Higher Voltage Capacitors Using Film Dielectric Technology

Ralph M. Kerrigan
NWL
Riviera Beach, Florida
rkerriga@nwl.com

This presentation describes capacitors that are manufactured with film dielectric technology and applied in higher voltage systems. We are defining higher voltage systems as those starting at about 800 Volts DC and 600 volts AC

Major Film Capacitor Dielectrics

Film	K	Max T°C	1Khz DF (%) 10 µF	100 Khz DF (%) 10 µF	Available Thickness (µm)	Cost (1 - 10) Times
Polypropylene	2 . 2	105	.02	.05	3.8 to 30	1
HCPP	2 . 2	115	.02	.05	3.0 to 15	1
Rough PP	2 . 2	100	.02	.05	6 to 20	1 to 4
PET (polyester)	3 . 2	125	.50	1.0	0.9 to 8	1 to 2
PPS	2 . 9	150	.03	.05	0.9 to 15	10

K = the dielectric constant
DF = the dissipation factor
Cost factor has 1 as the lowest
HCPP is high crystalline polypropylene
Rough PP is polypropylene with a roughened surface
PPS is polyphenylene sulfide

This slide shows common films used as dielectrics in capacitors in the early part of the 21st century. It shows some of the common attributes that a capacitor designer would be interested in. Knowing some of the details may also guide a components engineer. These films include Polypropylene in three different varieties since this film is the most important to higher voltage film capacitors. Polypropylene can have a smooth surface, which will not allow much oil to get into a capacitor, and this is made in a version with what we would term a normal film common for the last 40 years and a higher crystalline version that has become very important more recently. I will further describe the higher crystalline version later. For higher voltage capacitors that require complete oil impregnation, there is a rough surface polypropylene that is also very important.

PET or polyester has also been important. It still has its place, primarily in lower voltage systems yet is of less importance to higher voltage systems. Polyphenylene sulfide is a higher temperature film that is used in lower voltage capacitors.

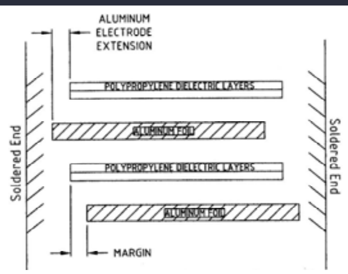
The dielectric constant will give the relative amount of capacitance that is obtained in a capacitor. The maximum operating temperature is also shown. For power systems, we can also be concerned with how much heat is generated in a capacitor fabricated from a given dielectric and this is represented as a dissipation factor. Here we show the dissipation factor at both 1 KHz and 10 KHz for a given size capacitor. We can also see some typical thicknesses of films fabricated from a given polymer type. I also am showing a relative cost of a capacitor made from a given film.

Film Capacitors By Construction

Film With Metal Foil-AC Capacitors Typical at ≥ 800 Vrms	Film With Metal Foil- DC Capacitors Applicable to very high current densities only.
Metalized Film- AC Capacitors Typical at < 800 Vrms	Metalized Film- DC Capacitors The standard for most DC applications

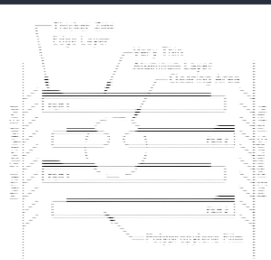
Film dielectric capacitors have two different types of electrodes. These are a discrete foil, which is typically aluminum or a very thin metallization that is vacuum deposited on the film. In addition to two different electrodes, we also can divide the capacitors into AC and DC applications. This produces a two by two matrix. We can see for AC capacitors, the film with metal foil construction is preferred at greater than or equal to 800 Vrms and the metallized film is typically employed at lower voltages. For DC capacitors, film with metal foil was very important in higher voltage constructions or all current levels. Now in DC capacitors, film with foil is usually applicable to very high current densities only. The latest metallized film constructions are very good in DC applications up to much higher voltages as long as the current density is not too high.

Film With Metal Foil Construction

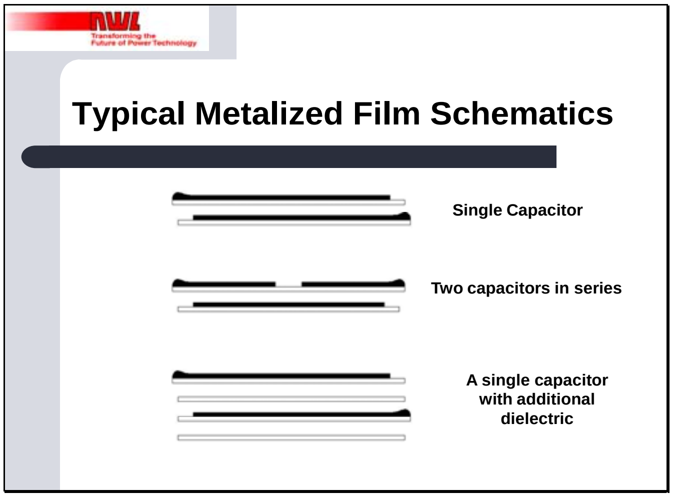


Here is a schematic of a film with metal foil construction. You can see the discrete foils independent from layers of polypropylene film. In this drawing, you can see the aluminum foil ends are soldered to make a connection. It is also common practice to attach to the foil ends with other mechanical connections if the current s are not too high.

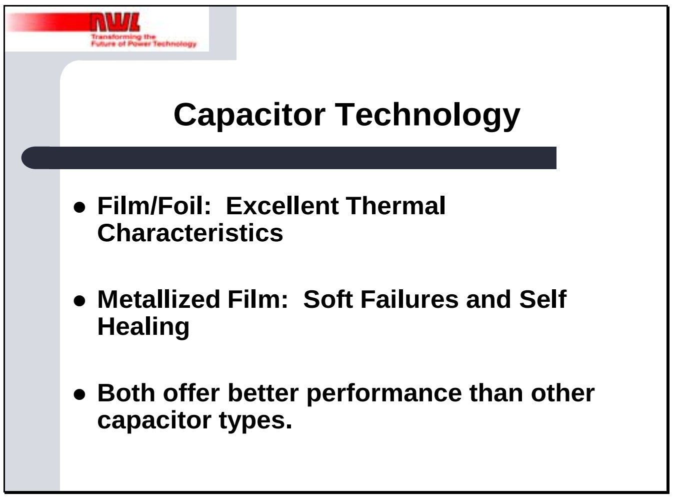
Metallized Film Construction



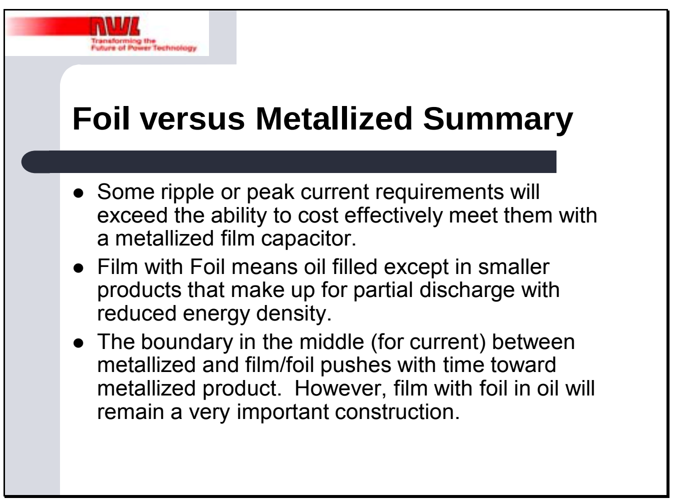
Here is a schematic of a metallized film construction. In the most recent products, the metallization that is vacuum deposited on the films is profiled so it is thicker where it is attached to make an external connection and thinner in the inside of the capacitor body. The internal metallization being thinner allows for a more efficient self-healing process. Self-healing is a process where if a dielectric fault occurs, the area surrounding that fault is evaporated and electrically taken out of the capacitor. The external connection of a metallized film capacitor is made by spraying metal on the ends which then can be soldered to if higher currents are desired or some type of a spot welding process.



Here are some additional examples of metallized film schematics. You can pattern the metallization in many ways for higher voltage applications. On the top, you can see a single capacitor. You can also have two capacitors in series, which can increase the voltage, or you can increase voltage by adding additional layers of plain film dielectric.



We can summarize on the film with metal foil and metallized constructions that are the building blocks of higher voltage film capacitors. The film with foil has the best ability to handle the highest ripple and peak currents. Metallized constructions can be designed to handle higher currents yet their ability is not as high as the discrete foil. The metallized construction has the ability to self-heal, which can prevent a permanent short circuit.



At some point in ripple or peak currents, the metallized film constructions capabilities can be exceeded. This is why most high voltage AC product uses the discrete foil. When using film with foil at higher voltages, the capacitor is almost always oil filled. It is possible to design a metallized film capacitor that is smaller in size than those using the discrete foil for most applications. This usually translates to a lower cost. Newer solutions increase the current capabilities of metallized film capacitors so many of the applications that were always using foil can now used metallized electrodes.

The Stable Loss Factor Of Polypropylene Dielectric Is Excellent For Power Capacitors

Electrical Losses (Tgδ x 10^4)
Tgδ is commonly called the dissipation factor

		Polypropylene	PET
20ºC	50 Hz	< 2	20
	1 Khz	< 2	50
	1 Mhz	< 2	210
100ºC	50 Hz	< 2	40
	1 Khz	< 2	30
	1 Mhz	< 2	230

Polypropylene is the dielectric of choice for high voltage, film dielectric capacitors. This is due to superior and stable losses of this film versus temperature and frequency. Here we can see that at 20°C and 100°C as well as up to 1 MHz, polypropylene has the same low power losses. Another film dielectric that has been used called PET or polyester has a much greater variation versus temperature and frequency.

Density vs. Dielectric Strength

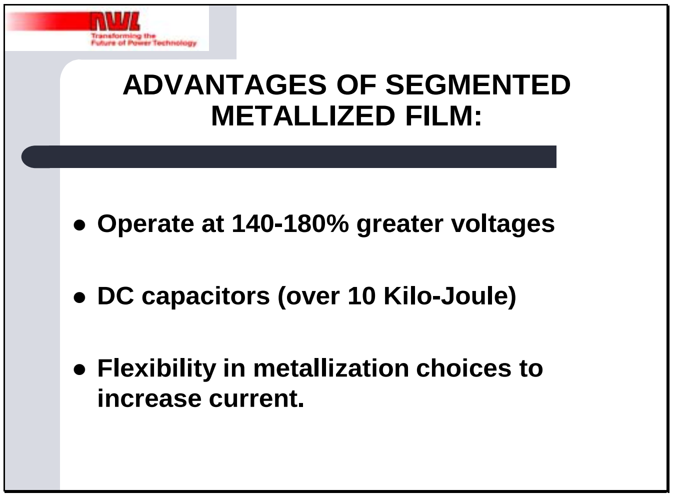
- Capacitance (density) is inversely proportional to the square of the dielectric thickness.
- Capacitance is directly proportional to the dielectric constant (k).
- Modern polypropylene has a dielectric strength of 700 V/µm vs. 500 V/µm for PET (polyester). The 500 V/µm is common to many alternatively proposed films.
- Polypropylene with a k=2.2, PET with k=3.2 means polypropylene typically has a 33% better energy density because of dielectric strength.
- Polypropylene has a better performance for power electronics and now with better energy density, PET has faded except in low voltage applications.

It is important to discuss how energy density is determined for higher voltage film capacitors. We know intuitively that dielectric strength is proportional to dielectric thickness. However, capacitance is inversely proportional to the square of the dielectric thickness. This means that increasing the dielectric thickness by a factor of two in order to double the dielectric strength, increases size by a factor of four. Therefore, in designing these higher voltage capacitors it becomes very important to be able to reduce the dielectric needed in order to keep size and cost reasonable. In comparing two dielectrics again, we can see that the latest polypropylene grades have a dielectric strength 40% more than PET or polyester. Although polyester has a greater dielectric constant almost 50% greater than polypropylene, a typical polypropylene capacitor will have am energy density 33% greater than polyester. Because of this, PET has become less important for higher voltage applications and some major manufacturers of PET for capacitor applications have discontinued thicker grades of film.

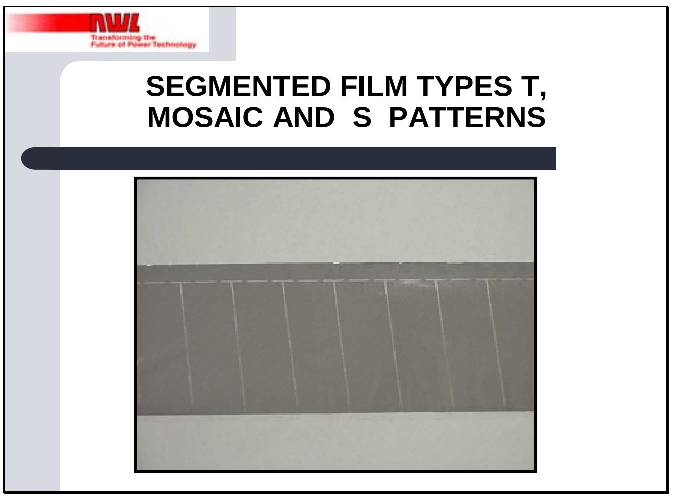
High Crystalline Metallized Polypropylene (HCPP)

- **Allows a 33% reduction in volumes over previous generation products.**
- **Allows a 115 degrees C maximum continuous operating temperature capability.**
- **High crystalline metallized polypropylene also enables resin encapsulated capacitors with increased energy densities for many voltage levels.**
- **This is a 21st Century Major Improvement.**

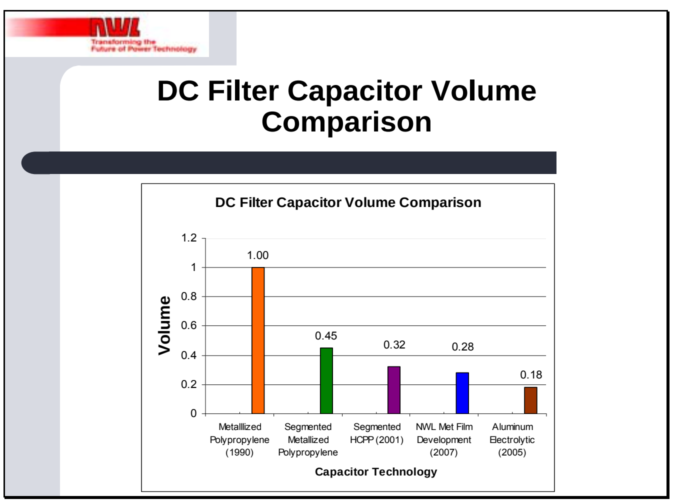
One of the most dramatic improvements in polypropylene for capacitor applications is a higher crystalline grade. This material improvement allows higher voltage operation for a given dielectric thickness as well as an increase in the operating temperatures. Due to this materials characteristics, it has been possible to change the maximum operating voltage for a given metallized capacitor design without oil. Therefore resin filled designs are becoming more common at higher voltages than they were in the past.



Another technique that is applicable making higher voltage capacitors with film dielectric is the use of segmented metallized film. Segmented film is the adding a pattern to the metallization on the film that is essentially dividing the capacitor into a large number of independently fused areas or segments. By doing this, you can increase the operating voltage since in a metallized capacitor when self-healing occurs there is also heat generated. The heat generated during self-healing can cause damage if it is too great. The segments act to isolate an area that may have this more significant heating before it can do further damage. This allows making very large high voltage capacitors. It also allow a capacitor designer to use greater metal thicknesses to increase current handling and still have the ability to self-heal.



Here is an example of a typical segmented pattern on a metallized film. You can see the film surface is divided into multiple independent areas. You can see that there are little open areas, which can be called gates for current to flow thru. These gates are devices that act like fuses. In their case, when a large fault or self-healing occurs they close and prevent further current from flowing in that region. Thus, the region is isolated with only a smaller amount of capacitance reduction.



Here is a representation how the applications of segmented metallization and higher crystalline base film have contributed to a dramatic increase in energy density for film capacitors in higher voltage systems. The volume of the film dielectric capacitor about 20 years ago is represented by a 1 or 100%. We can see the use of segmented electrodes make the approximate volume 45% or the original volume. In the start of the 21st century, the addition of high crystalline grade film made the volume 33% of the original. Further refinements of these technologies are still occurring yet we are under 30% of the original volume. We then can compare this volumetric efficiency versus the competing aluminum electrolytic technology and see where the film technology was over five times the volume of the aluminum electrolytics in a system, it is now within a much closer range.

Metallized DC Filter Capacitors

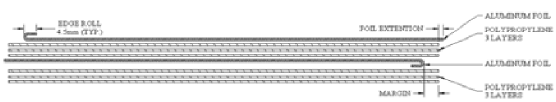
Another feature of higher voltage, metallized film capacitors is that they can be packaged in convenient rectangular packages. You can see in the foreground, four rectangular film capacitors in a row with a small amount of spacing. Also represented is a liquid cooled capacitor with integral liquid cooling. In many high voltage power systems, the power semiconductors and other components may be liquid cooled. A capacitor with integral liquid cooling may also be an attractive option for thermal management.

Partial Discharge

- Partial discharge can have a dramatic effect on energy density and cost.
- Partial discharge makes limitations on voltage per capacitor element. This in turn leads to designing with capacitor elements in series.
- Capacitor elements in series increases volume, material usage and associated cost.

Any discussion of a higher voltage system would be incomplete without discussing partial discharge. Partial discharge effects the size and cost of a capacitor. It requires multiple capacitor elements to be wired in series in order to minimize it. This series wiring may be done externally be the user of internally to the capacitor. More series wiring increases size and cost.

Foil folding reduces partial discharge of AC Film/Foil products.



For higher voltage capacitors with film dielectric and aluminum foil electrodes, there are techniques available to reduce partial discharge. One such technique is to fold the aluminum foil to produce a rounded edge. Here is a drawing of what this looks like.

High Speed Film Foil Winding

Here is a photo of a piece of winding equipment that is used for making high voltage capacitors with film dielectric and aluminum foil electrodes. This allows a capacitor element to be made in an automatic repeatable fashion including the folded foil attributes for partial discharge elimination.

Advantages of High Voltage Oil Filled Film Capacitors

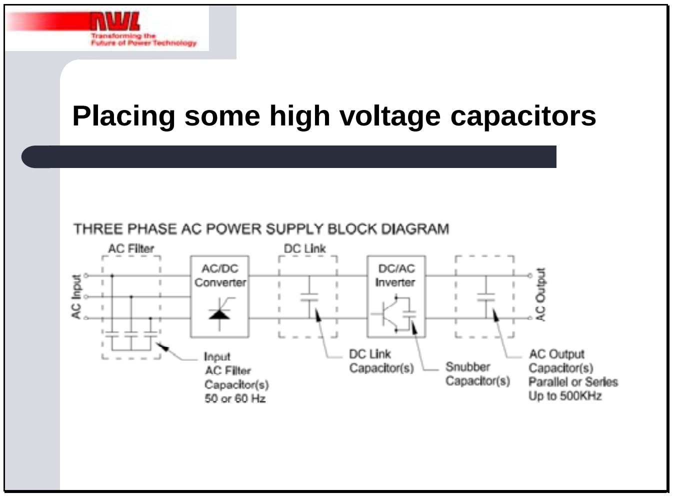
- Oil filled AC and DC film dielectric capacitors have certain advantages in life and thermal transfer over dry capacitors.
- Oil filled AC capacitors are still the industry accepted standard for most ratings. A smaller amount of AC ratings are available in constructions that are not oil filled.

Oil filled high voltage capacitors due have some advantages in life and thermal transfer over non oil filled versions. For AC capacitors, oil filled versions are still the industry standard.

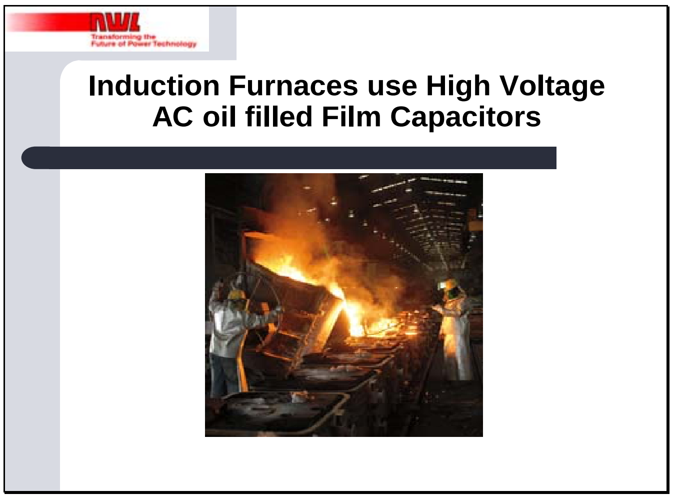
Where does dry construction apply?

- **Concerns on fire retardancy and disposal.**
- **Standards such as NESC (National Electric Safety Code) state if not oil filled “don’t worry” yet if oil filled “take these precautions”.**
- **Resin filled has a broader temperature range than vegetable oil. Resin filling has a typical range -50 C to +115C, Vegetable oil which is common for DC Link capacitors as a range of -25 C to +90 C.**

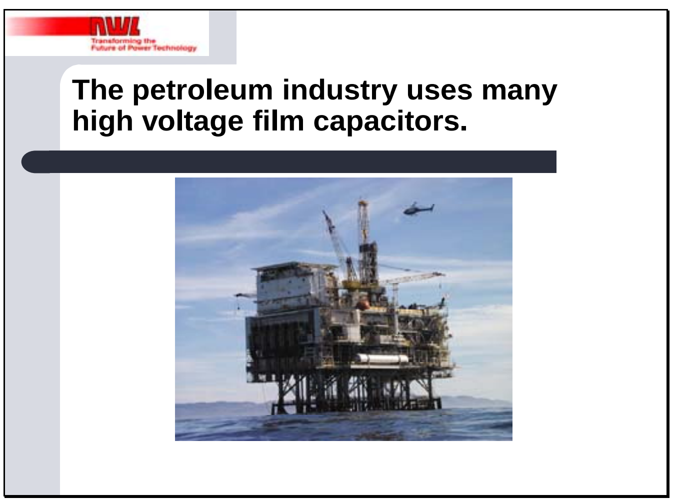
Large oil filled capacitors without oil filling have become more common in higher voltage systems. These designs can alleviate some concerns that may occur due to fire retardancy and disposal. Oils used today are much more environmentally friendly than many years ago. In DC applications, the oils usually have very high fire points and flash points. However, if there is no oil, some specifications will say do not worry yet with oil to take some precautions. It is usually common for resin filled designs to be able to operate at lower temperatures and higher temperatures than oil filled ones.



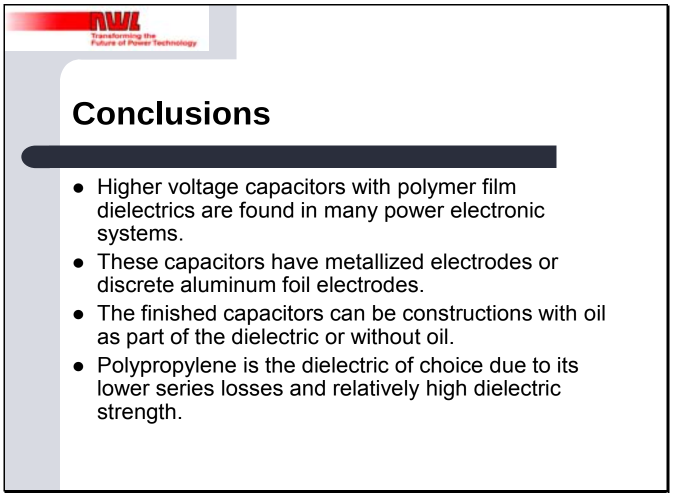
Here is a schematic showing how some of these higher voltage, film dielectric capacitors can be applied in a medium voltage system. On the input we may have a filter capacitor or capacitors seeing a 50 or 60 Hz voltage with superimposed harmonics. A system of this type may typically be used from 400 to 7200 Vac. The AC input voltage will be rectified in an AC/DC converter. The output will then be a DC waveform with a ripple voltage. Then we may be seeing a DC link or multiple DC link capacitors in the range of 600 to 10 KVdc. Film capacitors of this type can do this with lower amount of series and parallel wiring. If this is an AC to AC system, the DC voltage will be converted in an inverter. On many designs we may then have snubber capacitors. On the output we may have parallel or series resonant capacitors. For film technology, typical frequencies may be up to 500 KHz.



An application where the system looks very much like the schematic that was shown is Induction Furnaces. They actually use most of the technologies of high voltage, film dielectric capacitors that was presented on the previous matrix. This includes AC capacitors with aluminum foil electrodes. The reactive power is so high that they are almost always water cooled. The DC Link capacitors are usually water cooled as well.



The petroleum industry uses medium voltage motor drives for pumping and transferring oil and natural gas. These systems may also look similar to the previous schematic. We would also see high voltage metallized film and film with foil capacitors in these applications.



We would conclude with a summary that the higher voltage, film dielectric technology capacitors are found in many power electronic systems. These capacitors may be using metallized film or have film with aluminum foil electrodes. The finished parts can be oil filled or be manufacturer without oil filling. Due to its superior electric characteristics, polypropylene is the most widely used dielectric for these capacitors. Thank you for your attention.