12. Systems Engineering

There are two systems level considerations presented in this chapter. The first concept is power and the second concept is manufacturability.

12.1. Power

12.1.1. Power System Specification

There are three elements of a power efficient system definition. First, we need to make a **Power Budget**. This means we determine the maximum amount of power that can be supported by the power source. Second, we need to identify and analyze required system tasks. This means we determine the tasks that need to be performed by the system and estimate the power required to perform these tasks. It is important to consider timing of the tasks and synchronization to I/O events. For example executing about once a second (e.g., smoke detector checking for fires) will require less power than executing exactly once a second (digital watch). The third element is to develop a **power strategy**. Having a strategy for power helps the power needed to perform the required system tasks to fit within the power budget.

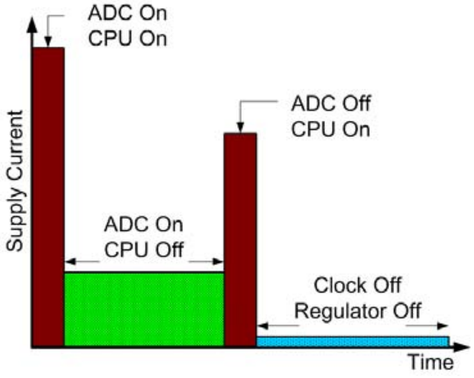
A **Power Budget** is a quick first order calculation that gives you a ballpark figure of the “total average current” supported by your power source. From the system specifications we are given how long the system must operate without replacing batteries, $\mathbf{t_{life}}$ in hours. From the battery datasheet we determine the storage capacity of the battery, **E** in mA-hours. Be aware, however, that for many batteries the storage capacity depends also on current.

Average Current must be less than $\mathbf{E/\ t_{life}}$

12.1.2. Power System Design

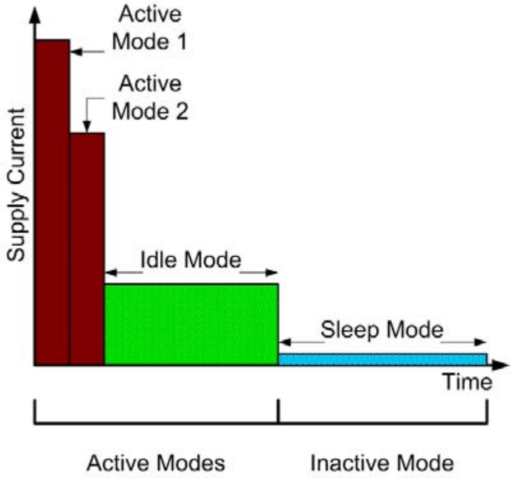
Designing a power efficient embedded system has three key elements. First, we must select a power efficient microcontroller. Some power efficient features include low-voltage RAM retention, reduced current digital outputs, performing I/O in sleep mode, low power real-time clocks, and fast wakeup from sleep mode. For example, sometimes we wish to wakeup approximately once 1 second. This type of clock can be lower power than a clock that wakes up exactly once a second. Second, we must design power efficient hardware. This means choosing lower power parts and creating mechanisms to dynamically use power only when necessary. Choose sensors and other components that have a quick turn on time and a low standby current. The quick turn on time allows the system to spend less time in “Active Mode”. The low standby current allows the system to be power efficient. Examples include devices powered by a Port I/O pin, and devices with a “shutdown” pin. Third, we must write power efficient software. Each application has a set of required tasks. For example, an application can have the following task list.

- Initiate an ADC sample.
- Wait for conversion to complete.
- Perform post-sample processing and print result to a Terminal or LCD.
- Enter a low power mode.

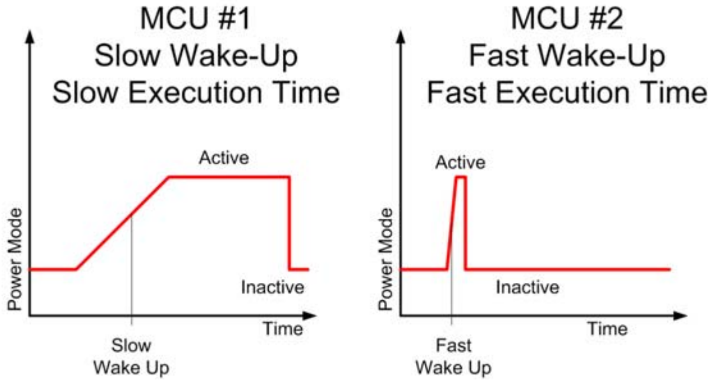


The required tasks can be used to create a custom charge utilization profile. “Average current” is proportional to the “area” under the charge utilization profile. Most systems will have at least 2 power modes. Active modes are when the microcomputer is performing required tasks. There can be more than one active mode. Inactive modes are when the microcomputer is not performing tasks, thus conserving energy. When synchronizing to I/O, there are two possibilities to minimize power

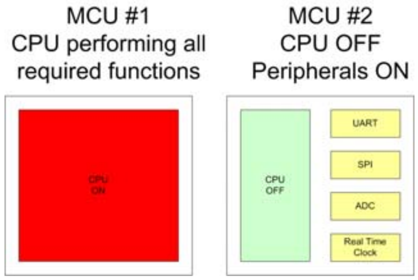
Busy-wait synchronization: slow CPU clock to as slow as it will go to finish tasks on time.
Interrupt synchronization: run at maximum CPU clock and go to sleep while waiting.



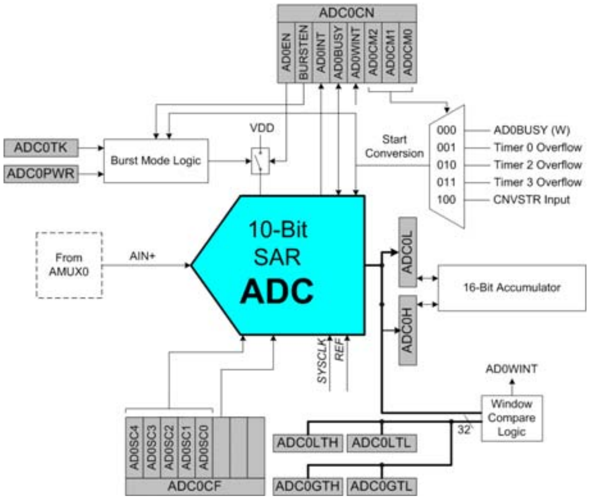
A fast wakeup time and fast code execution allow the system to minimize the time spent in active mode and maximize the time spent in the inactive mode. ADCs typically consume a significant amount of power when enabled. The best power saving strategy when using an ADC is to turn it on, take the required samples, then turn it back off as quickly as possible. Fast acquisition time is determined by VREF turn-on time and ADC sample acquisition time. Since most MCUs cannot be in the lowest power mode when acquiring samples, faster acquisition time allows the system to spend more time sleeping resulting in a reduced average current.



The CPU is the largest contributor to overall power consumption. If hardware has peripherals that work autonomously, the CPU can remain “OFF” for a longer period of time. Two methods to reduce power. First, turn off devices not needed. Second, select a microcontroller that allows I/O activity to occur while the processor is sleeping.



For example, the Silicon Labs C8051F9xx C8051F9xx microcontroller has a burst mode allowing the ADC to autonomously capture and sum up to 64 samples for each convert start received. The ADC uses an independent clock when in Burst Mode.



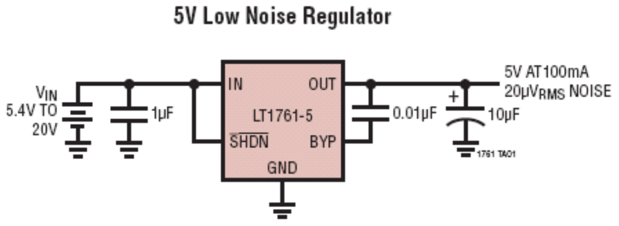
The C8051F9xx Family has three inactive modes

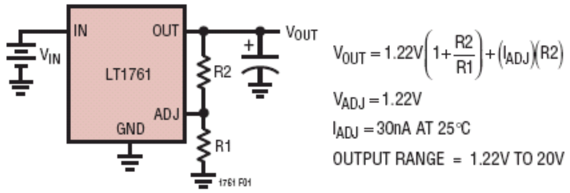
Mode	Functionality	Wakeup	Typical Supply Current
Stop	Clock Stopped	Reset	~ 75 μA
Suspend	System Clock Suspended	SmaRTClock Port Match Comparator0	~75 μA
Sleep	Internal Regulator Shutdown, RAM is preserved.	SmaRTClock Port Match Comparator0*	w/ smaRTClock 0.6 μA w/o smaRTClock 50 nA

*In Sleep Mode, Comparator0 can only be used as a wakeup source in two-cell mode.

12.1.3. Regulator

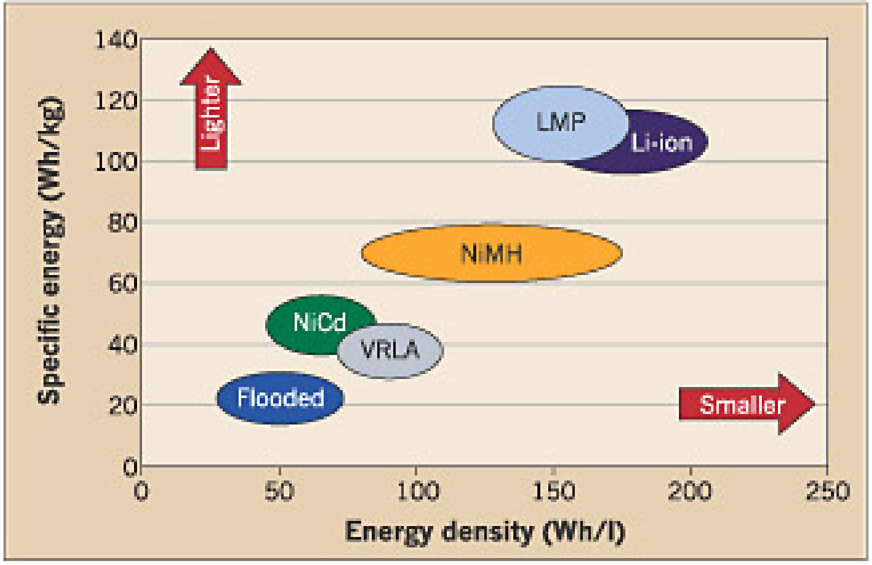
The LT1761 is a regulator with a digital enable pin. It comes in fixed voltage outputs, e.g., the +5V regulator on the left and a variable output on the right. The output voltage can be designed by selecting the R1 and R2 resistors. The SHDN pin is used to put the LT1761 regulators into a low power shutdown state. The output will be off when the SHDN pin is pulled low. The SHDN pin can be driven either by 5V logic or open-collector logic with a pull-up resistor. The pull-up resistor is required to supply the pull-up current of the open-collector gate, normally several microamperes, and the SHDN pin current, typically 1μA. If unused, the SHDN pin must be connected to VIN. The external capacitance of the load circuits will determine the time it takes to switch from low-power to active mode.





12.1.4. Battery Power

A *battery* is a source of energy that can be used in an embedded system to make the system portable. Another application of batteries is to supply power to a mission-critical system when the regular AC power is lost temporarily. Typically, a battery has three parts. The anode is the negative terminal of the battery, the cathode is the positive terminal and the electrolyte is a liquid solution that accepts stores and releases energy. These three components can be constructed from many different materials and configured in an almost endless array of sizes and shapes. The type, size and shape of the materials play a major role in determining the battery performance. A *primary battery* is used once and discarded, and a *secondary battery* can be recharged and reused.



There are many parameters to consider when selecting a battery. *Nominal voltage* is the typical voltage of the battery when fully charged. Some batteries maintain a fairly constant voltage output while energy is being discharged. However, other batteries will drop its voltage steadily during usage. Physical parameters of the battery, such as *volume*, *weight*, and *shape*, often play a significant role in the overall appeal of an embedded system. The *energy storage* of a battery is typically defined in amp-hours, because the voltage is assumed constant. The standard units of energy are watt-hours (1 W-hr is 3600 J). One can estimate the operation time of a battery-powered embedded system by dividing the energy storage by the required current to run the system. *Peak current* is the maximum current the battery can deliver. Shelf-life, operating temperature, and storage temperature are other parameters to consider when choosing a battery. *Memory effect*, is an observable condition in some rechargeable batteries that causes them to hold less charge over time.

Heavy duty batteries, were first made with Zinc-carbon in the mid-1800's, but now are made with Zinc chloride. They are a low cost, low performance battery, but are not appropriate for most embedded applications. An *alkaline* battery is made with alkaline manganese. Alkaline batteries are appropriate for situations that require long shelf life, but size and weight are not important. There are two kinds of *lead acid* batteries. Flooded lead acid vent inflammable gasses and require additional water to maintain the proper specific gravity of the acid. Valve-regulated lead-acid (VRLA also called sealed lead battery) have about a two-to-one advantage over the flooded type battery in specific energy and energy density. In the VRLA cell, the vent for the gas space incorporates a pressure relief valve to minimize the gas loss and to prevent direct contact between the headspace and outside air. Lead acid batteries can be used for backing up power on systems that require large currents. Lead acid batteries have a maximum storage time of six months at temperatures between 20°C and 30°C, after which they require a freshening charge. Zinc chloride, alkaline and lead acid batteries all have voltages that drop as energy is drained from them (see following figure). In these systems the voltage can be monitored as a measure of the energy left in the battery. However, embedded systems that use these types of battery will require a voltage regulator to maintain a constant voltage for the electronics. For example, a +5V 9S12DP512 will operate with a power supply voltage from 4.5 to 5.25 V. The curve on the left is a BR1225 Lithium battery, which maintains a constant voltage until 85-90% of the energy is discharged.

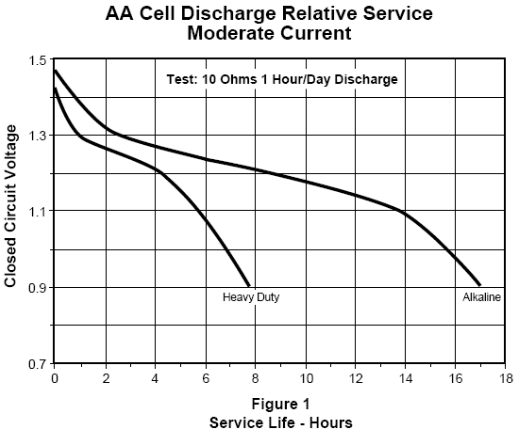
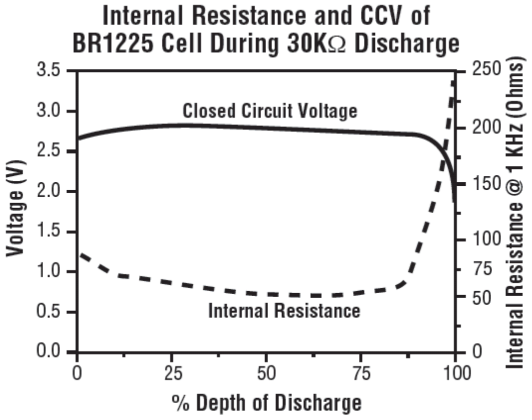
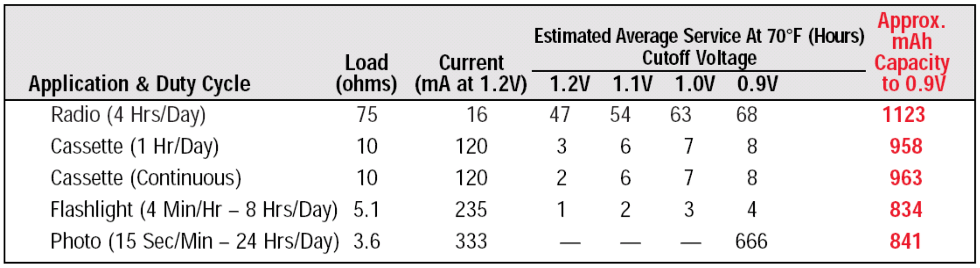


Figure 1



Notice also that more power energy can be extracted from an alkaline battery when it is used in a low constant current application, such as a radio. This data is for a AAA alkaline from Rayovac®.



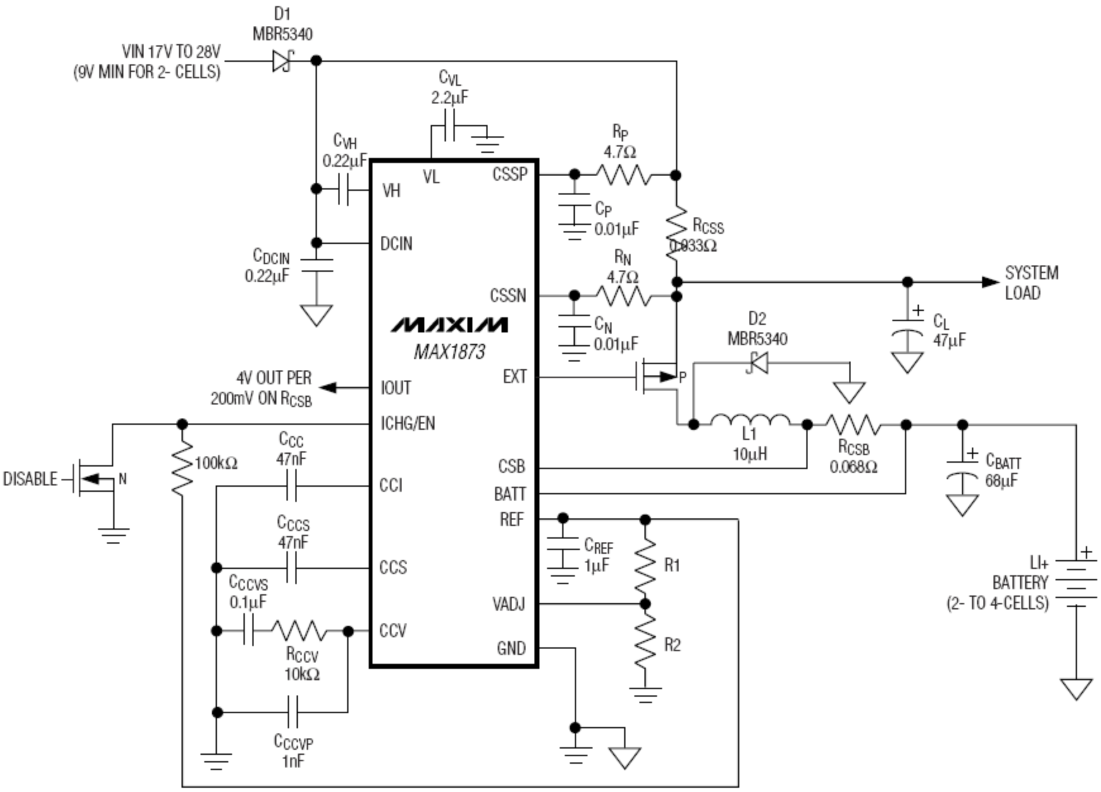
Application & Duty Cycle	Load (ohms)	Current (mA at 1.2V)	Estimated Average Service At 70°F (Hours) Cutoff Voltage 1.2V	1.1V	1.0V	0.9V	Approx. mAh Capacity to 0.9V
Radio (4 Hrs/Day)	75	16	47	54	63	68	1123
Cassette (1 Hr/Day)	10	120	3	6	7	8	958
Cassette (Continuous)	10	120	2	6	7	8	963
Flashlight (4 Min/Hr – 8 Hrs/Day)	5.1	235	1	2	3	4	834
Photo (15 Sec/Min – 24 Hrs/Day)	3.6	333	—	—	—	666	841

Nickel-cadmium (NiCad) and *Nickel-metal hydride* (NiMH) are lost-cost rechargeable batteries that used to be popular for embedded systems. NiMH batteries have about twice the storage capacity as NiCad. Certain NiCd batteries gradually lose their maximum energy capacity if they are repeatedly recharged after being only partially discharged. Most NiMH batteries do not suffer from a memory-effect. The NiMH batteries operate between 10 °C to 55 °C, and have a projected life of seven and a half years at 30 °C. You should cycle new NiMH batteries three to five times to achieve peak performance. Cycling or conditioning a NiMH battery is performed by completely discharging it then completely recharging it. At room temperature, NiMH batteries will self-discharge in 30 to 60 days without usage, depending on environmental condition. In general, you can expect NiMH batteries to last up to 500 recharges.

The search for a lighter battery that uses metallic lithium as its anode was driven by the fact that lithium is the lightest and the most electropositive of metals. The specific energy of lithium metal (1727Ah/lb) is greater than lead (118Ah/lb) and cadmium (218Ah/lb). There are a whole range of batteries based on Lithium, both single use (used in cameras) and rechargeable. The most common rechargeable type is called *Lithium-ion* (Li-ion). When energy is being discharged, the lithium ion moves from the anode to the cathode. During charging, the lithium ion moves from the cathode to the anode. Because of their excellent energy to weight and energy to size ratios, Lithium-ion rechargeable batteries are commonly employed in portable embedded systems. Table A3.4 shows energy storage for typical AA-sized batteries (50 mm tall by 14 mm diameter).

Battery	Voltage (V)	Energy (mAh)	Type
Alkaline	1.5	2000	Primary
Lithium	1.5	3000	Primary
NiCad	1.2	1200	Secondary
NiMH	1.2	1800	Secondary
Li-ion	3.6	1900	Secondary

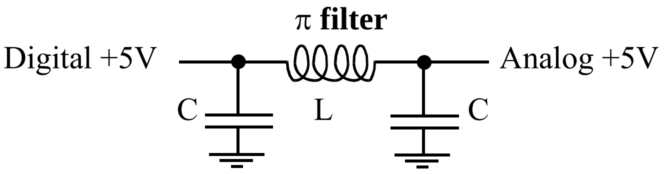
Table 12.4. Energy storage for different battery types.



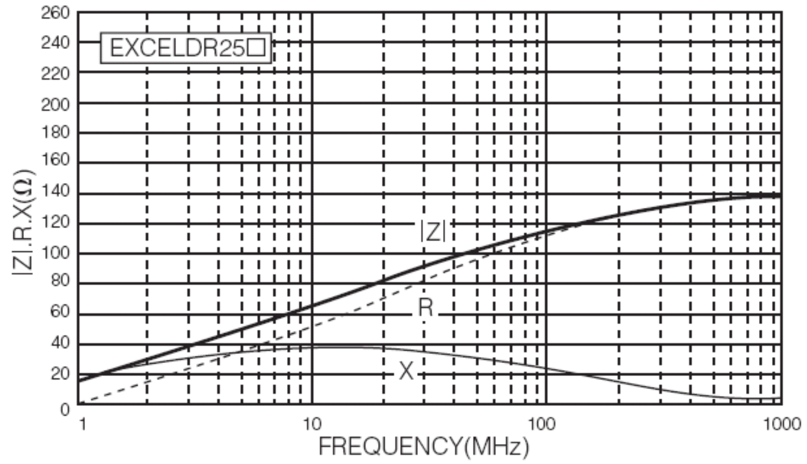
http://www.engineersedge.com/battery/battery_knowledge_menu.shtml

12.1.5. Power line noise

A **CLC filter** can be used to create a blocking filter to separate current spikes generated by digital logic from becoming voltage noise on analog power lines. This filter is also called a π filter.



For the inductor, one can use a ferrite bead. At DC the bead is essentially a short current. The ferrite bead increases both its real and reactive impedance at high frequencies. The bead should be selected to have a large impedance at the digital clock frequency. Panasonic makes a series of ferrite beads. In the following figure, X is the reactance (in Ω), determined by the magnitude |jωL|. R is the real part of the resistance (also in Ω), which also increase with frequency. |Z| is the overall impedance. The Panasonic EXC-ELDR25C has a DC resistance of 0.08 Ω, can conduct 7A DC, but has an 80-Ω impedance at 24 MHz.



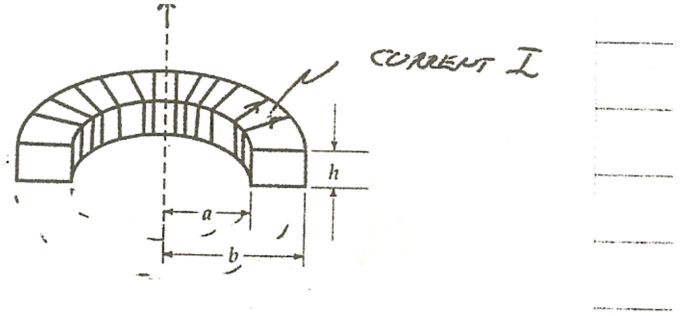
Another way to create the ferrite bead is to use a torroid and wrap around the coil effectively creating the inductance. We can use Ampere's Law to show the magnetic field created by the current is

$$\vec{B} = \begin{cases} \dfrac{\mu_0 NI}{2\pi r}\hat{\phi} & \text{for r inside torroid} \\ 0 & \text{for r outside torroid} \end{cases}$$

Assuming the torroid has a rectangular cross section, we can calculate the inductance to be

$$L = \frac{\mu_0 N^2 h \ln(b/a)}{2\pi}$$

where N is the number of turns, a is the inside radius, b is the outside radius, and h is the height of the torroid.



12.1.6. References

http://www.rayovac.com/technical/pdfs/pg_battery.pdf
http://www.rayovac.com/technical/pdfs/pg_lithium.pdf
http://data.energizer.com/PDFs/carbonzinc_appman.pdf
http://ecmweb.com/mag/electric_selecting_right_battery_2/
"The Impact of Lithium-Metal-Polymer Battery Characteristics on Telecom Power System Design."
The impact of lithium-metal-polymer battery characteristics on telecom power system design
Robillard, C.; Vallee, A.; Wilkinson, H.
Telecommunications Energy Conference, 2004. INTELEC 2004. 26th Annual International
Volume , Issue , 19-23 Sept. 2004 Page(s): 25 – 31
Aug 1, 2005 12:00 PM, By Alexander Kusko, Sc.D, P.E., Exponent, Inc., and John DeDad, Editorial Director
http://www.panasonic.com/industrial/components/pdf/AEH0000CE7.pdf

12.2. Design for Manufacturability

12.2.1. Resistors

Using standard values for resistors and capacitors makes finding parts quicker. Standard values for 1% resistors range from 10 Ω to 2.2 MΩ. We can multiply a number in Table 12.1 by powers of 10 to select a standard value 1% resistor. For example, if we need a 5 kΩ 1% resistor, the closest number is 49.9*100, or 4.99 kΩ.

10.0	10.2	10.5	10.7	11.0	11.3	11.5	11.8	12.1	12.4	12.7	13.0
13.3	13.7	14.0	14.3	14.7	15.0	15.4	15.8	16.2	16.5	16.9	17.4
17.8	18.2	18.7	19.1	19.6	20.0	20.5	21.0	21.5	22.1	22.6	23.2
23.7	24.3	24.9	25.5	26.1	26.7	27.4	28.0	28.7	29.4	30.1	30.9
31.6	32.4	33.2	34.0	34.8	35.7	36.5	37.4	38.3	39.2	40.2	41.2
42.2	43.2	44.2	45.3	46.4	47.5	48.7	49.9	51.1	52.3	53.6	54.9
56.2	57.6	59.0	60.4	61.9	63.4	64.9	66.5	68.1	69.8	71.5	73.2
75.0	76.8	78.7	80.6	82.5	84.5	86.6	88.7	90.9	93.1	95.3	97.6

Table 12.1. Standard resistor values for 1% tolerance

Standard values for 5% resistors range from 10 Ω to 22 MΩ. We can multiply a number in Table 12.2 by powers of 10 to select a standard value 5% resistor. For example, if we need a 25 kΩ 5% resistor, the closest number is 24*1000, or 24 kΩ. Table 12.3 shows standard capacitor values.

10	11	12	13	15	16	18	20	22	24	27	30
33	36	39	43	47	51	56	62	68	75	82	91

Table 12.2. Standard resistor values for 5% tolerance

12.2.3 Capacitors

10pF	100pF	1000pF	0.010μF	0.10μF	1.0μF	10μF
12pF	120pF	1200pF	0.012μF	0.12μF	1.2μF	
15pF	150pF	1500pF	0.015μF	0.15μF	1.5μF	
18pF	180pF	1800pF	0.018μF	0.18μF	1.8μF	
22pF	220pF	2200pF	0.022μF	0.22μF	2.2μF	22μF
27pF	270pF	2700pF	0.027μF	0.27μF	2.7μF	
33pF	330pF	3300pF	0.033μF	0.33μF	3.3μF	33μF
39pF	390pF	3900pF	0.039μF	0.39μF	3.9μF	
47pF	470pF	4700pF	0.047μF	0.47μF	4.7μF	47uF
56pF	560pF	5600pF	0.056μF	0.56μF	5.6μF	
68pF	680pF	6800pF	0.068μF	0.68μF	6.8μF	
82pF	820pF	8200pF	0.082μF	0.82μF	8.2μF	

Table 12.3. Standard capacitor values for 10% tolerance

12.2.3. Places to get samples

Parts
Analog Devices http://www.analog.com/en/index.html
Maxim IC, http://www.maxim-ic.com/
Texas Instruments, http://www.ti.com
Connectors
SamTec, http://www.samtec.com/index.aspx
Enclosures
PacTec, http://www.pactecenclosures.com/

12.2.4. ANSI Hardware

Screw Size	Class Thread	Major Diameter			Pitch Diameter			Minor Diameter
		Basic	Max.	Min.	Basic	Max.	Min.	Max.
0-80	2A	0.06	0.0595	0.0563	0.0519	0.0514	0.0496	0.0442
0-80	3A	0.06	0.06	0.0568	0.0519	0.0519	0.0506	0.0447
1-64.	2A	0.073	0.0724	0.0686	0.0629	0.0623	0.0603	0.0532
1-64.	3A	0.073	0.073	0.0692	0.0629	0.0629	0.0614	0.0538
1-72.	2A	0.073	0.0724	0.0689	0.064	0.0634	0.0615	0.0554
1-72.	3A	0.073	0.073	0.0695	0.064	0.064	0.0626	0.056
2-56.	2A	0.086	0.0854	0.0813	0.0744	0.0738	0.0717	0.0635
2-56.	3A	0.086	0.086	0.0819	0.0744	0.0744	0.0728	0.0641
2-64.	2A	0.086	0.0854	0.0816	0.0759	0.0753	0.0733	0.0662
2-64.	3A	0.086	0.086	0.0822	0.0759	0.0759	0.0744	0.0668
3-48.	2A	0.099	0.0983	0.0938	0.0855	0.0848	0.0825	0.0727
3-48.	3A	0.099	0.099	0.0945	0.0855	0.0855	0.0838	0.0734
3-56.	2A	0.099	0.0983	0.0942	0.0874	0.0867	0.0845	0.0764
3-56.	3A	0.099	0.099	0.0949	0.0874	0.0874	0.0858	0.0771
4-40.	2A	0.112	0.1112	0.1061	0.0958	0.095	0.0925	0.0805
4-40.	3A	0.112	0.112	0.1069	0.0958	0.0958	0.0939	0.0813
4-48.	2A	0.112	0.1113	0.1068	0.0985	0.0978	0.0954	0.0857
4-48.	3A	0.112	0.112	0.1075	0.0985	0.0985	0.0967	0.0864
5-40.	2A	0.125	0.1242	0.1191	0.1088	0.108	0.1054	0.0935
5-40.	3A	0.125	0.125	0.1199	0.1088	0.1088	0.1069	0.0943
5-44.	2A	0.125	0.1243	0.1195	0.1102	0.1095	0.107	0.0964
5-44.	3A	0.125	0.125	0.1202	0.1102	0.1102	0.1083	0.0971
6-32.	2A	0.138	0.1372	0.1312	0.1177	0.1169	0.1141	0.0989
6-32.	3A	0.138	0.138	0.132	0.1177	0.1177	0.1156	0.0997
6-40.	2A	0.138	0.1372	0.1321	0.1218	0.121	0.1184	0.1065
6-40.	3A	0.138	0.138	0.1329	0.1218	0.1218	0.1198	0.1073
8-32.	2A	0.164	0.1631	0.1571	0.1437	0.1428	0.1399	0.1248
8-32.	3A	0.164	0.164	0.158	0.1437	0.1437	0.1415	0.1257

http://www.engineersedge.com/Design_Data.shtml
http://www.engineersedge.com/ansi_hardware_menu.shtml
http://www.engineersedge.com/screw_threads_chart.htm