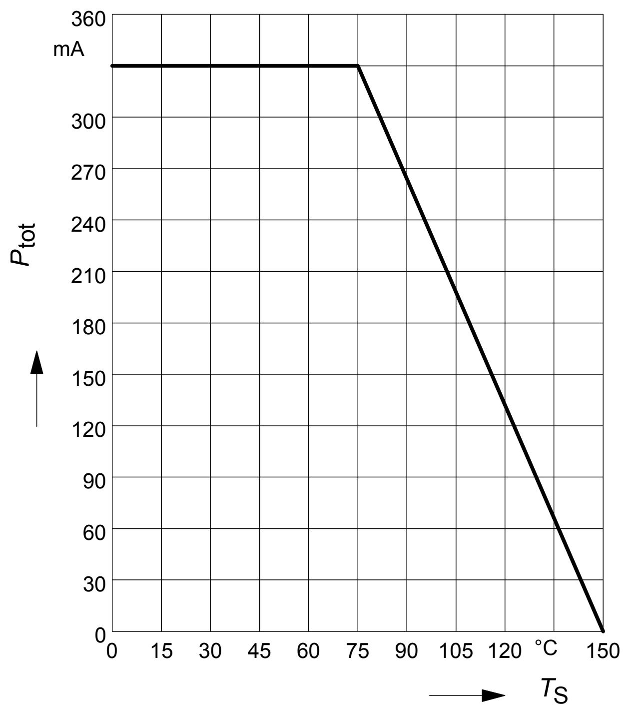
[1] Pb-containing package may be available upon special request

[2] For calculation of R_{thJA} please refer to Application Note Thermal Resistance

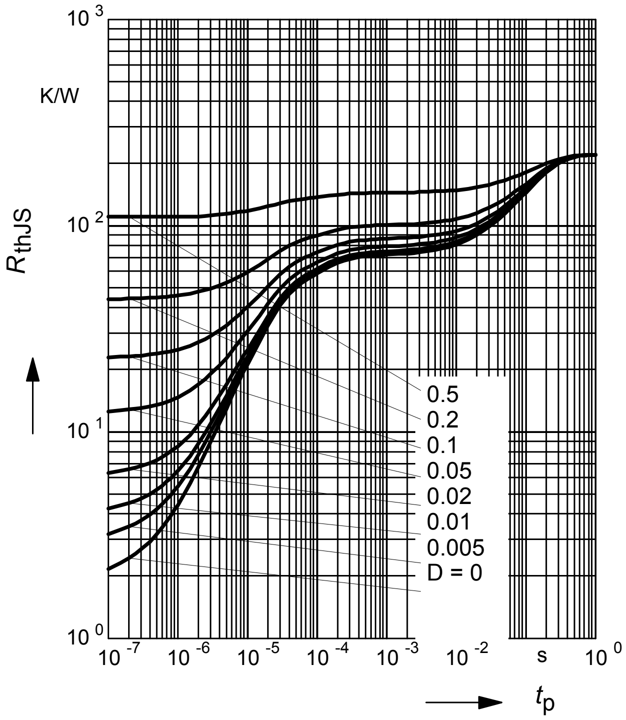
Electrical Characteristics at T_A=25°C, unless otherwise specified

Parameter	**Symbol**	**Values**			**Unit**
		min.	**typ.**	**max.**	
Characteristics					
Supply current V_S = 10 V	I_S	350	440	540	µA
Output current V_S = 10 V, V_{out} = 7.6 V	I_{out}	9	10	11	mA
DC Characteristics with stabilized LED load					
Lowest sufficient battery voltage overhead I_{out} > 8mA	V_{Smin}	-	1.2	-	V
Voltage drop (V_S - V_{CE}) I_{out} = 20 mA	V_{drop}	-	0.75	-	
Output current change versus T_A V_S = 10 V	Δ*I*out/*I*out	-	-0.3	-	%/K
Output current change versus V_S V_S = 10 V	Δ*I*out/*I*out	-	2	-	%/V

Total power dissipation $P_{tot} = f(T_S)$

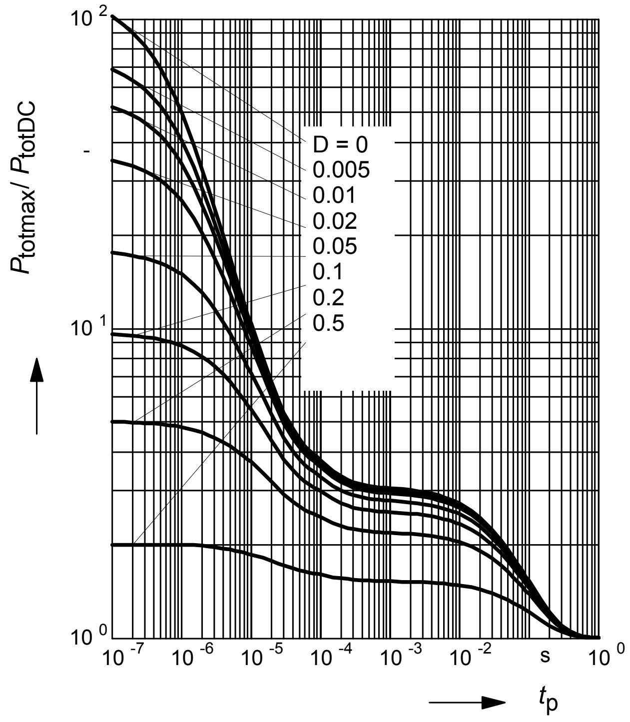


Permissible Pulse Load $R_{thJS} = f(t_p)$



Permissible Pulse Load

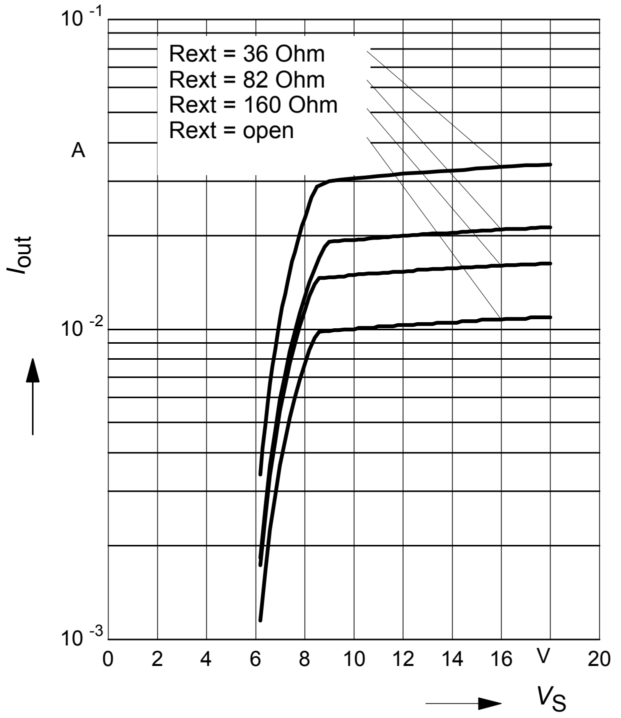
$P_{totmax} / P_{totDC} = f(t_p)$



Output current versus supply voltage

$I_{out} = f(V_S)$; R_{ext} = Parameter

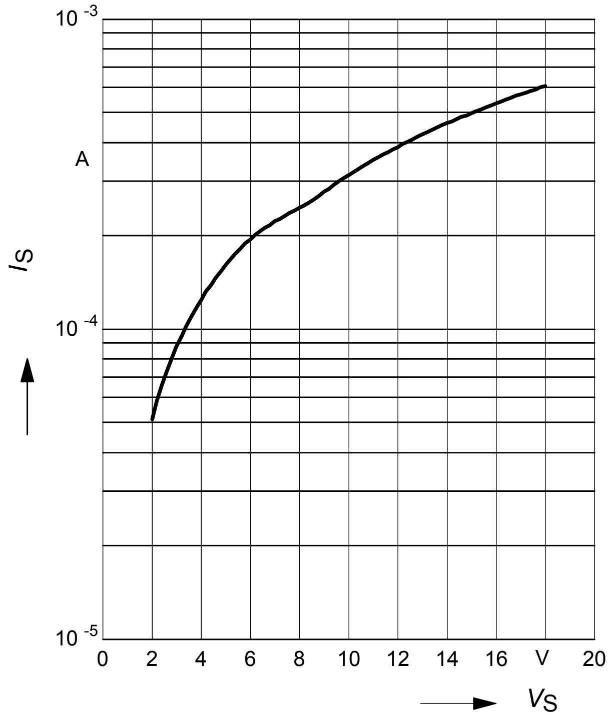
Load: two LEDs with V_F = 3.8V in series



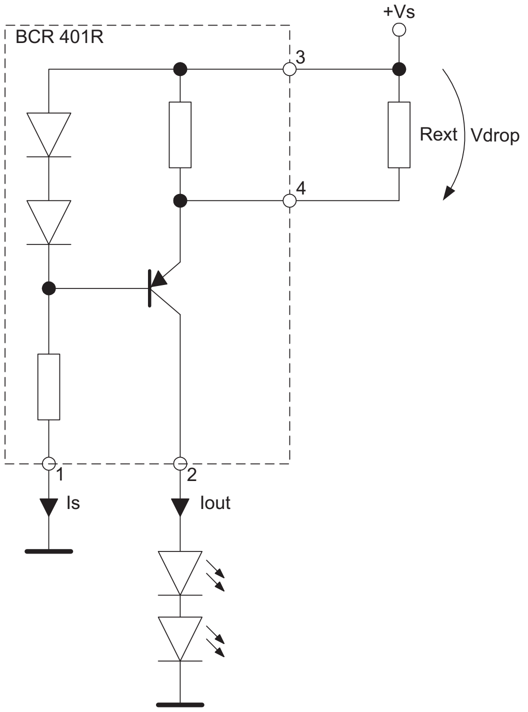
Supply current versus supply voltage

$I_S = f(V_S)$

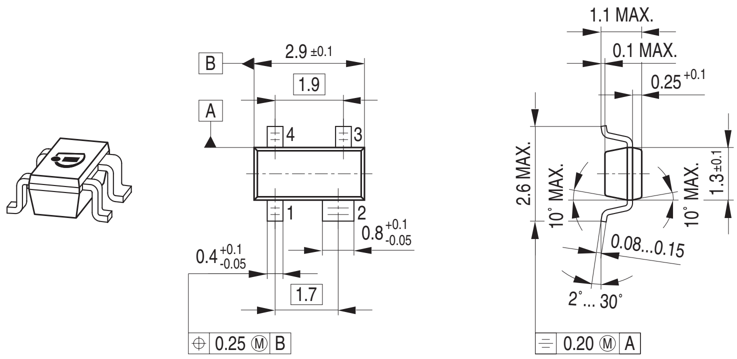
Load: two LEDs with V_F = 3.8V in series



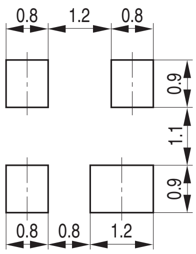
Application Circuit:



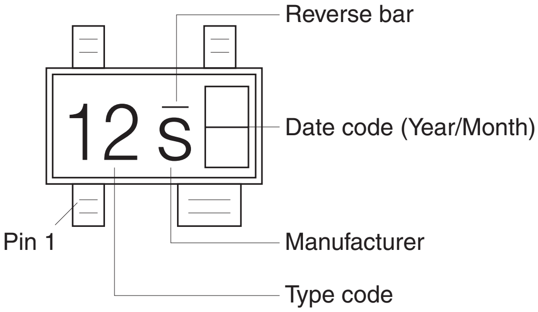
Package Outline

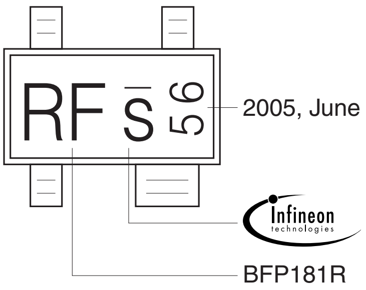


Foot Print



Marking Layout

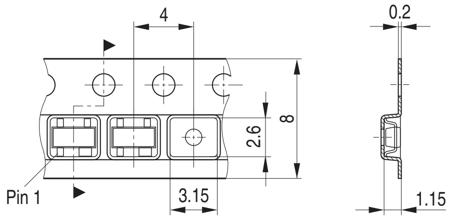




Example

Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø330 mm = 10.000 Pieces/Reel



Published by
Infineon Technologies AG
81726 München, Germany

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Cost Effective, Reduced Depth, Shielded Line Filter

SRB Series

UL Recognized
CSA Certified
VDE Approved

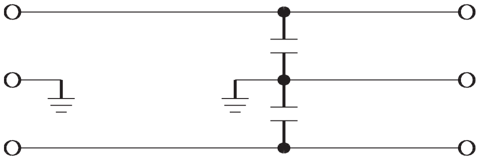
SRB Series

With one of the smallest depths available on the market today, the SRB Series features a complete shield design with various capacitance values. This unique combination offers varying levels of common mode performance which minimizes conducted emissions and may reduce radiated emissions.

The SRB Series is rated up to 15 Amps, 250 VAC.* All configurations are available unfiltered or with one of eight different capacitor values to address different performance needs. The SRB Series features a multitude of installation and termination options including flange or snap-in mounting, and quick connect terminal, wire leaded, and pin termination options. This product is ideally suited for power supplies or other applications which require a minimum depth low cost solution.

*10 Amps VDE

Electrical Schematic

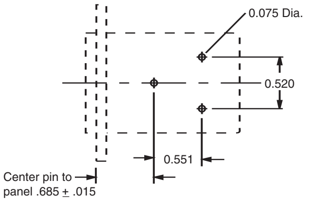


Capacitor Options

Capacitor Value Identifier	Capacitor Value
Q	33pF
R	100pF
S	220pF
T	330pF
W	470pF
X	1000pF
Y*	2200pF
Z *	3300pF

*Not available in SRB8 Styles.

PCB Layout



Specifications

Maximum leakage current,each line-to-ground

Capacitor Identifier/Value	@120 VAC 60 Hz	@250 VAC 50Hz
Blank/None	2uA	5uA
Q / 33pF	2.1uA	3.65uA
R / 100pF	9.6uA	16.6uA
S / 220pF	19.2uA	33.2uA
T / 330pF	24.0uA	41.5uA
W / 470pF	0.04mA	0.07mA
X / 1000pF	0.07mA	0.13mA
Y / 2200pF	0.16mA	0.28mA
Z / 3300pF	0.24mA	0.42mA

Hipot rating (one minute):

line-to-ground	1500 VDC
line-to-line	1450 VDC

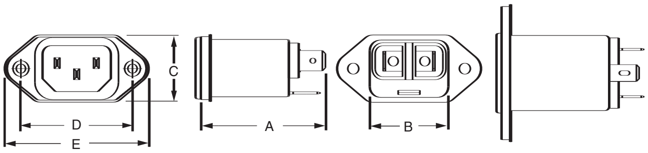
Operating frequency:	50/60 Hz
Rated voltage (max.):	250 VAC

Minimum insertion loss in dB:
Line-to-ground in 50 ohm circuit

Capacitor	Frequency Mhz					
ID	1	5	10	50	100	300
Q	-	-	-	-	-	20
R	-	-	-	3	6	22
S	-	-	1	6	17	19
T	-	-	2	13	13	19
W	-	2	4	18	13	20
X	-	5	9	25	10	17
Y	1	10	15	20	8	22
Z	2	14	18	17	7	15

Case Styles

SRB1

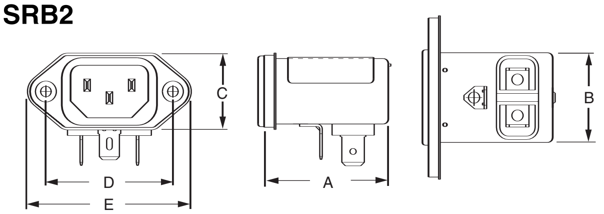


Cost Effective, Reduced Depth, Shielded Line Filter (Continued)

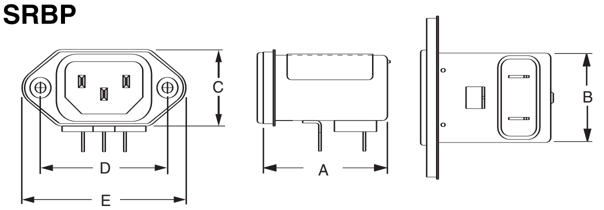
SRB Series

Case Styles (continued)

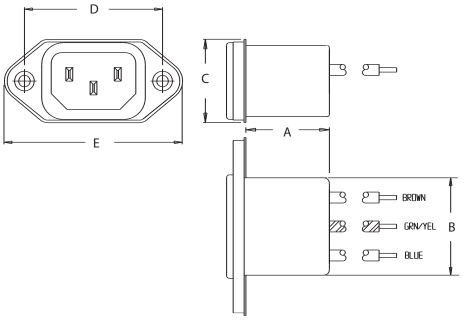
SRB2



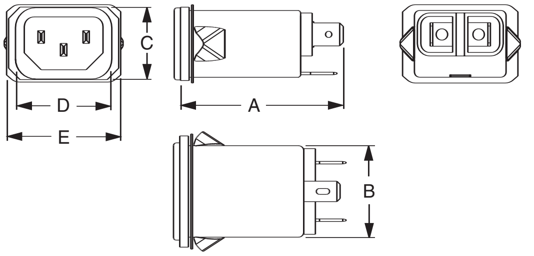
SRBP



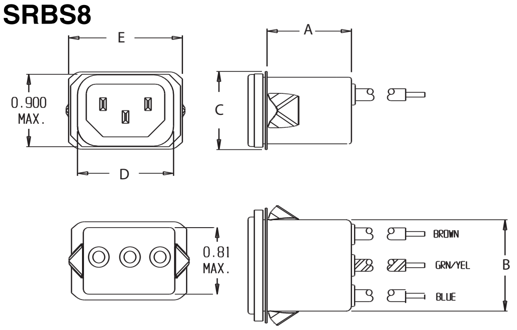
SRB8



SRBS1



SRBS8



Typical dimensions:
Terminals: .250 [*6.35*] (3) Holes: .07 [*1.8*] Dia.(2) Slot: .07 x .16 [*1.8 x 4.1*]
Mounting holes: .132 [*3.35*] Dia. (2) w/.236 Dia. x 90° countersunk for a #4 flathead screw
Style 8 wire leads: 4.0 [*101.6*] min. 1-15A, 18AWG

Case Dimensions

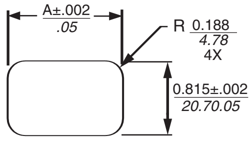
Part No.	A (max)	B (max)	C (max)	D ± .015 ± .380	E (max)
15SRB1	**1.75** *44.45*	**1.13** *28.70*	**0.96** *24.38*	**1.580** *40.00*	**2.04** *51.76*
15SRB2	**1.54** *39.12*	**1.13** *28.70*	**0.96** *24.38*	**1.58** *40.00*	**2.04** *51.76*
15SRBP	**1.54** *39.12*	**1.13** *28.70*	**0.96** *24.38*	**1.58** *40.00*	**2.04** *51.76*
15SRB8	**.94** *23.82*	**1.13** *28.70*	**0.96** *24.38*	**1.58** *40.00*	**2.04** *51.76*
15SRBS1	**1.75** *44.45*	**1.13** *28.70*	**0.96** *24.38*	**1.19** *30.10*	**1.41** *35.81*
15SRBS8	**1.12** *28.45*	**1.13** *28.70*	**0.96** *24.38*	**1.19** *30.10*	**1.41** *35.81*

Part Numbers

15SRB1
15SRBS1
15SRB2
15SRB8
15SRBS8
15SRBP
15SRB1-Q
15SRBS1-Q
15SRB2-Q
15SRB8-Q
15SRBS8-Q
15SRBP-Q
15SRB1-R
15SRBS1-R
15SRB2-R
15SRB8-R
15SRBS8-R
15SRBP-R
15SRB1-S
15SRBS1-S
15SRB2-S
15SRB8-S
15SRBS8-S
15SRBP-S
15SRB1-T
15SRBS1-T
15SRB2-T
15SRB8-T
15SRBS8-T
15SRBP-T
15SRB1-W
15SRBS1-W
15SRB2-W
15SRB8-W
15SRBS8-W
15SRBP-W
15SRB1-X
15SRBS1-X
15SRB2-X
15SRB8-X
15SRBS8-X
15SRBP-X
15SRB1-Y
15SRBS1-Y
15SRB2-Y
15SRBP-Y
15SRB1-Z
15SRBS1-Z
15SRB2-Z
15SRBP-Z

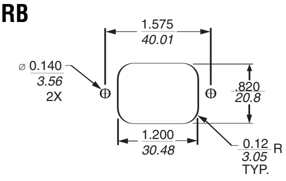
Recommended Panel Cutouts

SRBS

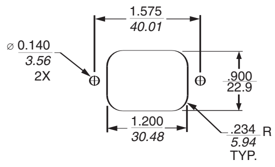


Panel Thickness	A Dim. ±.002
.031-.052 [*.79-1.32*]	1.260 [*32.00*]
0.046-0.068 [*1.17-1.73*]	1.350 [*34.29*]

SRB



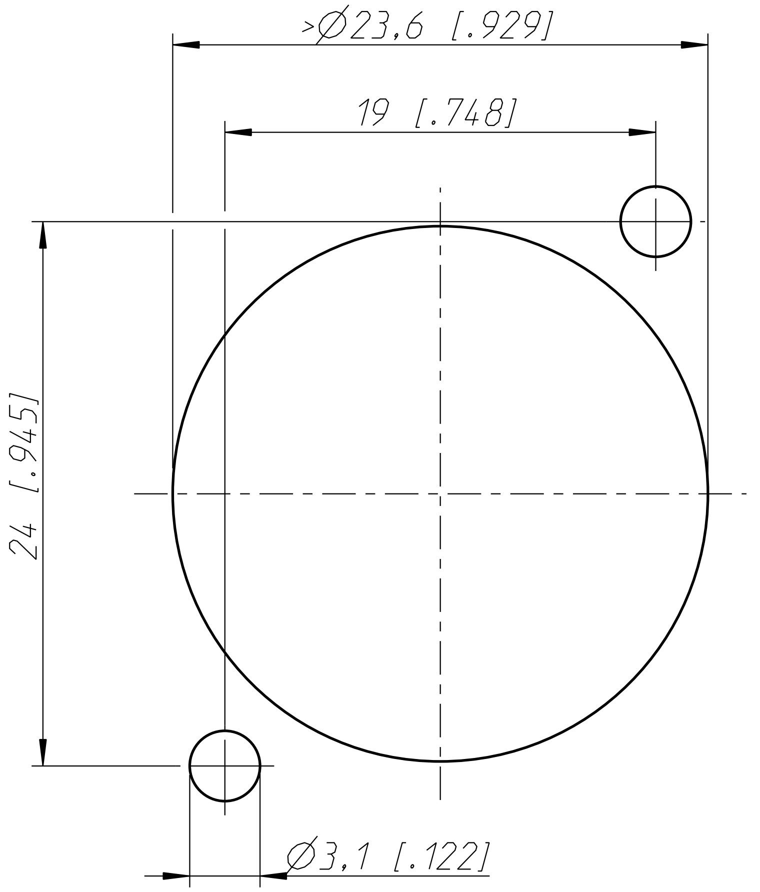
Panel Cutout (front mount)

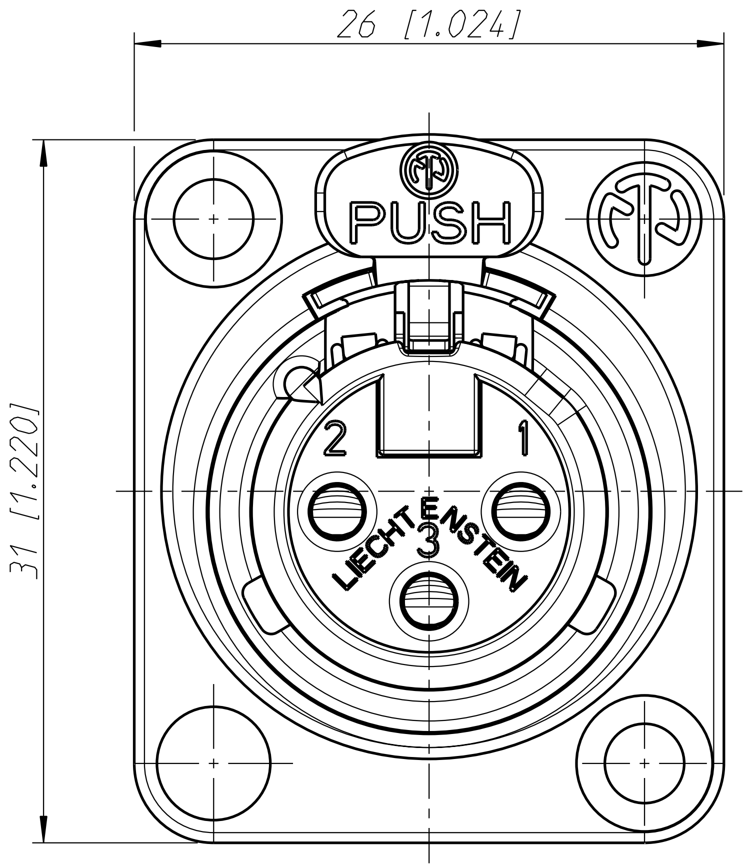


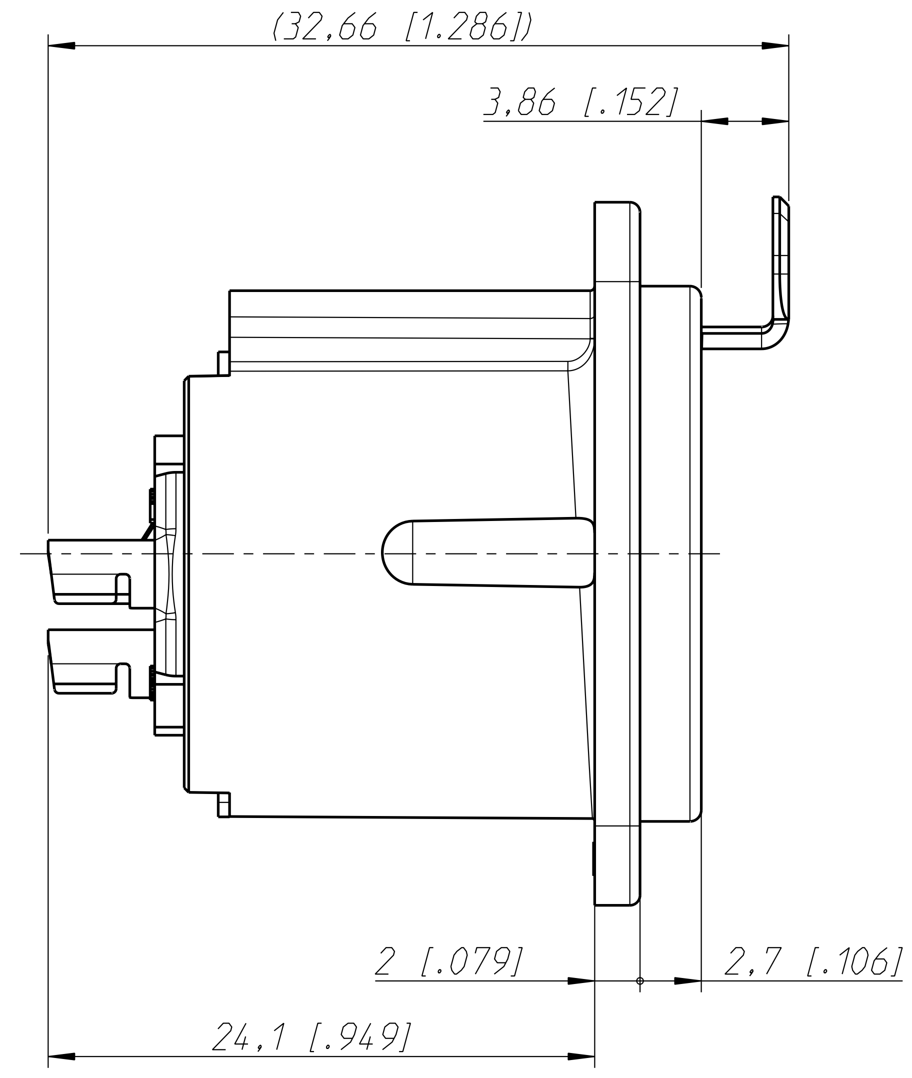
Panel Cutout (back mount)

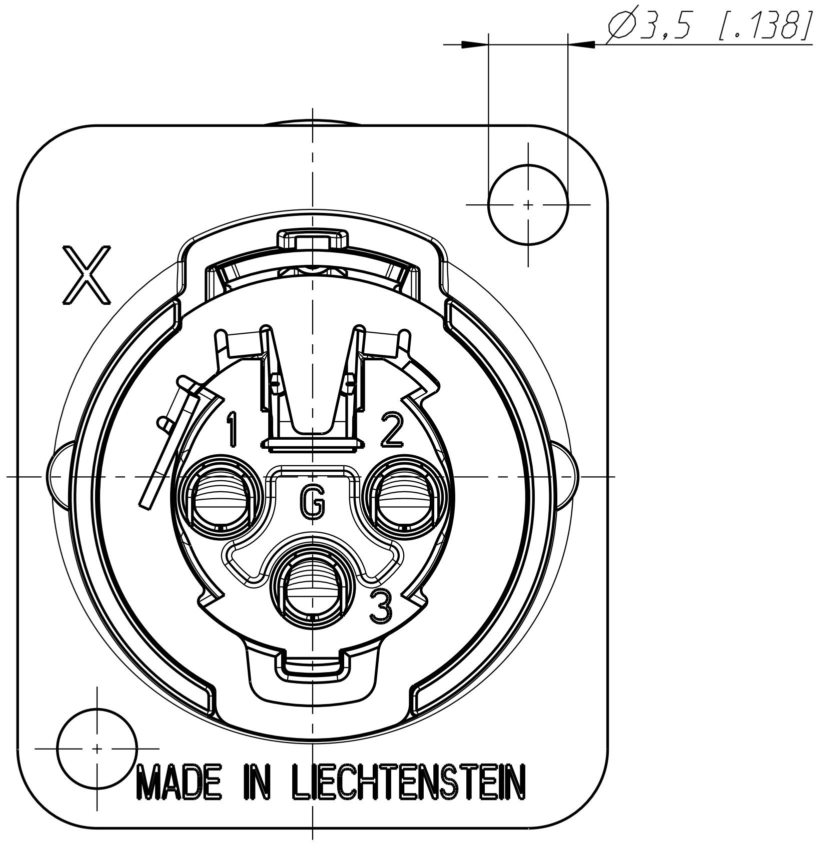
Notes:
Tolerance ± .005 [0.13]
Panel Thickness .031-.047 [.78-1.19]
SRB1 and SRB8 styles allow for front or back mounting
SRB2 and SRBP allow for back mounting only

Frontplattenausschnitt (Rückseite)
panel cut out (rear side)









Allgemeintoleranzen ISO 2768-m	Werkstoff	Massstab:		Datum	Name
	KEIN_MAT	3:1	Gezeichnet	19.06.06	Ender
Zeichnung urheberrechtlich geschuetzt (DIN 34) (C)	-	(A3)	Freigegeben	-	-
			Geaendert	-	-
Benennung NC3FD-LX NC3FD-LX			Aend.-Nr. -		Aend.-Index
			Ersatz fuer:		Blatt 1 von 1 Bl.
NEUTRIK AG FL-9494 SCHAAN			Zeichn. Nr. ST-NC3FD-LX		