THE GRAVITY, HEAT & SOUND CONTROLLED MAGIC E-CANDLE FOR ROMANTIC DINING EXPERIENCES.

H. Holden. April 2025.

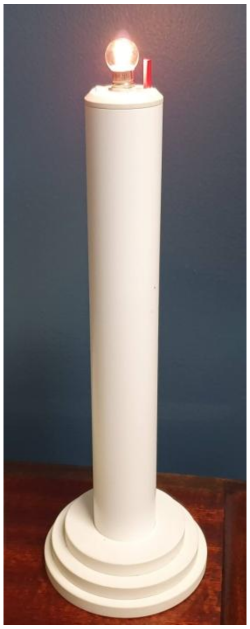
INTRODUCTION:

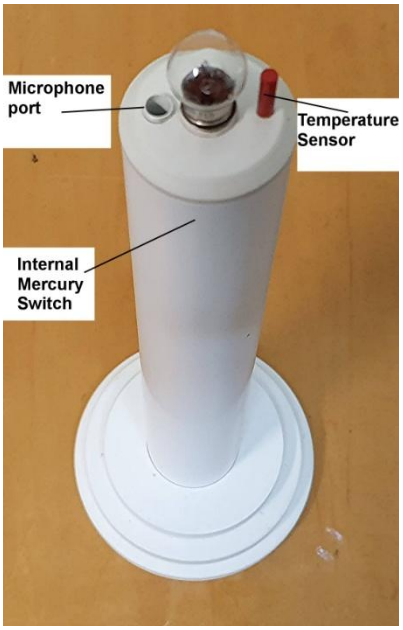
After the invention of the Transistor at Bell Labs in 1948, many portable battery powered projects became possible that were previously impractical with Vacuum Tubes. Various projects appeared in hobby magazines in the 1950's to 1970's era using transistors in different roles.

One such project used a small light bulb to simulate a Wax Candle. You could activate it with a burning Match or Cigarette lighter held near the Lamp and then blow it out (switch it off) with your breath, in the same manner that you blow out a real Wax Candle. I attempted to make one of these in the early 1970's but the design was not ideal and it didn't work properly.

Later, other "special effects" to make the Lamp or LED flicker in the manner of a Wax Candle's flame had been designed. Some have involved using Microcontrollers and code to simulate random movement of the Candle's flame. And using small electromagnetic manipulators to move an LED illuminated flame shaped plate. The basic idea there being to resemble a Candle's flickering flame.

I thought it would be fun revisit this idea. However not to attempt a total Wax Candle lookalike, but rather something that was more obviously electrical in nature. It would still serve a similar purpose to a Wax Candle, to provide a romantic light source at a dinner engagement. The color temperature and intensity of the Lamp being arranged to provide similar illumination and colour temperature to a single Wax Candle. Moreover it would have the ability to be lit by a match or lighter flame and be blown out, just like a real Wax Candle. And have backup systems to activate it, if a match or lighter was not available and be fully automatic, without the need for an external on-off switch.





DESIGNING THE MAGIC E-CANDLE:

For this design I chose to use NTC resistors (Thermistors) for temperature sensing, rather than Thermocouple sensors or IC sensor types using a pn junction at their core. The NTC's are inexpensive and very small in size. They have a high range output voltage per °C when configured with a simple series resistor and their linearity is not an issue that requires correction in this case.

I decided that the suitable power source should be three C cells for the reason that four C cells stacked on each other would make the Candle structure too long for its diameter. Also with D cells it would be a little too large in diameter and heavy and create more shading from the Candle's top surface below the Lamp.

AA cells are a little thin and too low in Ah capacity for the task. I chose an incandescent lamp, rather than an LED. This is because I find the appearance of the incandescent lamp, especially run at a suitable filament temperature, more pleasing and relaxing than an LED light source and more similar to a Candle. This is because, in essence, a Candle is incandescent. They both emit a continuous spectrum of light. A candle burns a yellow colour due to the incandescence of burning carbon particles (soot) in the wax.

Comparing a Wax candle to a lamp, a wax candle generally has a light output in the vicinity of 5 to 7 Watts. I elected to use a 6V 5W rated Auto lamp, running from an average voltage of around 4 Volts as this gave the equivalent of about a 2.2 Watt lamp, but with a similar color temperature to a Candle and I found that was plenty of light output for the task.

For this design, the overall length excluding the lamp is 10 inches (254mm) to accommodate three C cell batteries and the remaining parts. The main tube has about a 30mm internal diameter. This is required for clearance of one of the battery connections to pass by the three C cells in the tube. The C cell is in the order of 1 inch or 25.4mm diameter.

Conveniently the Bunnings Hardware stores carry a suitable white plastic pressure pipe, made by Holman and said to be a "25mm nominal pressure pipe" part number PVP2512-1. On searching the detailed specifications, this pipe is supposed to be 34mm OD and 30mm ID. However the actual pipe I bought measured around 29.5mm internally and 33.5mm externally *on the average*, because it was just a little ovoid. However the pipe was a good press fit into 33mm holes cut in the base rings with a standard 33mm hole cutter tool which cuts the hole a little oversized.

The Alkaline C cells have a 4 to 8Ah capacity, which varies depending on their quality and brand. This capacity is suited to power an incandescent light bulb, which was chosen to be a 6V 5W part (0.83A) but to run below its normal operating temperature and current at around 0.56A, so as to better simulate the colour of a candle. Being a little whiter than a wax candle with fresh batteries, but still just useable with a more orange color when the total supply voltage was down to 1V per Cell.

The Energizer Max C cells are said to have an 8Ah capacity, therefore in this application one could expect a life of about 14 Hrs, but likely it can work out a little less depending on the usage pattern.

I would estimate that the E-Candle would serve at least ten 1 hour dinners before the batteries required replacing. The "Energizer Max" Alkaline C cells also now boast a 10 year shelf life. To make use of this, if that were possible, requires that the E-Candle's power consumption would be zero or near zero when not in use. This was another design target, because I did not want this E-Candle to have a mechanical Off-On power switch. The basic plan was that it would be Lit (bulb activated) by a match or a lighter and extinguished (switched off) by a blow of air from the mouth, with backup system to switch it off or bring it on by inverting it in the Gravity field.

The measured current consumption when not in use for the E-Candle presented here is close to 4nA, which is very low, it does not shorten the Battery's shelf life to any significance at all.

Then there is the Battery's discharged state and final voltage during use to consider. Fresh 1.5V Alkaline cells tend to have a terminal voltage of around 1.6V. They are thought to be largely discharged when their terminal voltage falls below 1 Volt. This means that the total voltage from three new cells would initially be around 4.8V and when discharged around 3V with an average value of close to 3.8 to 4V in use. Although with a moderate load, the voltage drops due to the battery's internal resistance of around 200 milli-Ohms each, so 600 mR for three and that drops the terminal voltage by about 336mV with a 0.56A load.

However, using a 3V figure as a minimum working voltage for the electronic control system is not satisfactory. This is because there is still some more life to be squeezed out of the batteries, in that at 3V the lamp brightness is still quite reasonable and useful even for the 6v lamp. The voltage has to fall to around 2V before the lamp has become a dull orange.

If the electronic circuitry failed to operate below 3 volts, this would inhibit using the E-Candle and not get the best out of the batteries. Therefore, ideally, the electronic control system should work reliably down to close to 2 volts battery supply. This feature created a few interesting design challenges.

The minimum battery operating voltage that occurs with this design prototype, where the electronics fails to operate, is 2V and at that point the lamp is only a very dull orange and there is little point in having it function below that voltage.

I have defined the minimum operating voltage for the design as 2.2 volts, provided that the particular 2N7000 Mosfet specimens in the power start up circuit and lamp driver circuit are a selected part for its Gate Threshold Voltage (see end of article) This ensures the Magic E-Candle's electronic functions do not limit extracting all of the useful energy from the set of three C cells.

Thermal Inertia and Cooling Time of a Thermal Sensor:

In this design the Thermistor temperature sensor/s have been placed inside a hollow brass tube that is close to 1/8” in outer diameter (3.175mm) and 34mm long and with a wall thickness of 0.014” or about 0.355mm**.**The Brass tube itself dominates the Thermodynamic properties of the Sensor, because the mass of the Brass and its surface area and specific heat capacity are substantially higher than the small Thermistor Beads placed inside it.

Examining the thermal properties of the Brass tube, the first question to answer was:

If the tube is heated above ambient temperature, say by 10°**C,** how long might it take to cool back down to ambient temperature?

Generally, objects can gain or lose heat by Radiation, Conduction and Convection.

In this case there is some conduction of heat towards the Brass tube (when the lamp is on) from its mounting contact with the 8mm thick base it is mounted to, along with the lamp’s socket. And when the lamp is running, there is some Radiation to the section of the tube on the top area, near the Lamp.

For small objects that are not extremely hot, convection tends to dominate over loss of heat by radiation. Radiation dominates in a vacuum and is a weak mechanism of heat loss, unless the object very hot or very big. Cooling by radiation alone depends on the difference between the 4^{th} powers of the temperature of the object and the 4^{th} power of the environment temperature. This component of heat loss can be calculated with the Stefan-Boltzmann constant and the equation for radiated heat loss. Using this method, it predicted that the particular tube, if heated 10°**C** above ambient would take around 6.5 Hours to cool to within 3% of ambient temperature by radiation alone.

However, Newton’s Law of cooling time takes the practical convection cooling into account and gives the Temperature T as a function of time T(t), the object cools in an exponential decay, “To” is the object’s initial temperature and “Tenv” the environment’s temperature, the temperature values for this equation can be entered either as °C or °K:

$$T(t) = Tenv + (To - Tenv)e^{-kt}$$

In many cases the decay constant k is found by experiment however there is a way to estimate it:

$$k = hA/mc$$

A is the surface area, m the mass, and c the specific heat capacity of the material. And *h* is the “convective heat transfer coefficient” It depends on the geometry of the object, orientation, air or fluid convection and surface air speed if forced convection.

In free air the *h* value typically varies between 5 and 25. The cooling time constant TC, to decay to by 63% TC= 1/k. Or in 3 x TC, it would have 95% cooled down toward ambient temperature.

For a small tube cooling in air we can assume an *h* value of around 10. For the Brass tube used here the constants are:

m = 0.000914kg c= 380J/kg°K A= 3.55×10^{-4} m^2 thus making k = 0.0102

And the "time constant of cooling" (somewhat analogous to the time constant for a capacitor to discharge to 37% of its initial value) 1/0.0102 = 98 Seconds. Or in 3 x 98 seconds it would have cooled down 95% back toward ambient temperature.

The above calculation indicates that there is a moderate thermal inertia in the small Brass tube, much more so than the Thermistors themselves which have a thermal time constant of about 7 to 10 seconds. But, you cannot just place the small fragile Thermistors in the space by the Lamp, they must have some form of mechanical protection and support and therefore the Brass tube or a similar tube is required. And it also means that a type of differential temperature sensor is required, that can detect a small change in temperature and still work over a wide range of ambient temperatures.

Human Body Heat and Breath Temperatures versus Ambient Temperature:

Heat will only transfer to an object or a sensor, from the human body, when the sensor temperature is below body heat. If it is equally to body heat no energy will transfer to it, and if it hotter than body heat, heat energy will transfer to the body. This is what makes the difference between an object feeling cold, neutral or warm.

When the ambient temperature (and therefore the initial sensor temperature) in the E-Candle is already in the 25°C to 33°C vicinity. Which is around the temperature between a Thumb and Finger, it is possible that little thermal change could be detected by touching the sensor tube.

Likewise, when blowing onto the sensor, the breath temperature is around 29°C. Therefore whether the sensor heats or cools or doesn't change temperature at all, depends on the sensor's initial temperature, which is normally ambient temperature. Forced Convection cooling with air relies on the air temperature being lower than what is being cooled. Therefore, depending on the ambient temperature, human breath could either cool or heat the sensor or do nothing at all. It is the same problem as touching the sensor.

On the other hand, the heat from a lighted match or cigarette lighter is always significantly higher than ambient temperature and body heat, at least an ambient temperature range that is compatible with Human life.

I concluded that the heat generated between the finger and thumb was not 100% reliable as "Alternate Lamp Starting Option" and it was better to use a Timer function in conjunction with the Mercury Switch.

I also concluded that using a Temperature Sensor to detect Human breath is an unreliable method to blow out the Lamp. Therefore the task of blowing out the Lamp was assigned to an Electret Microphone.

The E-Candle presented here required a design such that, in the absence of a match or lighter, the Lamp could be activated with 100% guaranteed operation with an alternative method. A timer, based on inverting the E-Candle in the Gravity field, for 4 or more seconds, is provided. This is just in case there are no matches or lighters available and the user wants to switch on the E-Candle.

Even though the large temperature gradient, provided by the lighted match is well above any common ambient temperature, it still required a special arrangement of Thermistor sensors into a differential bridge arrangement. This is to decrease the response time in detecting heating and to shorten the recovery time after the sensor tube has been significantly heated.

Operation: Two ways to switch ON and Two ways to switch OFF:

When the Candle has not been in use for a few minutes (the Lamp is off) or just in storage, it goes into a super low power shut down mode of near zero Amps (4nA) current consumption. If the E-Candle is inverted for a second or two and returned upright, Gravity activates a Mercury switch and the circuitry within the E-Candle's electronics remains fully powered with a current consumption of around 20mA for about 2 minutes, awaiting the Lamp to be lit by a match.

To switch ON - Two methods:

 # Match or Lighter. The flame only needs to be placed near the sensor tube beside the Lamp, not actually touch it and the Lamp will activate within a couple of seconds and not take so song that the match will burn down near the fingers.

 # Candle Inversion. If done for more than 4 seconds and the E-Candle returned upright, the lamp will be in the ON state.

To Switch OFF - Two methods:

 # Blow on the top area of the E-candle around the lamp.

The sensitive microphone picks up the sound of the "blow" and extinguishes the lamp.

Invert the E-Candle for a second or two and return it upright.** This brings it up in the Lamp OFF mode again waiting to be Lit. If not Lit, the E-Candle, after 3 to 4 minutes, reverts to its super low current drain state.

The challenge of reliable Lamp activation with a Heat Source:

It is a little more difficult than it first appears to deploy one Thermistor on its own as a thermal sensor for this specific application. Some of the reasons are outlined above in the topic of thermal inertia and cooling time.

The reasons are that in this application the desired signal to detect is a *dynamic increase* in temperature, from a variable existing ambient value, to a higher value. This occurs over the time window that a typical match could heat the protective metal tube containing the Thermistor's body, but not take so long that the match could burn down to the fingers as it sometimes does, trying to light a stubborn real Wax Candle.

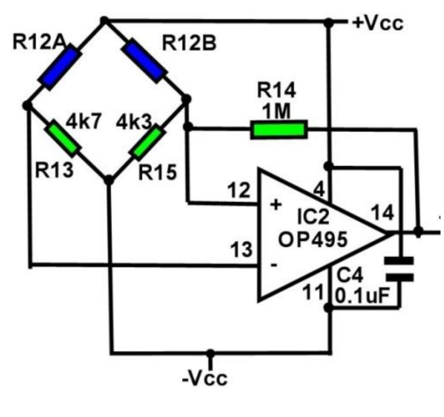
And there is the issue of the overall sensor arrangement's Thermal Recovery Time after significant heating by the match. In other words, when is the sensor able to be re-deployed after significant heating?

On top of this, once the Lamp is lit, this generates heat and radiant energy, which also affects the sensor tube and Thermistors and this requires some mitigation.

As one example; if a single sensor is set up as a Thermometer, and arranged to activate that Lamp at some specific temperature, say 45°C, it takes too long to bring the temperature up from a much lower ambient temperature of 20°C or colder, due to thermal inertia of the sensor itself and the protective Brass tube that accommodates it. Of course one solution can be done in firmware with a CPU, polling the temperature values at regular intervals and deciding if some upwards increment has taken place within a specific time frame. However, this design has been optimised for super low standby power consumption in all Analog hardware so the Thermodynamics of the situation required a more detailed analysis because clearly one sensor was not adequate.

The Thermal Sensor Design:

From the electronic perspective, two Thermistors R12A and R12B are wired into a bridge circuit and feed an OP Amp used as a Comparator with a small amount of Hysteresis:

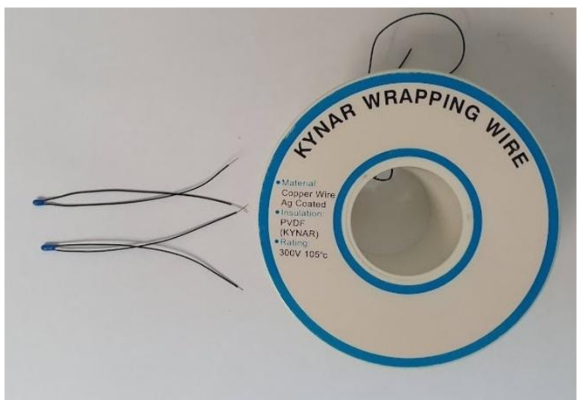


When the comparator output goes positive, the Lamp is activated and is held on by an S-R Flip Flop.

The Thermistors used are RS Part 151-221. 5K Thermistors generally have a sensitivity in the range of -4% per °C at 25°C. These are some of the features from the data sheet:

Interchangeability over wide temperature ranges, this permits the circuit designer to standardise on circuitry, eliminating the need to individually adjust circuits and allowing the thermistors to be easily replaced without the need for re-calibration. Interchangeability to ±0.2°

Given that the internal Brass tube diameter is 0.246mm it could have been a little tight to pass the wires of R12B past R12A in the tube(see below) however the 151-221 parts I had were a little smaller than their 2.4mm stated maximum diameter at just under 2mm and they were slightly ovoid. They come with bare wires. I used some insulation taken from some thin insulated Kynar wire wrap wire to insulate their bare wires:



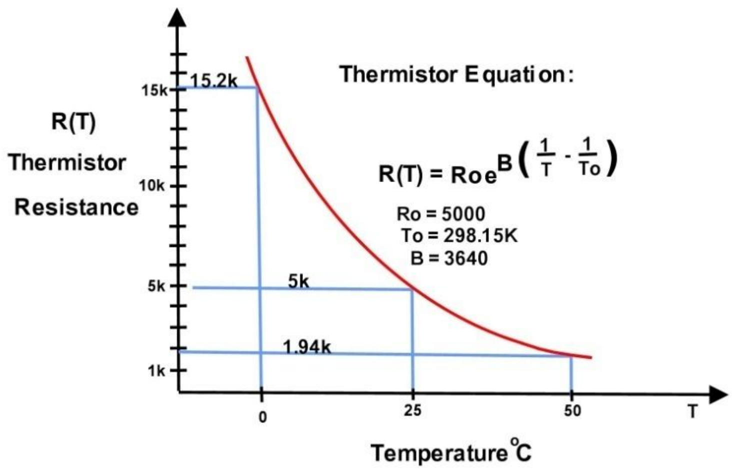
An easier part to fit in some cases could be RS part 484-0133. These EPCOS 5k Thermistors are only 1.3mm diameter making more room for the lead wires.

It would not be wise to increase the diameter of the Brass tube for a larger sized Thermistor, because this increases the thermal inertia due to the increased mass of the Brass and this delays the overall response to heating and cooling.

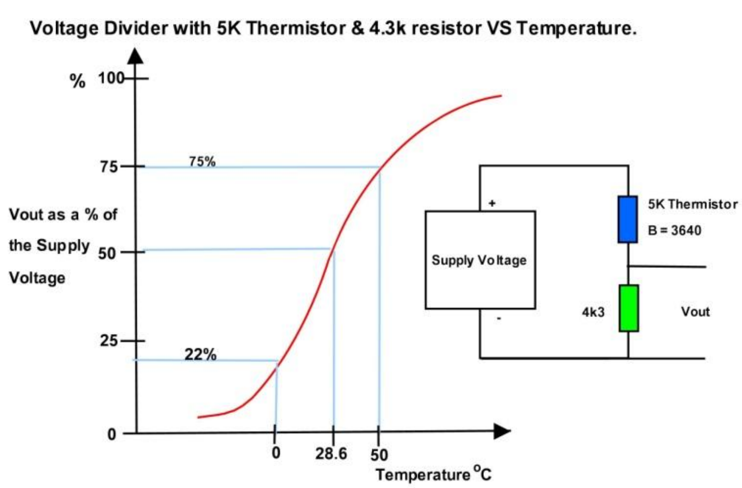
With the temperature coefficient of around -4% per °C @ 25°C, a change of +1°C would drop the 5k Thermistor's resistance in the order of 200 Ohms if the temperature increased to from 25°C to 26°C. However, it is a *percentage change*.

A plot of resistance versus increasing temperature for a Thermistor has a familiar exponential decay format and the tangent to the graph, representing change in resistance with a change in temperature decreases with increasing temperature.

It is ideal to know what the Thermistor's resistance is at any temperature. This can be calculated from the B value, this value is often in the range of 3000, but I could not find it in the 151-221 Thermistor's data sheet or a resistance graph for that matter. However, working backwards from the -4% specification I was able to calculate the B value at around 3640 and could plot a graph for the RS 151-221Thermistors. The temperature T must be placed in the equation in degrees Kelvin. As can be seen the resistance would be in the order of 15k at 0°C and around 2k at 50°C.



When the Thermistor is placed in a voltage divider, with a resistor, it is required that if you want to know what that voltage is with temperature variations, you must place the Thermistor's resistance equation into the equation for the voltage divider. The result produces an S like curve. One point to note is that the slope of the curve around the 25°C area is greater for decreasing temperatures than for higher temperatures.



The graph of the Thermistor with the 4k7 resistor is essentially the same as the one for the Thermistor with the 4k3 resistor, except it is shifted up the Y axis with a small offset.

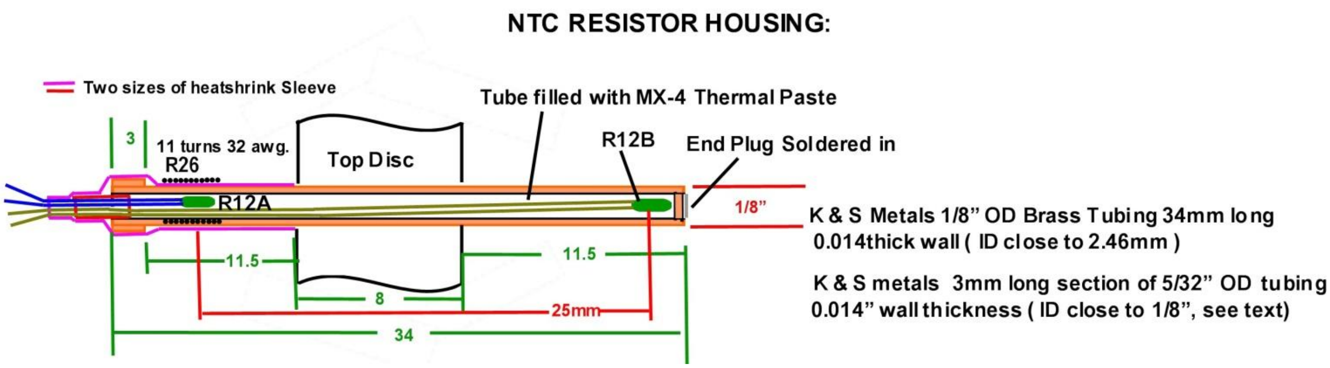
It is a difference between two Thermistor temperatures being detected and the types of Thermistors I used are designed to track each other and have matched curves, this helps.

The bridge circuit works effectively for the application over the full voltage range and a wide temperature range. It does not require that the voltage or current supply to the Bridge needs to be stabilized or regulated. I found it was not necessary to compensate for the non-linearity, or the effects of lowering battery voltage. Also the offset voltage due the 4k3 and 4k7 resistors is much higher than the OP Amp's (Comparator's) input voltage offset specification. Of note it is required that the 4k3 and 4k7 resistors are 1% tolerance parts.

Another advantage of the bridge arrangement is the small amount of self heating of the Thermistors due to their operating current is largely cancelled out.

The 4k7 and 4k3 resistors in the voltage dividers on the Comparator inputs set up a 180mV offset, with new batteries (and about half that with discharged batteries) which corresponds to an approximate 2°C offset at 25°C. This offset keeps the Comparator output negative, unless there is a ***transient*** temperature gradient with R12B being hotter than R12A and this drives the comparator output positive.

The offset of 2°C is used so that the response time can be as fast as possible once the match's flame is held in proximity to the Brass tube, holding the Thermistors.



I settled on the design shown above, using the Thermodynamic properties of heat transfer along a metal tube. It uses two Thermistors, one at each end of a 34mm long hollow 1/8" (3.175mm) diameter Brass tube spaced about 25mm apart. The tube is filled with MX-4 Thermal Paste.

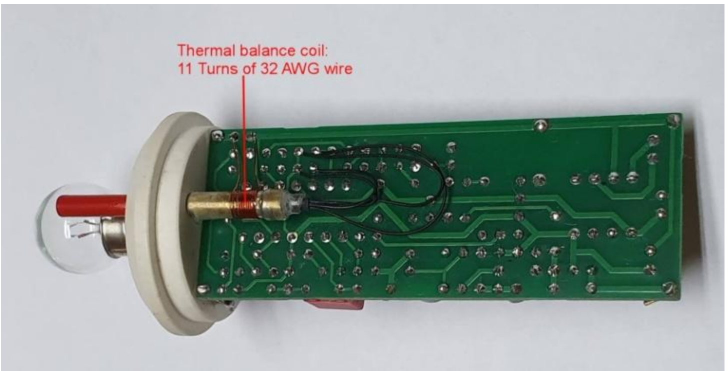
One end of the tube is a blind end (sealed with a small disc of Brass & Solder), containing one Thermistor R12B. This part of the tube projects 11.5mm above the top surface of the E-Candle's body, beside the Lamp. A 14.5mm length of the tube projects inside the Candle body where 3mm of it there has an external metal sleeve. This helps the assembly retain the Heat Shrink sleeve without there being a chance it could slip off the tube.

The 4 wires from the two Thermistors exit this end of the sensor tube. The wire end of the tube is sealed with two pieces of Heat-Shrink sleeve, which helps retain the Thermal Paste. This sensor arrangement can be glued into the hole in the top disc if it was a loose fit. I found that the 1/8" brass tube was a good press fit into a 1/8" mm hole drilled in the top disc, because the particular tube measured 3.2mm even though 1/8" is officially 3.175mm.

When assembling the sensor tube, the MX-4 thermal paste is introduced with a Dispensing Needle (readily available on ebay).

The needle is inserted until is reaches the blind end and withdrawn as the paste is slowly introduced to fill the hollow tube. R12B is inserted first until it reaches the blind end. Then R12A is inserted. Since each Thermistor has the same length Lead Wires, it is easy to tell when they are about 25mm apart. The a small section of heat shrink sleeve is paced over the wires and slipped a mm or two into the end and then other larger diameter piece of heat shrink sleeve is slipped over the 14.5 mm length of tube, so a piece of 17 to 18mm long heat shrink is fine for that task. This helps retain the MX-4 paste.

The 11 turn coil (which acts as a resistor which senses the lamp current and produces some heat) can then be wound over that heat shrink sleeve. Once the coil is wound a small amount of epoxy resin can be used to keep the turns in place, or another piece of heat shrink sleeve could be used over it. I used the resin because it makes it easier to see the coil in the photos:



It is very fortunate that model shops and Ebay sellers stock this standard Brass tube made by K & S Metals. All of the 0.014" thick wall Brass tubes they make are designed to slide inside each other. Sometimes they can be a firm fit and press together well. In the case that they are a little loose they are easily soldered together, or glued if heat transfer is not required (such as the Microphone mount, see below)

The purpose of the Thermal Paste in the tube is not to significantly improve the thermal conductivity along the length of the tube. The Brass metal itself has 10 to 40 times or more thermal conductivity than the Paste, depending on the brand of paste. The overall thermal conductivity along the tube is dominated by the Brass tube and its cross sectional area, not the Paste within it.

The Paste helps the thermal coupling of the Thermistor bodies to the inner wall of the Brass tube. An air gap here would not be helpful because air has only a fraction (0.3%) of the Thermal conductivity of Thermal Paste.

Holding the match flame within a few mm of the Brass tube near the Lamp (the flame does not have to touch the sensor tube, merely warm it) activates the Lamp in 2 or 3 seconds due to the heating of R12B and the imbalance in the sensor Bridge Circuit. It takes longer, in the order of 8 seconds, for the heat to propagate down the tube to reach R12A and start the heating there.

Experimenting with the K & S metals 1/8" OD Brass tubing I found that there was roughly about an 8 second delay after applying the abrupt heat from a nearby match or lighter flame near one end of the tube, before the temperature elevated 2 degrees or more above ambient temperature at the other end of the tube, where R12A is placed. The time delay, t in seconds, can be calculated from the equation for Transient Heat Diffusion. The equation for the thermal timing is:

$$t = \frac{L^2}{\alpha\pi^2} \ln\frac{4\Delta T1}{\Delta T2}$$

Where L is the length of a metal rod, α the thermal Diffusivity of Brass which is in the order of 34 x 10^{-6} m^2/s. ΔT1 and ΔT2 are the temperature increases at either end of the rod or tube.

Starting from an ambient temperature of 25 degrees, if one end of the tube is elevated abruptly by 15 degrees, to 40 degrees, then ΔT1= 15. If we wait a time for the other end of the tube to increase from 25 degrees to 27 degrees, then ΔT2 = 2 Degrees. In this case the length of the tube between the sensors is 25mm or 0.025m. Plugging in those numbers:

$$t = \frac{0.025^2}{34 \times 10^{-6} \times 9.87} \ln\left(\frac{60}{2}\right)$$

$$= 6.3 \text{ Seconds.}$$

This very approximately agrees with the results of experiments on the Brass Tube.

After the match flame is removed, which is the natural response after the Lamp has Lit, the Brass tube and sensor temperatures settle to a fairly uniform temperature along the tube length. The Comparator output then returns negative. The tube cools back down to near ambient temperature fairly slowly over some minutes, but due to offset voltage, the comparator output is still negative.

In other words, even though the total thermal inertia of the Brass tube is high, as previously noted, taking in the order of 98 seconds to lose 63% of the acquired temperature increase, the sensor system becomes re-operational much more quickly, because of the bridge arrangement of the two sensors.

It is important to know the Thermal recovery time of the sensor because there may be a scenario where the user lights the Lamp with the match and the sensor tube has been significantly heated by the match and then the user, in short order, blows the Lamp out. Then they change their mind and decide to quickly re-light the lamp.

This scenario could also crop in a demonstration of the E-Candle. The question being; when does the thermal sensor system become re-usable again to re-light the lamp after it was recently lit by a match and blown out?

On examining the comparator output, after the match is removed, the heat in the Brass tube equilibrates in about 8 to 10 seconds (Similar to the thermal delay time between the two sensors) This renders both the sensors to a similar resistance value and the output of the comparator falls negative again. At that point it can be re-deployed and the sensor re-used with another match to light the lamp. This is another great advantage of having the two sensors in the same Brass tube, wired in a bridge configuration.

It will also be noted on the schematic below, that the output from the heat sensor’s Comparator is AC coupled, with a 1 second time constant, into the S-R flip flop which controls the Lamp’s ON-OFF function. The Flip Flop is then driven with a pulse when the Comparator output goes Positive. The reason for this is that the 10 second sensor thermal recovery time could inhibit the S-R flip flop and prevent the user from blowing the lamp out in a short time frame, immediately after they lit it with the match, if they so chose to do that.

Lamp Heat Mitigation:

With the Lamp running, R12B runs a little hotter than R12A.

In steady state conditions, heat propagation down a tube’s wall or a solid rod, has many features in common with the flow of electrical current; in that the flow of current = Voltage gradient divided by resistance, or put another way; electrical current flow = electrical conductivity x Voltage gradient.

By analogy, in thermal systems, the flow of heat energy in Joules per second is equal to thermal conductivity x Temperature gradient.

Different materials have different thermal conductivity values, just as different materials have differing electrical conductivity. The thermal conductivity of Brass is very high in the order of 110 Watts per meter-Kelvin, vastly higher than the usual white Thermal Paste at around 3 to 8 Watts per meter-Kelvin. Air on the other hand is a very poor thermal conductor, only in the order of 0.026 Watts per meter-Kelvin.

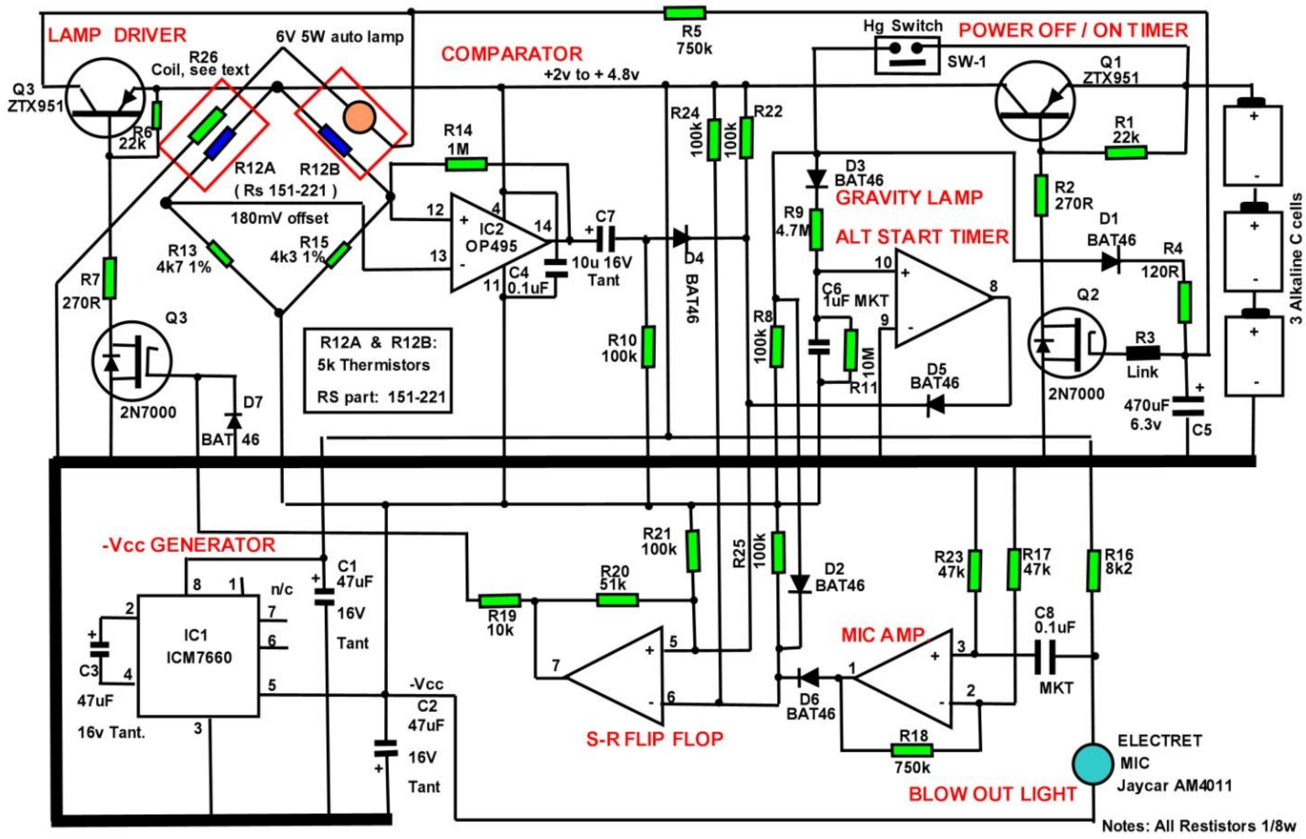
When the lamp is running, it results in a temperature gradient along the Brass tube where the Thermistor R12B is heated more than R12A. This reduces the offset voltage, which holds the OP amp's output voltage on pin 14 negative. Generally, it is otherwise around 180mV (with full battery voltage and half that with a battery voltage of around 2.3V)

To correct for this and make sure the sensor system did not become too sensitive, the Lamp's current is effectively monitored via R26 (the 11 turn coil composed of 32 AWG enamelled copper wire) this heats the R12A end of the Brass tube, applying around 30mW of heat. This balances out the thermal offset due to lamp heat and keeps the temperature along the Brass tube more uniform while the Lamp is running and thereby keeping the compartor's offset voltage stable.

The items in series with the lamp circuit include the voltage dropped by R26 of around 50m V and the two saturation voltage drops of the ZTX951 transistors of only about 60mV to 70mV each and along with the internal resistance of the C Cells provide a good operating current of around 0.5 to 0.56 Amps for the 6V 5W lamp. It results in a good color temperature with new C cells, perhaps just a little whiter than a candle, but, as the batteries discharge, the color transitions in the more yellow and then orange direction.

The circuit is somewhat more elaborate than I imagined it had to be before starting this project, however all of it was required to ensure the E-Candle worked properly.

One might wonder why the emitter of Q3 was not fed directly from the battery supply which would gain an extra 60mV for the lamp. When the unit is in the process of going into automatic power down mode, when the Lamp has not been on for some minutes, the OP495's total power rail voltage falls below 2.6V or around +/-1.3V supply voltage. This can cause the S-R latch output, pin 7 of the OP495 to go to a positive output value and re-initiate the the charging of C5. With the arrangement settled on, with the power to the Lamp's driver circuit, sourced via Q1, there is not enough energy as the power rail, provided by Q1 is collapsing, so as to raise the Lamp's filament temperature and develop any significant voltage across across the Lamp. This prevents current via R5, starting to recharge C5 and re-activating the power supply and lamp.



Gravity, Heat & Sound Controlled Electric Candle. H. Holden. March. 2025.

Why PNP BJT's were used and not Pch Mosfets:

Sooner or later, people fit batteries in reverse. The ZTX951 provides reverse Battery protection because of their B-E reverse breakdown voltage being higher than 4.5V. On the other hand the D-S diodes in Pch Mosfets, if used instead of these BJT's would not provide this protection and make the reverse polarity problem worse, without other components added to mitigate it.

Power ON-OFF Timer:

The 470uF capacitor C5 provides significant charge storage in the Gate circuit of the 2N7000 Mosfet Q2. When the Candle is inverted the Mercury switch closes and C5 is rapidly charged via D1 and current limiting resistor R4 to the battery voltage (less the forward drop of D1). This causes Q2 to conduct Drain current and this switches the ZTX951 Q1 into a saturated state. Also via D2 the S-R flip flop is reset to a condition where the Lamp is off.

The E-Candle after being inverted in the gravity field for a second or two and returned upright is now "Armed" and ready to be lit. This condition stays active for at least 2 minutes so there is plenty of time to light the E-Candle. If it is not lit, after 3 or more minutes the charge stored in

C5 is depleted via R5 and the Lamp's filament and the circuit goes back into the low current standby mode.

The Data sheet for the 2N7000 suggested that the Drain-Source leakage current (with a zero gate to source voltage) could be as high as 1uA, but for the ones I have at least, the leakage current is in the 4nA region with zero gate to source voltage. Even if it were as high as 1uA, that would still take over 900 years to discharge the C Cells.

To allow the circuitry to operate down to low total battery voltages of around 2.2V an ICM7660 has been deployed to generate a negative voltage rail. A near doubled total voltage supply for the OP495 OP amp is obtained. The ICM7660 operates down to 1.5V. The more modern versions of these, which are pin compatible, are the MAX-1044 (Of note the original IC(**L)**7660 parts had a latch up issue and required an external diode to prevent it. The ICM7660 and the Maxim part as far as I am aware, does not have this issue)

With the ICM7660, the minimum total voltage the OP amp receives is in the order of 4V even with batteries discharged down to 2.2V (0.73 volts per Cell). While there are very low voltage OP amps available, I found it better to simply provide a more standard OP amp with the boosted supply via the ICM7660 which also creates a split supply too.

If the Lamp is activated, R5, the current flow is reversed in the 750k resistor R5, this prevents C5 from discharging, so the Lamp stays on unless the S-R flip flop is toggled from the output of the microphone amplifier, or a brief candle inversion is initiated to turn the lamp off. I tested a number of 470uF 6.3V capacitors and in general their normal leakage resistance is 10 Meg Ohms or more and this does not cause any difficulties using an electrolytic capacitor in this application with a 750k charge-discharge resistor.

As noted before, the output from the Thermal sensor's Comparator is AC coupled to the S-R Flip Flop which has been created from an OP amp. This allows a blow of air near the E-Candle's lamp via the Microphone port and the Microphone's Amplifier, to reset the S-R Flip Flop and switch off the lamp, even if the Thermal Sensor's Comparator's output has not fallen negative yet.

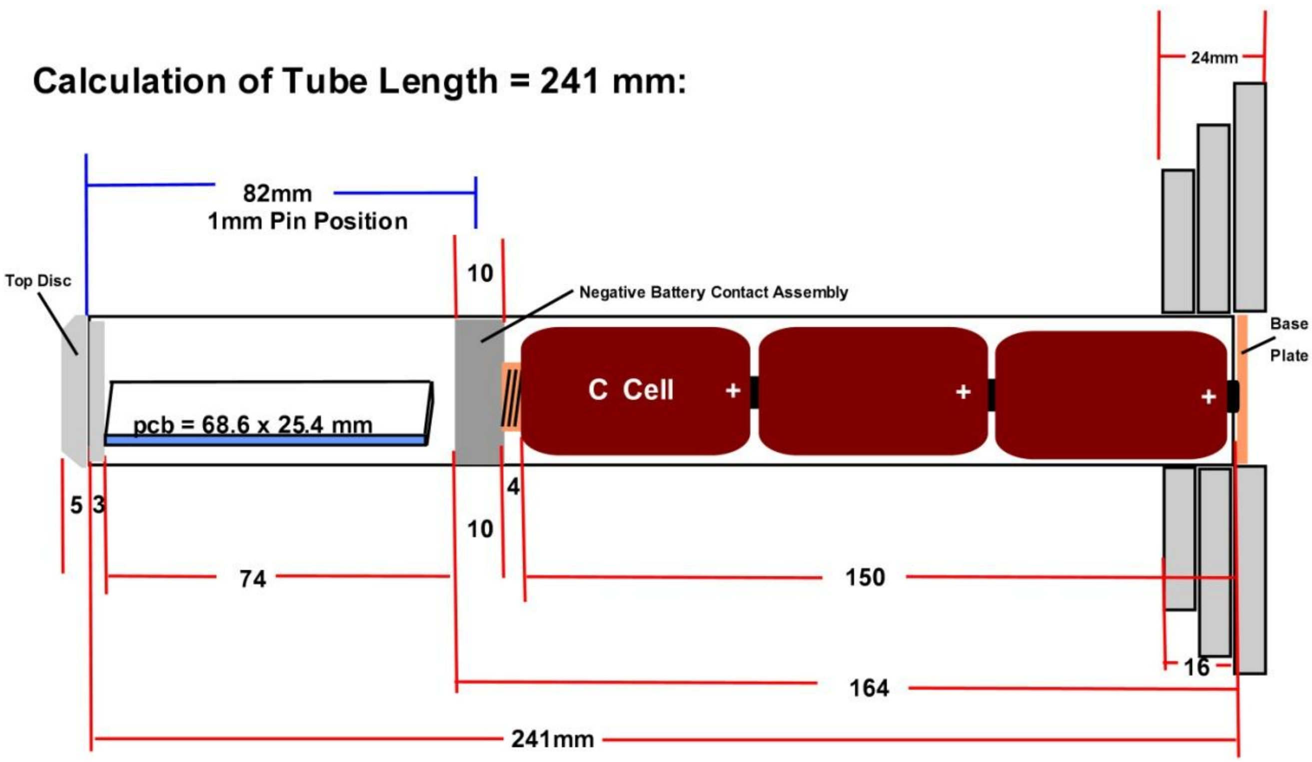
A blow of air from the mouth onto the area near the Lamp from any direction is enough to extinguish the Lamp. The microphone port does not have to be blown into directly just blowing toward the lamp from any angle will extinguish it. The arrangement is resistant to background noise and also, within limits of taping hard on the E- Candle body is quite stable. It blows out in a very similar way to a Wax Candle, but a little easier.

The microphone arrangement is surprisingly resistant to moderate ambient noise. For example holding the activated E-Candle right at the output vent of a window air conditioner, running on full fan speed, won't extinguish the lamp nor will fairly loud voices or noises nearby, yet a blow on it from the mouth will easily do it.

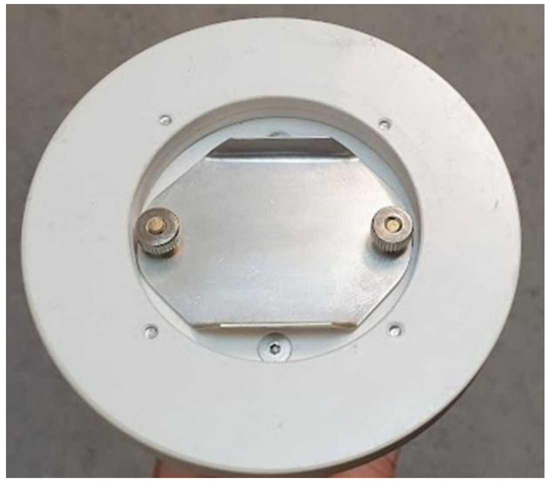
As noted, if the E-Candle is held inverted for more than about 4 seconds, this charges capacitor C6 and also sets the S-R latch to switch on the Lamp. This is an “alternative Lamp start” method, in case a match or a lighter is not available.

Physical Construction of the Magic E-Candle:

The diagram below shows the basic dimensions and how the length of the PVC tube section was calculated:

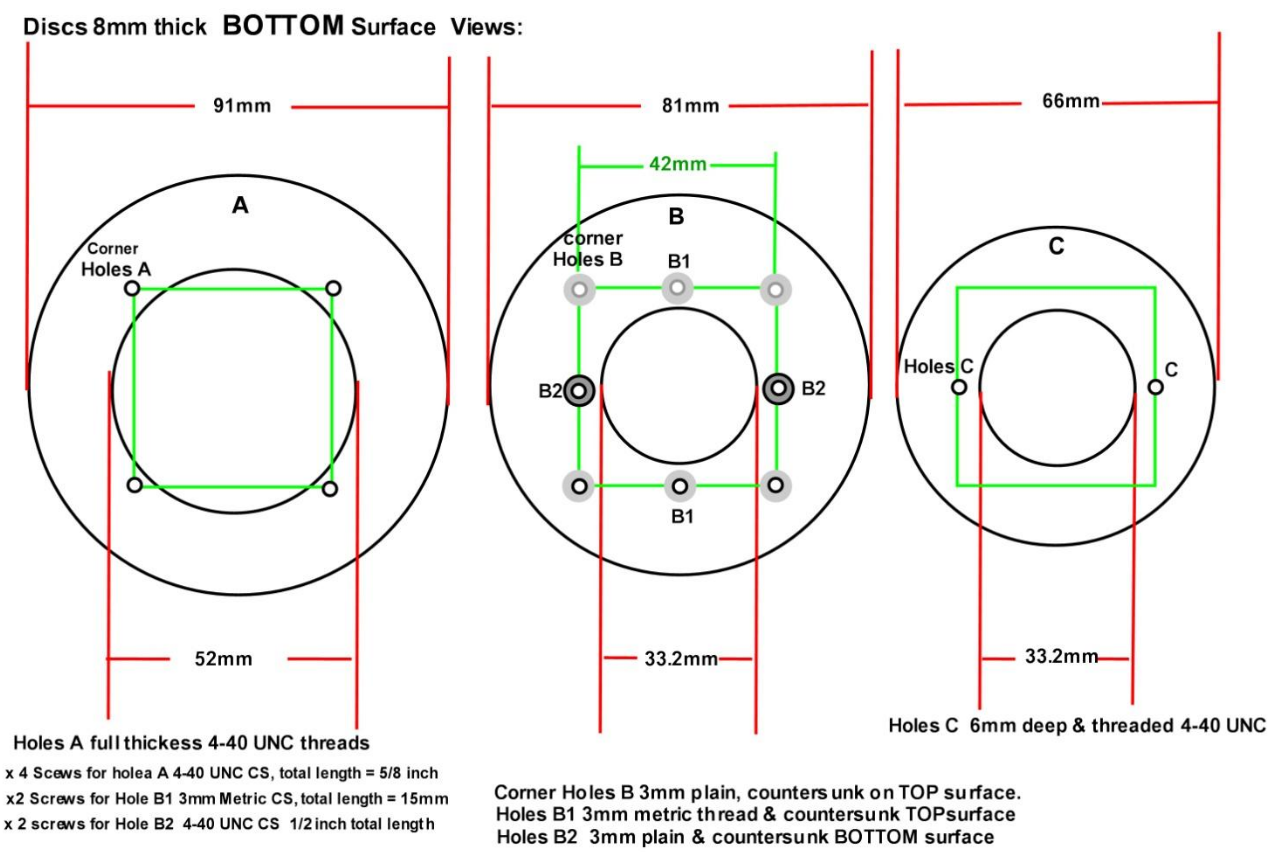


The Base Rings:



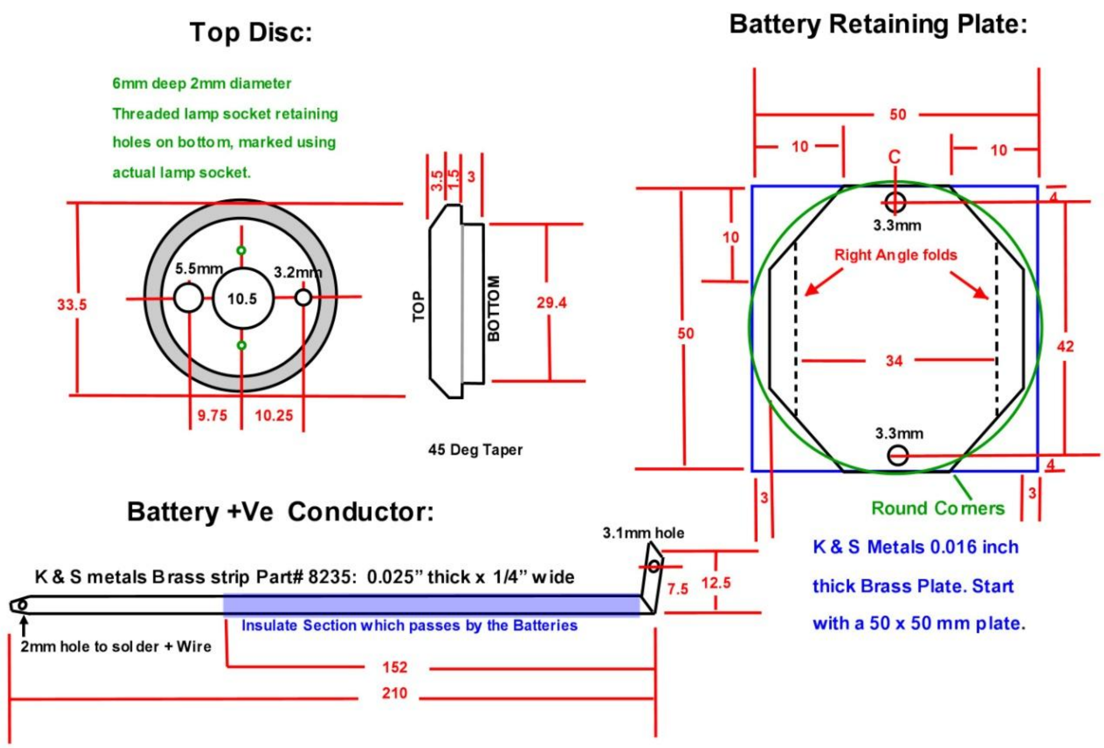
The size I made the base rings was determined by the hole saws I had in my tool kit. They can be modified as desired. I used a white material called Bramite once used on Australian power boards that is hard to get now. However, 8mm thick white Acrylic or HDPE, PEHD is suitable too and readily available on ebay. Or FR4 fiberglass would work and could be spray painted white.

A Plastics company can easily cut discs to size. I found that a 33mm hole cutter made a hole that was a little over 33mm and created an interference fit with the Bunnings PVC tube, so that no glue was required, but glue can be used as required.



The Battery +Ve contact plate and the battery positive conductor, were both rubbed down with a product called “nushine” designed to Silver Plate worn Tea Pots, available on Ebay, this is why they look like Silver and not Brass.

I found that for the particular Bunnings tube, that making the diameter of the the Top Disc around 29.4mm was a tight press fit. Glue can be added if required. Making the outer diameter around 33.5mm closely matched the outer diameter of the pipe. The taper is a good idea on the Top Disc of material because this way there is less shading of the light around the lamp’s base.



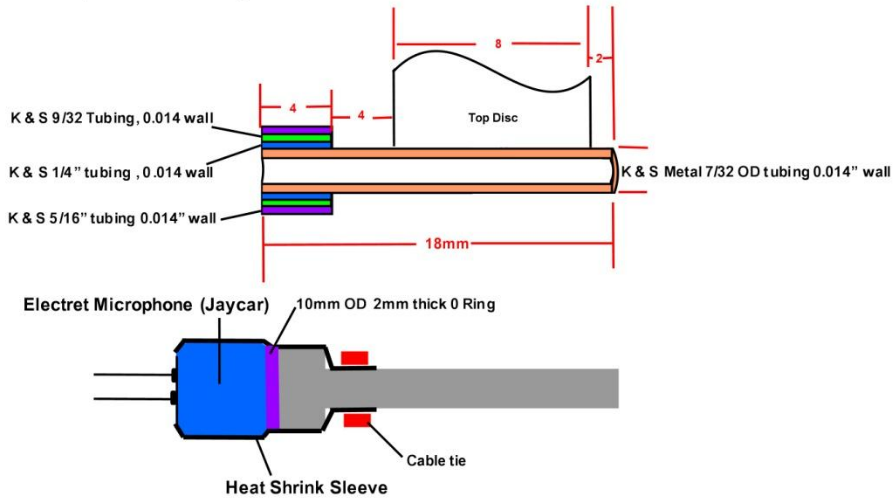
The light bulb socket is harvested from a Jaycar lamp socket part: SL2659.It has flare on it where the lamp screws in, so the hole in the top disc needs to be made 10.5mm rather than 10mm. I wrapped some scotch 27 tape around that to make sure the socket was a good central fit in the hole.

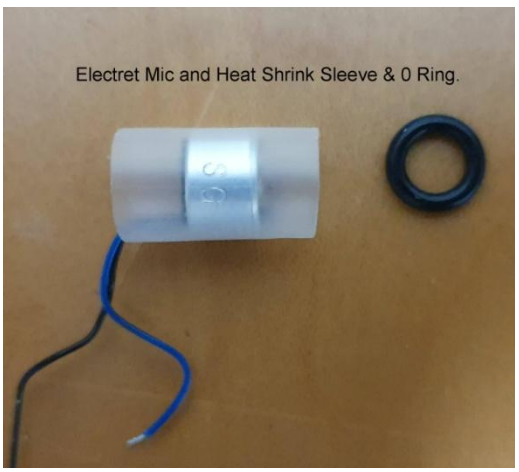
The Top Disc itself can be made from a number of white materials FR4 fibreglass would be fine and it can be painted white. Hard to see on the photo, there is a layer of clear heat shrink on the wire side of the sensor tube. The enamelled 32 AWG wire is wound directly onto this heat shrink. The top parts of the sensor tube is painted with red VHT paint, so it is obvious that the match flame would be held nearby it and not near the microphone port, the top part of which I painted White:

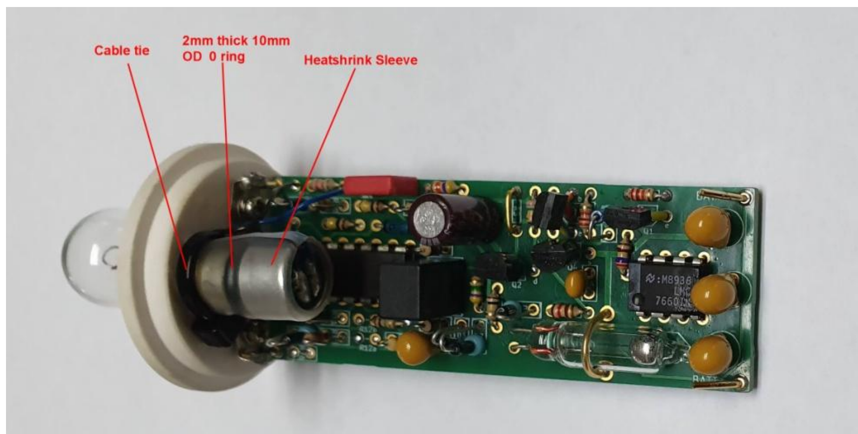
The holes for the 2mm screws are marked using the socket as a template. I used 2mm x 6mm long metric screws with spring washers. This requires drilling 6mm deep 1.5mm diameter holes and then cutting the 2mm thread into those with a taper & end Tap.

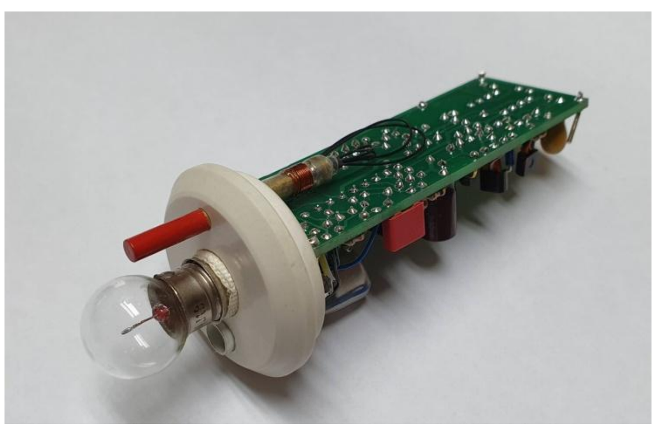
The microphone mounting tube is inserted into the the 5.5mm hole in the top disc until 2mm of it projects above the disc surface. It is a press fit because the OD of the Brass tube is 7/32" = 5.56mm, glue can be used if required. The three additional short sections of tubing can be glued to it or soldered if they are both Brass. This creates a way to mount the Microphone with a short section of heat shrink tubing. Since the diameter of heat shrink tubing, that fits over the microphone, when fully shrunk, doesn't quite get small enough in diameter to get a good grip on the 7/32" OD tubing I added a cable tie. Also to slightly soften the microphone mount I added a rubber 0 ring, this way the Microphone is not to sensitive to a knock on the candle's housing.

Microphone Mounting:



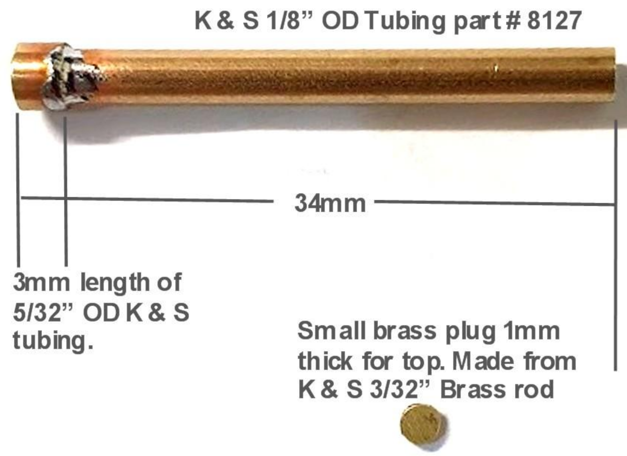






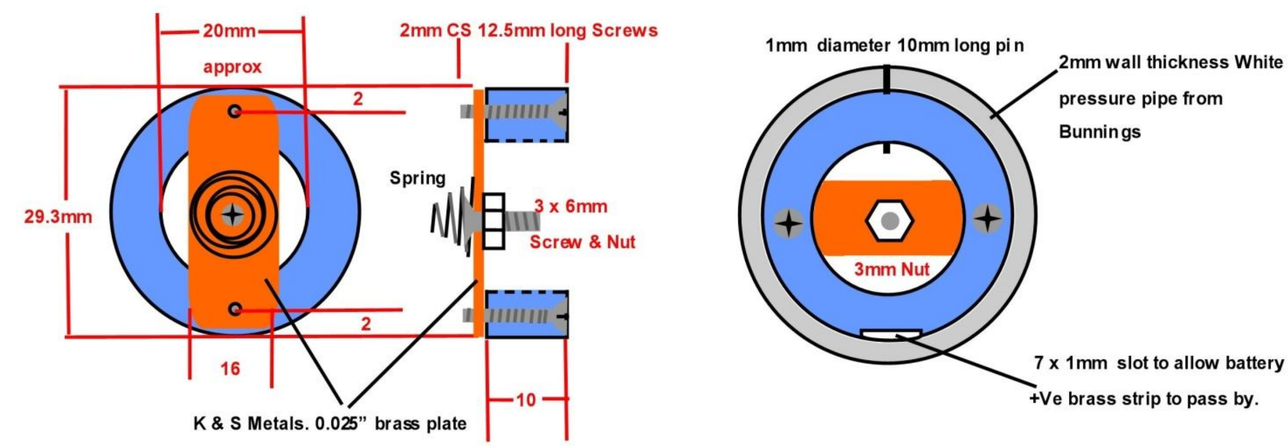
The pcb is attached to the bulb socket directly by soldering the Jaycar 0.9mm corner pins to the bulb socket connections.

In a similar manner the housing for the Thermistors R12A and R12B is made from Brass tubing. Again with a collar on one end, this helps to retain the Heat Shrink sleeve, which is used to seal in the Thermistors and the Thermal Paste.

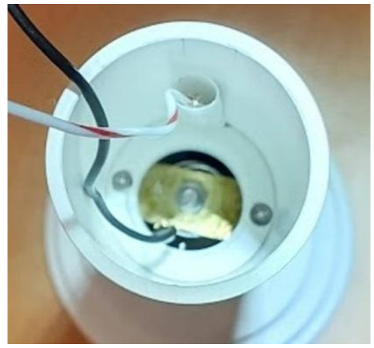


Battery Negative Terminal Assembly:

Spring taken from Jaycar C cell battery Holder.



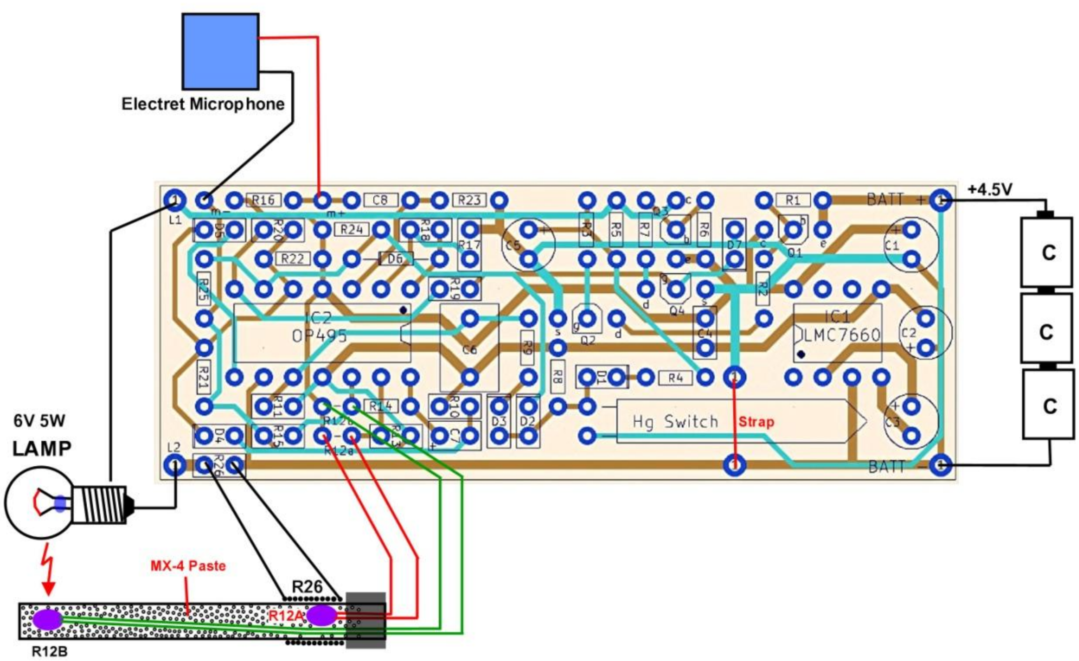
For the Battery's negative terminal, I made a ring of PVC taken from a Tap fitting from Bunnings. But any suitable material would work. I made it a firm press fit. When it was in position I drilled a 0.9mm hole through the side wall of the tube and pressed in a 1mm x 10mm long pin to retain it. This way is was not very obvious. And if it needs to be repaired or removed one day, the pin can be pressed through later and release the assembly. Since it was PVC, it could have been PVC glued into position in the PVC pipe, but that would be permanent and could have been messy. Still the battery contact plate, spring & screws could be undone if any repairs were needed even with the PVC ring glued in position.



The photo above shows the negative battery terminal assembly fitted to the tube. The retaining pin can be seen projecting into the central hole a little, just below and to the right of the negative (black) wire as it passes up through the hole.

0.9mm Jaycar PCB pins are used on the board corners. In one case they provide plug on connections for the two battery wires using their mating sockets. As noted near the Lamp socket the pins are soldered directly to the lamp socket tags. This attaches the pcb to the top disc.

The PCB details:



Differential Thermal Sensor with Thermal Balance

The pcb was designed in KiCad by hand (not using an automated router) is a double sided plated through hole board. All of the pcb pad holes are 0.7mm diameter except for the ones on the four corners and the two for the Mecury switch strap. These six holes are 1mm diameter for the Jaycar 0.9mm pcb pins and the two holes to receive the wire strap (with some clear sleeving) which holds the Mercury switch onto the pcb surface. The board is exactly 25.4mm x 68.58mm in size. To keep it as compact as possible, many of the 1/8W resistors and diodes are mounted upright on one end, in a manner reminiscent of vintage transistor radio construction. Or if wanted these ones could be replaced with surface mount parts.

Practical results and a Video:

I attempted a photo with the E-candle lighting an object on a table, to indicate the approximate amount of illumination it might provide on a person's face. One issue is that the light source from the Lamp's filament over-exposes the camera and it creates a purple halo, when if fact there is no purple halo, and the light is a yellow color. I masked out the E-Candle from the image, and it is easy to see the amount of light it casts. And this is a 6V 5W Lamp being powered by around 4V to produce about 2.2 Watts. The picture is not touched up. The table top is about 1 meter x 1 meter. I had given consideration to a diffuser over the Lamp, but I decided it was much more interesting and fun to be able to see the Lamp itself and with the lamp running a yellow color the glare in use is not a problem, no more than a real candle.

Here is a Video Link to show the Magic E-Candle in operation:

https://www.youtube.com/shorts/yPeLhmbzurw

Selecting the 2N7000's:

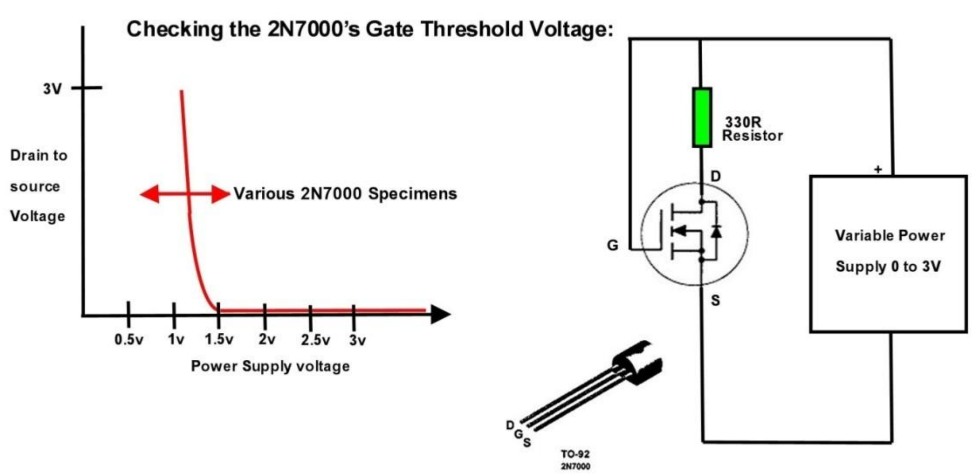
This project ideally requires that one component is selected. The reason is that if it is, it lowers the minimum possible operating voltage of the electronics when the battery is in a near fully discharged state. If the 2N7000 is not a selected part, everything still works, but it is possible that the circuitry would become disabled at a discharged battery voltage of around 2.5 to 3 V rather than the 2.2V that can be achieved if the 2N7000 is selected for a low range Gate threshold voltage.

I had seven 2N7000's in my Junk box, all but one had gate threshold voltages of close to 1.55V. One was was quite different at 2.5V.

The data sheet indicates it can range from 0.8V to 3V. Anything equal to or below 1.6V is ideal for the project.

I_{DSS} 2N7000	Zero Gate Voltage Drain Current	V_{DS} = 48 V, V_{GS} = 0 V 25 Deg C,	2N7000			1	μA
		T_J=125°C				1	mA
$V_{GS(th)}$ 2N7000	Gate Threshold Voltage	V_{DS} = V_{GS}, I_D = 1 mA	2N7000	0.8	2.1	3	V
		V_{DS} = V_{GS}, I_D = 250 μA	2N7002 NDS7002A	1	2.1	2.5	

To test it is simple as shown below done at a similar drain current that occurs in use with a discharged battery. As the power supply voltage in this test setup is reduced the Drain voltage will fairly abruptly rise at some point. Above that G-S voltage (power supply voltage) the Drain to source voltage will stay low:



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