Title: An Introduction to VIP Technology
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Abstract:

Vacuum insulation panels offer extraordinary performance in reducing the total heat transfer across a space. They work by eliminating convection, reducing radiation, and minimizing both solid and gaseous conduction. A review of vacuum insulation technology shows that efforts to produce such panels began about 20 years ago. Over this period of time, great progress has been made in improving the panels' performance and durability. These improvements include the filler material and the skin, and the manufacturing processes. Our fundamental understanding of the heat transfer mechanisms within the panel has also grown, leading to new panel designs and better methods of incorporating the panels into manufactured products.

Biography:

Therese K. Stovall received her B.S. in Mechanical Engineering from Purdue University in 1977 and her M.S. in Mechanical Engineering from the University of Tennessee in 1988. She joined the Metals and Ceramics Division of Oak Ridge National Laboratory in 1995. There, she has contributed to laboratory evaluations of a variety of insulation materials, focusing her efforts on powder-filled evacuated panels. She also revised the DOE Insulation Fact Sheet and is the chair of two ASTM Task Groups in the C16 Insulation Materials Committee. Therese is a licensed Professional Engineer in Tennessee and a member of ASME, ASTM, and ASHRAE.

Ms. Stovall was a member of the Engineering Technology Division of the Oak Ridge National Laboratory from 1978 to 1995. During this time, she worked on a variety of projects. She supported the Advanced Neutron Source program by evaluating the thermal hydraulic effects of a core inlet blockage. Therese also managed the Ice Storage Test Facility, a commercial ice storage testing program sponsored by the Electric Power Research Institute. Other thermal energy storage efforts have included analysis of load, energy use, and comfort effects associated with the use of phase-change materials in residential applications.

An Introduction to VIP Technology

Thank you for the opportunity to speak here. Vacuum panels offer extraordinary performance. Here's one of my favorite photos that demonstrates how you can get a lot of insulation performance into a very small space. This is a photo of two pieces of insulation, one fiberglass and the other a vacuum insulation panel, that offer the same performance. Note that the vacuum panel is about 1/7 the thickness of the fiberglass. How do these panels work? Not by magic; today I may tell you that vacuum insulation panels are the greatest thing since sliced bread, but I'm also going to tell you how they work. First, I will give you all a bit of heat transfer 101 and go over some of the terms we'll be using for the next two days. Then I'll move

on and cover some of the development history behind today's panels and discuss the panels' components.

Any insulation works by impeding the heat transfer from point a to point b. Energy will cross any space separating a hot region from a cold one, even if the space is insulated, via 3 heat transfer mechanisms: convection, conduction, and radiation.

Convection occurs when fluids (either gases or liquids) are moving, transporting energy from one place to another. Convection can be caused by forced flows, such as by fans, or by natural convection that occurs when colder/heavier particles fall and warmer/lighter particles rise. Convection is, under most circumstances, the most effective way to transfer heat. For example, forced convection is used in car radiators and other heat exchangers to transfer the most heat possible across the smallest possible temperature difference and in the smallest space. That's why every form of insulation must work to stop convection from occurring. Conventional insulation retards convective heat transfer by interfering with the air's movement. Vacuum panels eliminate convection by removing most of the gas from a space.

Conduction occurs when one molecule transfers energy to another molecule in direct contact. This is easiest to picture when you think of a solid material, such as when you touch the side of a cup holding a hot drink. The heat flows from inside the cup, through the cup material itself and into your hand. Solid materials used in insulation also conduct heat, although at a lower rate. Think of holding coffee in a glass cup vs in one made of Styrofoam. The heat will still flow into your hand, but at a slower rate and the temperature difference across the material will be greater, so that your hand will not feel burned. Liquids and gases also transfer heat by conduction. Whenever two molecules collide, or touch, energy is transported from the hotter one to the cooler one. This form of molecule movement occurs all the time, even when there is no fluid flowing. Thus, gas can transfer energy by conduction even when the air is still and no convection (or overall gas movement) occurs.

Radiation is the transfer of heat across any space, such as the heat we feel when we turn our faces to the sunshine. When radiation hits an object it can be reflected, or bounced, transmitted (think of light pouring through a pane of glass), or it can be absorbed (think of the temperature of your car upholstery after the car sits in the sun awhile). In this picture, the rays shown traveling all the way across this space may be bounced back into the space if the far wall is very reflective. They can pass through that wall if it's transparent. If the energy is absorbed in the wall, the wall will become warmer. Sometimes radiation interacts with intermediate objects within a space. For example, if the radiation hits a gas molecule or some solid object within the space, then that object can either reflect, transmit, or absorb the energy. So the energy can pass through the space in a series of steps instead of going directly from one side to the other. As you can imagine, this form of stepping radiation is not as efficient as when the radiation crosses the entire space in one jump. So insulation materials can reduce radiation heat transfer by placing such obstacles in its way.

Conventional insulation reduces convection and radiation and minimizes solid conduction, but it allows conduction through the still air trapped within the material. All three of the insulation materials shown here (fiberglass, foam, and a vacuum insulation panel) effectively eliminate convection. Less dense insulation, such as loose-fill fiberglass will permit convection if the temperature difference is large enough. Some radiation travels across all three of these insulation forms, although less than would travel across an empty space, because they all contain materials that interfere with the radiation as I've just shown you. Conduction also occurs in all three forms, but to varying degrees. In the fiberglass batt, you have solid conduction

through the fibers and gaseous conduction through the still air. In the foam insulation, some heat travels through the web of plastic from one side to the other and there is also conduction through the gases trapped within the foam cells. In the vacuum insulation, both solid and gaseous conduction also occur, but the gaseous conduction is very, very small, producing the much reduced heat flow through this form of insulation. Note the reduction in the heat flow shown here for fiberglass, foam, and vacuum panel insulation.

Let's talk for a minute about some of the terms used to describe the insulation's thermal resistance. English units for thermal resistance are hr-ft2-F/Btu-in. This mouthful is usually referred to as an R/in. For example, the fiberglass batt shown here is labeled 3.5 R/in. That means that an R-19 batt that you buy to put in your wall or attic will be almost 6 inches thick. A metric unit of resistance would be a meter-Kelvin/Watt. Thermal conductivity is the inverse of thermal resistivity, so you would talk about a Watt/meter-Kelvin, or an in./R. There are other combinations of these units in use, so the best practice is to follow the advise of my freshman physics professor: if you haven't checked your units, the problem isn't done.

Before we go on, let's talk for just a minute about the word, vacuum. It turns out that the term 'vacuum', is seldom absolute and there's always some small amount of gas left within the space. Think about dividing some length in half, over and over. The remaining length becomes very very short, but you will never get to a line of zero length. That's why vacuum pressures are often shown on logarithmic scales. Very small pressures (or very high vacuums) are usually given in a unit of measurement called a torr. A torr is equal to the pressure needed to hold up a column of mercury 1 mm tall. You're used to hearing about pressures expressed in inches of mercury or inches of water, and the concept is the same. At sea level, one atmosphere is about 760 torr, in the mountains of Tennessee, the pressure is usually around 740 torr. Within a vacuum panel, the pressure will be less than 10 torr, usually less than 1 torr, and often less than 0.1 torr. That should help demonstrate why we use logarithmic scales to describe the pressure within the panel. You can see that if we use a linear scale for the pressure, most of the useful information is squeezed to one side. This way of looking at the data, here we show thermal conductivity vs. pressure on a logarithmic scale, also tells us more about the physics within the panel and helps us to design a better panel. Sometimes we plot the thermal resistance on the vertical axis and sometimes we plot the thermal conductivity. Remember that the thermal resistance is just the inverse of the conductivity. We'll be talking more about the shape of this curve, and how to change it, over the next two days.

Where do we stand now on vacuum insulation technology? Where did we begin? Let's stop and think about the vacuum insulation that's been around as long as any of us. Think of the thermos bottles you use now for coffee, or that you used to take soup to school when you were little. These thermos bottles look like plastic or metal on the outside, but these coverings usually hide evacuated glass containers with very shiny surfaces. Did you ever drop one? In examining the debris, didn't you wonder why they were made of something as breakable as glass - and why they were shiny? First, glass is a very effective barrier to air and other gases, so it does a good job of holding a vacuum. Second, the shiny surface reduced the radiation heat transfer, much the same way that reflective window coatings work. Vacuum insulation has also been used for cryogenic systems for years. These systems have many layers of thin reflective material in an evacuated space. Most of these systems are hooked up to active vacuum systems that remove any air or water vapor that gets into the space. About 20 years ago, a number of people started working on more durable, and hopefully cheaper, forms of vacuum insulation that would be suitable for appliances. Their goal was to achieve very high thermal insulation values in much

smaller spaces. Based on early evaluations of refrigerator/freezer energy use, a target of 20 R/in. was established. Today we have products on the market that can deliver between 15 to 35 R/in., depending on how much you want to spend and how long you want them to last. What's been done in the last 20 years to bring us to where we are today?

The earliest such vacuum panel concepts turn up in patents granted in 1979 and 1983. The overall concept remains much the same today. There are two main components, the core and the barrier. These early patents used powders as the core material and flexible plastic films as barrier materials. These early developers soon discovered that if you were going to use a powdered filler that you would also need some kind of inner porous container between the core and the barrier so that you wouldn't suck all that powder into your vacuum system. These powders included fumed silica, opacified fumed silica, silica bag-house dust, perlite, precipitated silica, fly ash, clays, and many mixtures of these powders. Silica aerogels were discussed in those early days, but were very difficult to manufacture. Other developers were examining fibrous glass wool products with various opacifiers to reduce the radiation through the glass. Fibrous glass papers were examined in a quest for a load-bearing insulation product. Open-celled polyurethane foams were also tested. There were two classes of barrier materials in the earliest development period, plastic laminates and metallic foils. The plastic laminates were easier to seal, but were more permeable. The metallic foils required brazed, soldered, or welded edges, but were capable of holding a much lower pressure for extended periods of time. Later generations used barriers that were multi-layer plastics and multi-layers films that incorporate both plastic and metallic elements. Getters, or materials that can adsorb gases that find their way into the evacuated space, were developed. Manufacturing techniques have also evolved over this time, as well as our fundamental understanding of how the integrated system works.

We'll talk at great length later this morning about the core material. To give you a brief overview, the core must serve to support the barrier material (think of how a balloon goes flat if there is no air inside to press against the air pressure outside), it must have low thermal conductivity itself, and it must interfere with radiant heat transfer across the panel.

During this 20-year development process, we also learned how important the structure of the core is. Remember that there is some small amount of gas remaining within the evacuated space and that this gas will conduct heat whenever two gas molecules collide. The distance that a gas molecule typically travels before it touches another gas molecule is called the 'mean free path', and that depends on the size of the gas molecule, the temperature of the gas, and the pressure. It turns out that if the space *available* for a gas molecule to travel before it hits some part of the core - whether that be a powder particle or a foam strut - if that distance is shorter than the particle's mean free path, then the gaseous conduction is drastically reduced. So there are two things you can do: one is to lengthen the mean free path by reducing the pressure, and the other is to reduce the size of the spaces within the vacuum panel. This understanding led us to ever finer powders and smaller foam cell sizes.

Even with this understanding, much of the development process is still one of trial and error. For example, a significant amount of effort was spent on 'waste' powders, such as fly ash or steel mill waste. These powders were chosen for two reasons. First, as 'waste' products their cost would be very low, second they were known to consist largely of silica and to have small particle sizes. The most effective fillers before this examination were fine precipitated silica powders that tended to be quite expensive. Flyash was especially appealing because it is so plentiful, and because it poses a significant disposal problem for our society. Here are some photographs of flyash taken with a scanning electron microscope. You can see the flyash

particles come in a wide range of sizes. Almost every sphere is hollow and the larger ones contain a host of smaller spheres. The raw flyash is composed largely of silica-, aluminum-, calcium oxides. The structure is even more complex than you would suppose at first glance. When we looked at this specimen, we noticed a small flap in the broken wall. We zoomed in for a closer look, and we found spheres not only within the cavity of the large sphere, but also within the wall itself. We then modified the particle size distribution for the panel filler by milling and classifying the powder. If you compare the scales shown in these two photos, you'll see that the particle size has been shifted to much smaller values. Another way of looking at the powder size is laser doppler velocimetry. That also confirmed that the powder's particle size had been reduced. The horizontal axis shows the particle size in microns and the vertical axis shows what fraction of the powder specimen was found in that size range. You can see that the raw flyash showed a bimodal distribution, with many large particles and also a good number of particles near 0.4 microns. The milling process apparently broke many of those large spheres, freeing the smaller spheres that had been contained within their shells. That milling process tripled the thermal resistance of a flyash-filled vacuum panel. This graph shows the thermal resistance of the center of the panel vs the internal pressure and you can see that the flyash panel increased from less than 5 R/in. to more than 10 R/in. However, that still wasn't enough to make this waste product into an economic filler. Even if the flyash were free and there were no costs associated with the milling process, the cost of constructing the remainder of the vacuum panel is too high if all you're going to get is R-11/in. You'll hear more later today about some of the newer and more cost-effective fillers that are coming onto the market.

Now let's switch from discussing the panel's core to discussing the panel's skin. The skin of the panel must keep gas from entering the evacuated space. That's a lot harder than it sounds. They say that nature abhors a vacuum, and the air and water vapor molecules surrounding these panels work hard to prove that old adage true.

The barrier material selection must balance several important qualities. First, they must offer high resistance to gas transfer, something that metals excel at. Second, the skin must offer high resistance to heat transfer through the barrier material itself, an area where plastics are better than metals. This quality is important because of edge losses, or a thermal bypass around the vacuum insulation region. If the barrier material is highly conductive, heat will flow through this material itself and travel right around the insulating core region. Think of a detoured road going around a construction project. If the speed limit is 15 miles per hour, fewer cars can travel around the construction in an hour's time than if the speed limit is 70 miles per hour. A higher conductivity is like the higher speed limit. The magnitude of the thermal bypass effect is also determined by how thick the material is. Just as fewer cars can travel down a 1-lane road than on a 4-lane road, less heat can travel along a thinner barrier than along a thicker barrier. The third consideration is that the barrier must be cost effective to form and must be relatively easy to seal. Some multilayer films have been developed to try to offer the best qualities of both the plastic and metal materials, and you'll hear more about those later today.

The manufacturing challenges are manifold - they include devising cost-effective methods for: shaping, evacuating, testing, shipping, and final installation in a product. Some early methods used equipment originally designed for vacuum-sealed food products. One key challenge is to produce a durable evacuated product in a short period of time. To put this in perspective, we often take more than 24 hours to evacuate an experimental panel - obviously our methods would not be acceptable for commercial production. Also, the manufacturing techniques will differ greatly depending on the barrier and core material selection.

Testing methods have been refined as well as the panels themselves. Testing is important for comparing the performance of alternative panel designs and for quality control during the manufacturing process. There are several separate measurements that are key to understanding panel performance. Ultimately, you want to know the thermal conductivity of the panel. To help with that determination, you often want to know the pressure of the gases within the panel and the thermal conductivity of the panel components. Most of the traditional thermal conductivity measurement techniques were developed for homogenous materials, such as fiberglass or cellulose or foam. Also, the conventional testing methods were developed for materials with higher thermal conductivities. Using conventional testing equipment, therefore requires a careful evaluation of the physics involved. Corrections are usually required - often finite difference computer models are made of the both the insulation and the testing apparatus to determine the true panel performance. Here is a picture of a variable pressure panel we've devised to allow us to measure the thermal conductivity of various filler materials over a broad pressure range. You'll notice that we use a low conductivity plastic film to prevent edge losses from affecting the test results. The higher permeability of the material doesn't matter here because the panel interior is directly connected to a vacuum system that controls the pressure within the panel. The vacuum pump apparatus includes carefully calibrated pressure gauges. This is how we generate the kind of curves I've shown you of conductivity vs internal panel pressure. Note that this apparatus is useful for evaluating the performance of the core material, but not that of the barrier material.

That brings us to the issue of system performance. I've mentioned that you have to consider the conductivity of the barrier material itself. The system performance is also affected by the overall shape and size of the panel. If the panel is very large, the amount of heat that will flow around the edge will be a relatively small portion of the load on the panel. However, if the panel is small, the heat flow around the edge can undo all the heat resistance offered by the evacuated area. An analysis of the effect of the edge losses on the overall energy saving in a refrigerator was made by Ken Wilkes, who'll be talking later today. For this analysis, the panel sizes were selected to fit the refrigerator walls. This graph shows the energy savings in kWh/year vs the cladding thickness for 3 different cladding conductivities and 2 different filler resistivities. Notice the wide range, from almost 110 kWh/year down to about 30 kWh/year. Also notice that as the cladding thickness gets greater, the thermal resistance of the filler becomes less important.

I mentioned that during testing we often have to use computer models to fully understand the experimental data. Here is one way of doing that. The panel, shown by the smaller red square, is placed in a heat exchanger which is equipped with an array of heat flux transducers, indicated by each of these black squares. The heat flux through each of these squares is independently measured and recorded. As you can imagine, those squares over the edges show much higher heat fluxes than those in the center. This heat flow pattern is compared to the predictions from a mathematical model. You then vary the conductivity of the core or the barrier material assumed by the model until the model's heat flow patterns match those measured.

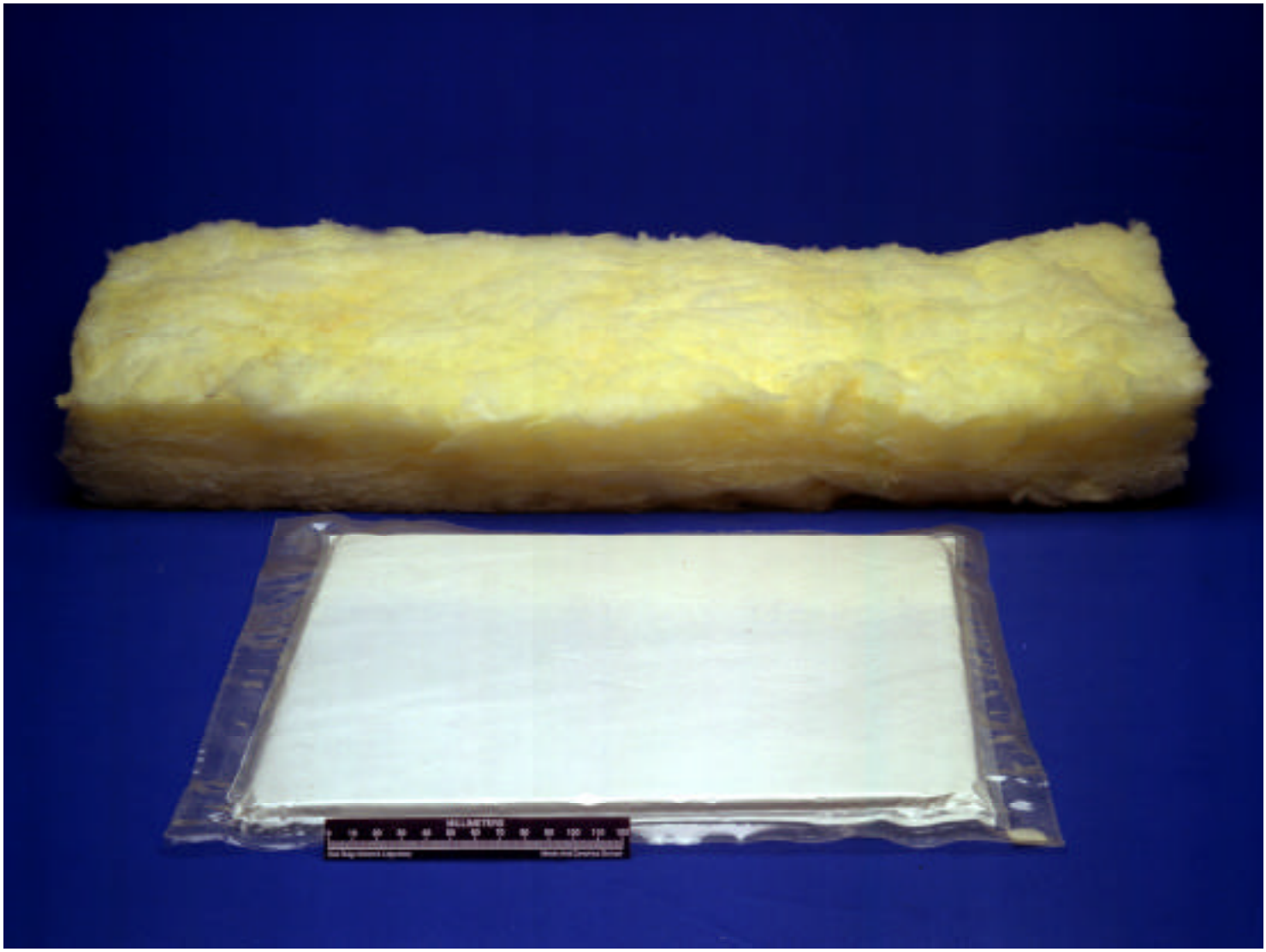
With many insulation materials, aging is a concern. For example, some loose-fill insulation will tend to settle, thereby offering less thermal resistance than when it was new. Some foam insulations also age as air seeps into the foam cavities and the less conductive blowing gases seep out. Vacuum insulation also ages because various gases find their way into the evacuated space. Some of these gases come from the environment outside the panel and gradually diffuse through the barrier material. This process can take place over a few years or over 20 years, depending on the permeability of the barrier itself. Other gases can come from the

panel materials themselves, from outgassing from the core or barrier. Panels can compensate for these phenomena by careful material selection, by starting with a lower pressure than needed, or by including special adsorbent material within the panel itself. These adsorbent materials, called getters, are designed to target specific gases. Some trap water vapor, others atmospheric gases, and still others can capture the gases that outgas out of various materials. Ongoing experiments have placed vacuum panels into 2-foot square refrigerator wall sections. These sections include one steel wall, one plastic wall, and the evacuated panel is surrounded by foam. The edges are sealed with metal tape. Some of these experimental panels have been measured over a 5-year period to determine how their performance changes. These and other experiments have shown that the panel's environment can play a significant role in controlling the aging process. Later in this conference, we'll go into more detail in how the aging process can be understood and controlled.

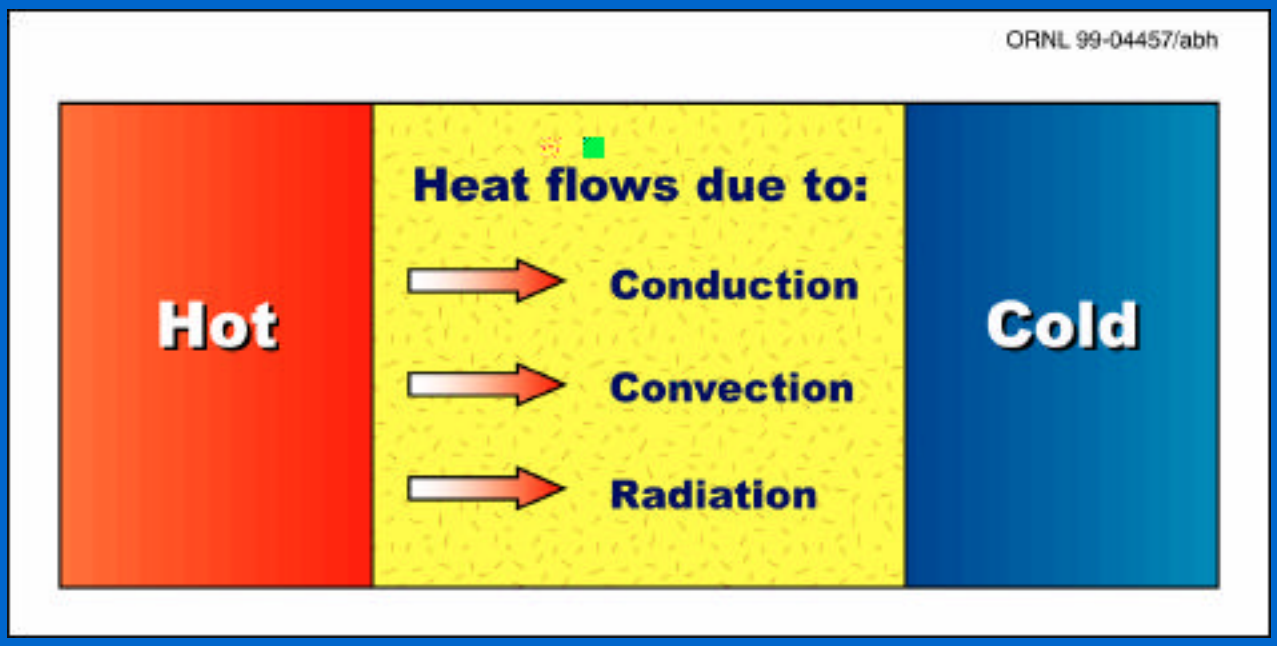
As I've shown you in this brief overview, vacuum insulated panels offer exceptional performance, but they're not as simple to use as other forms of insulation. How does the appliance designer or panel purchaser know what to ask for, which panel to purchase? To address this difficulty, a number of interested parties have been working through the American Society of Testing and Materials to develop a vacuum insulation materials standard. We're currently on draft nine and hope to make this standard available in the near future.

In summary then, vacuum insulation panels offer very high thermal resistance in a very small space. What was once a pie-in-sky idea is now on the market and the price is rapidly coming down from sky-high values as well. These products should be seriously considered for any application where space is limited, or where very high insulation values are needed. I've touched quickly on a host of issues this morning - I hope I've piqued your curiosity and given you a long list of questions that we can answer over the next two days.

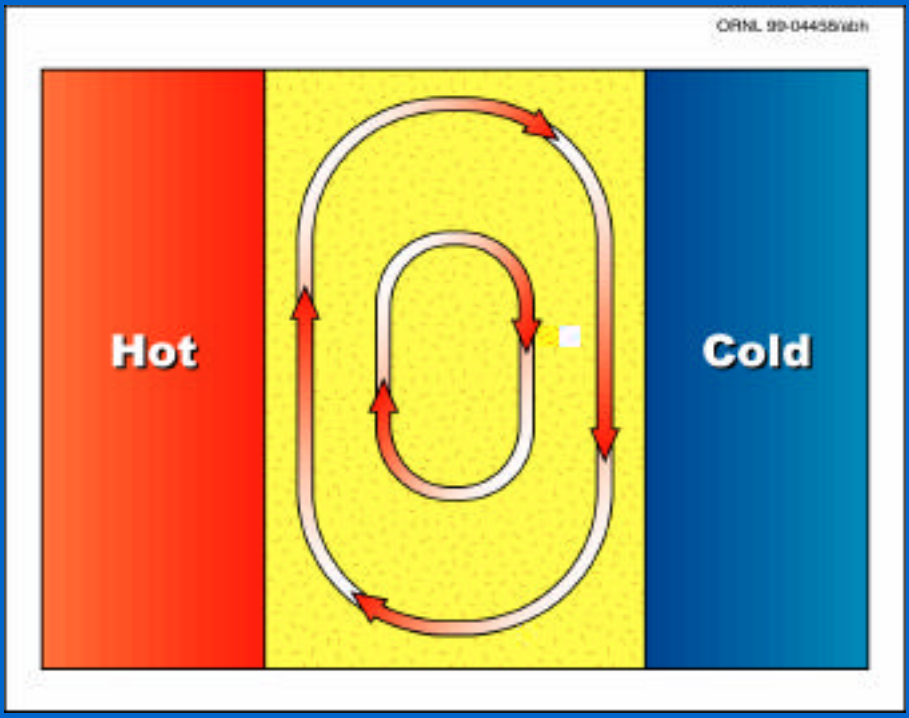
An Introduction to VIP


MILLIMETERS

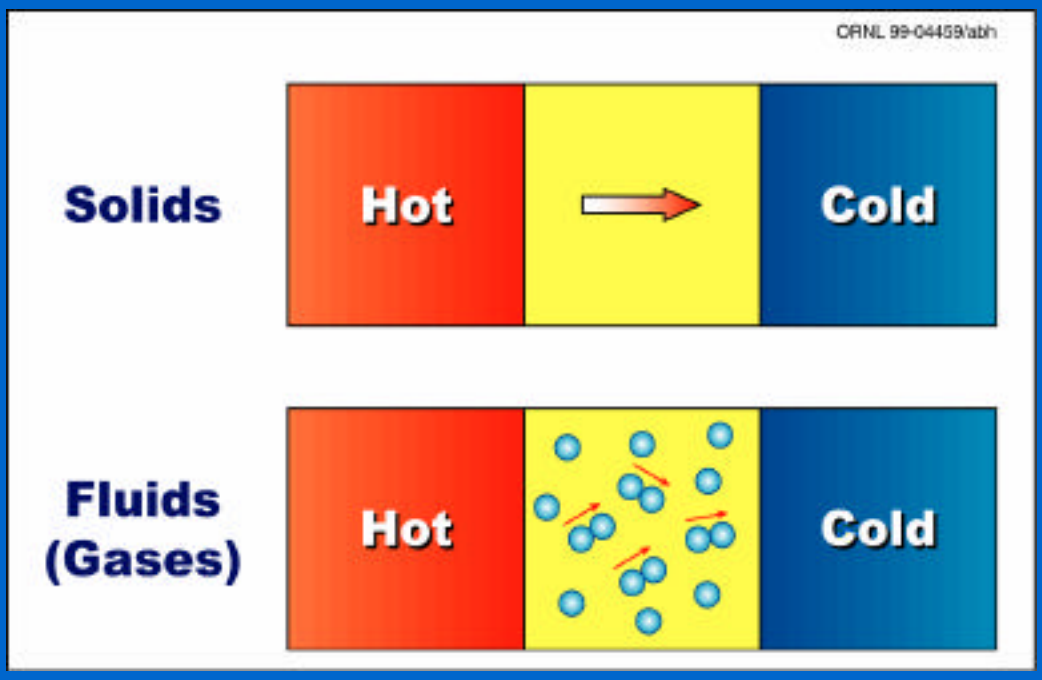
Heat transfer follows one of three paths



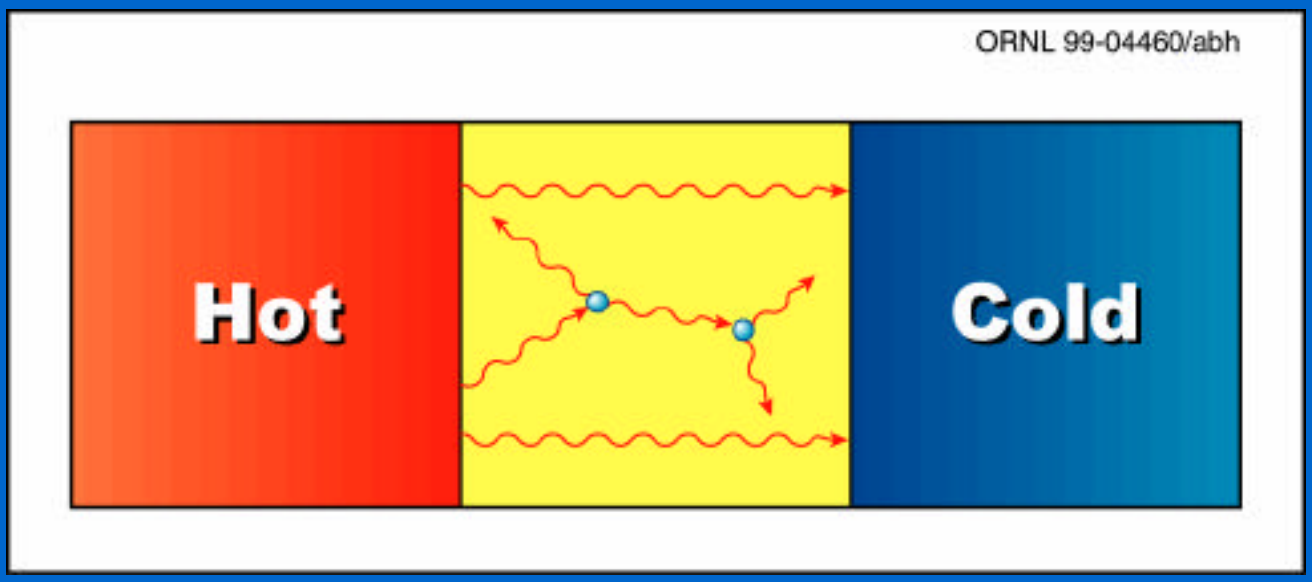
Convection involves moving fluids



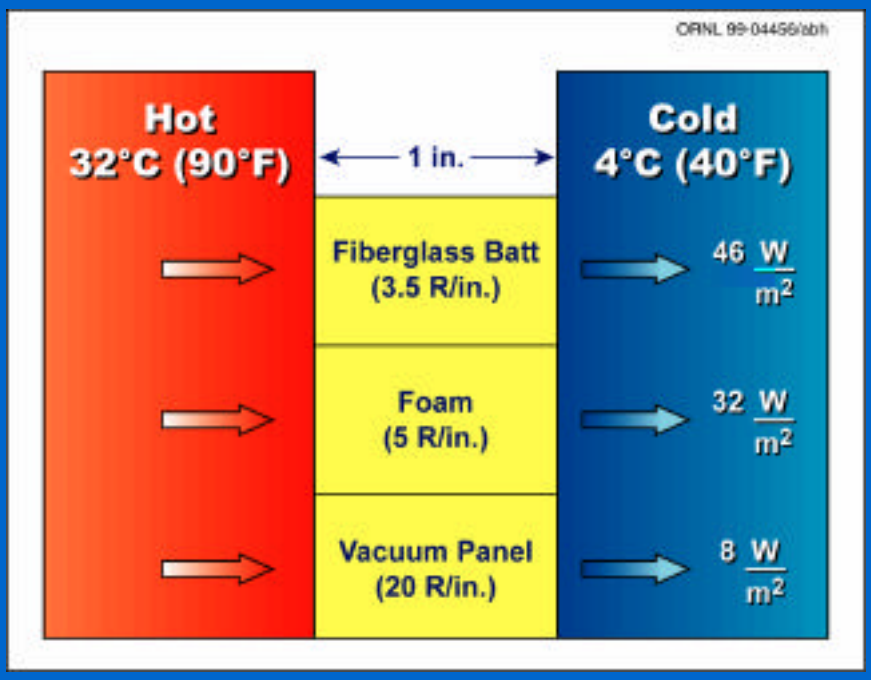
Conduction - heat transfer by touch



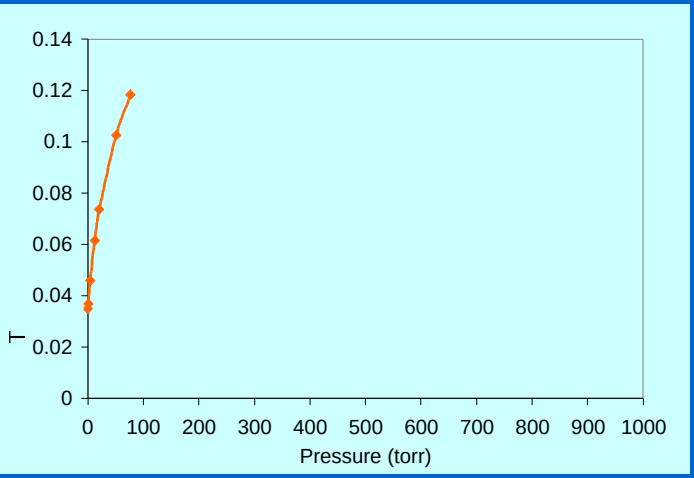
Radiation - waves of energy



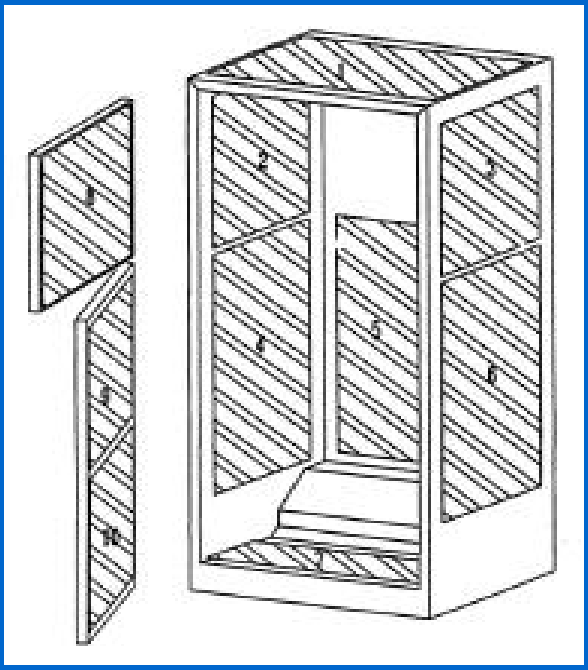
Insulation slows down heat transfer



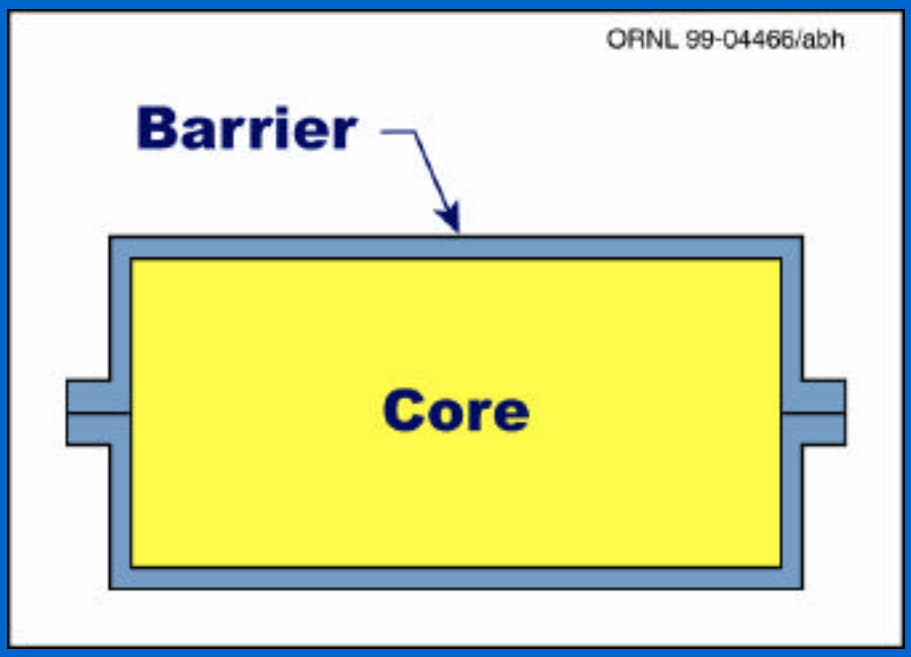
Vacuum pressure usually quoted in ‘torr’



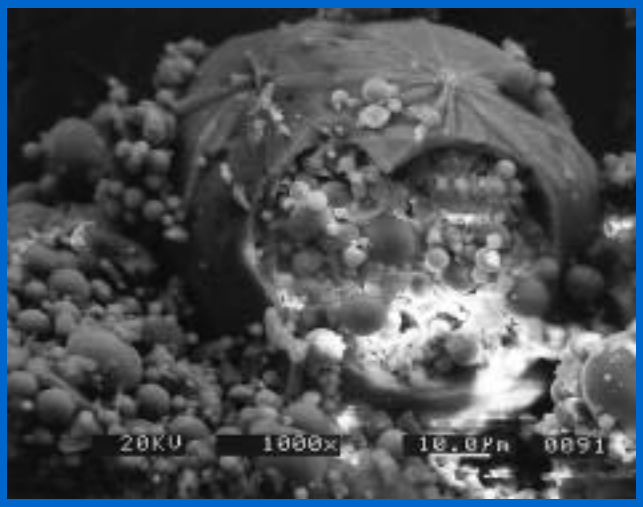
Early refrigerator/VIP concept



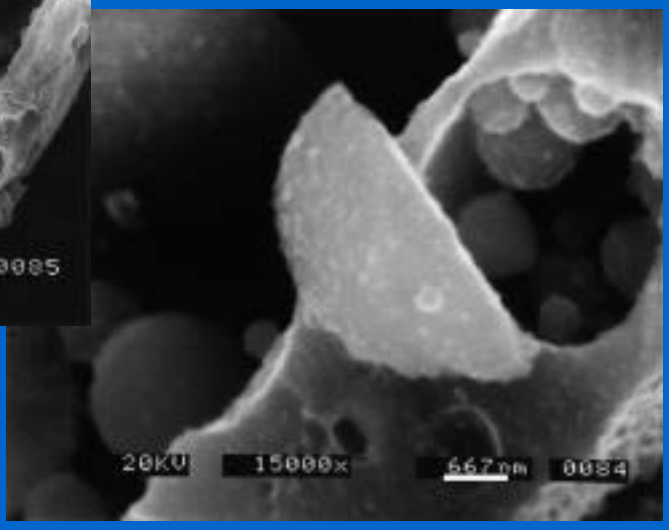
What is a Vacuum Insulation Panel?



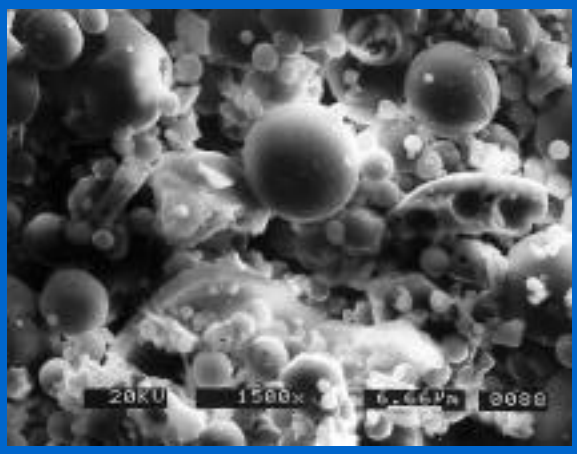
Powder morphology examined - flyash



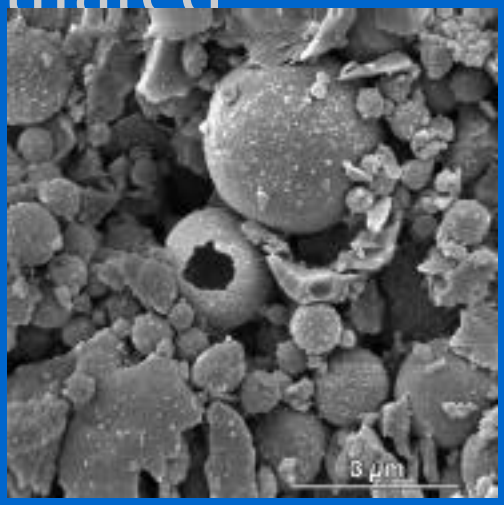
A closer look revealed spheres within the walls as well



Particle size was both measured and manipulated

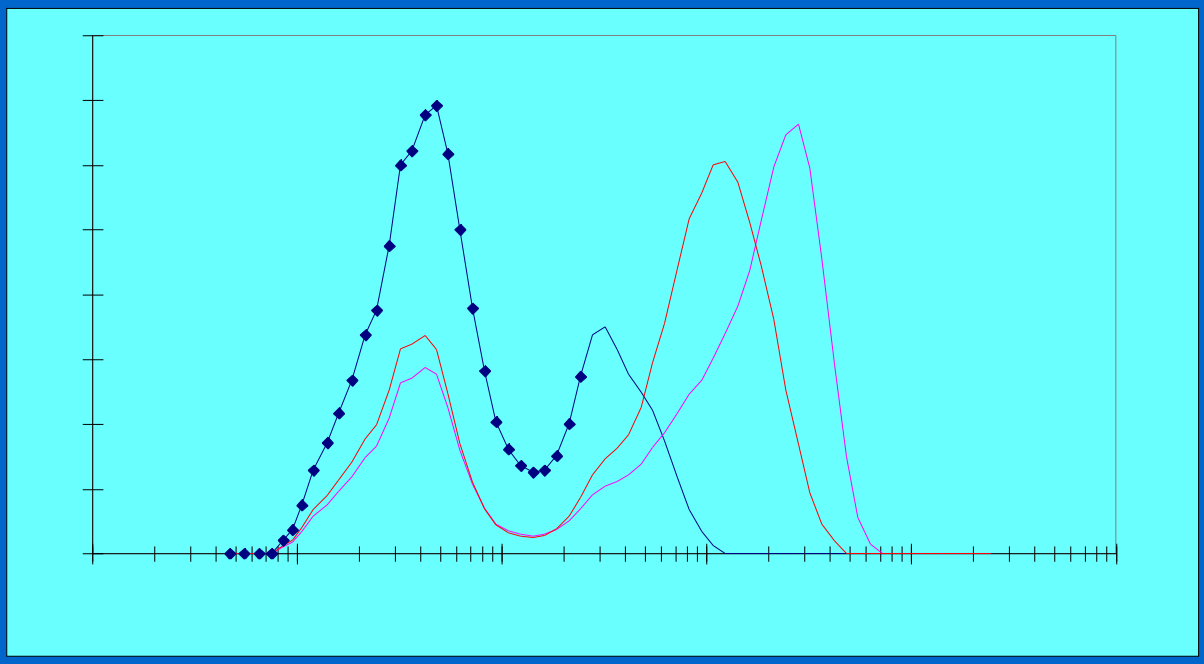


Course milled

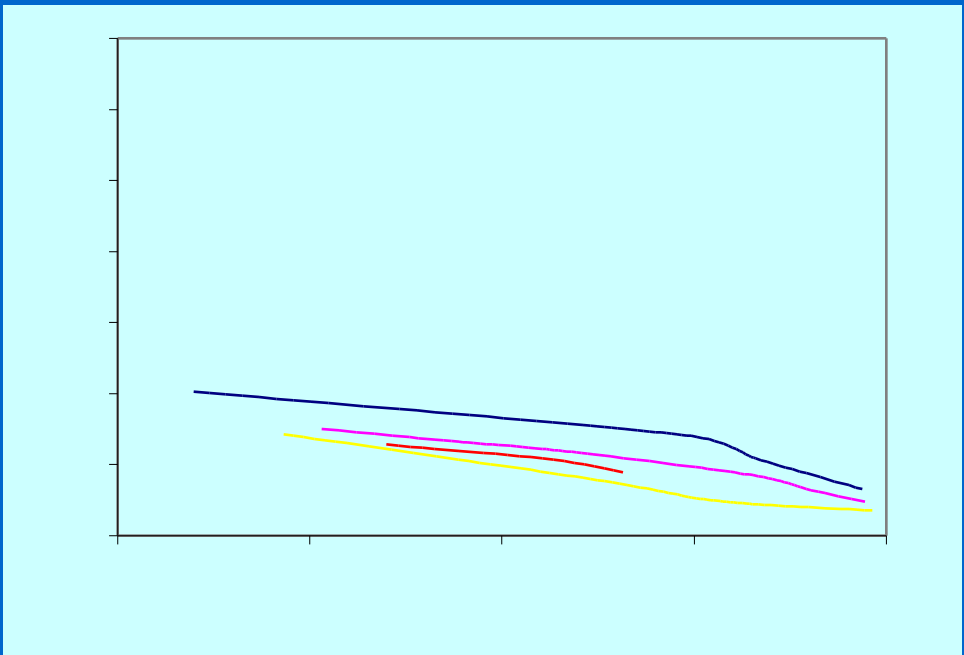


Filtered fines

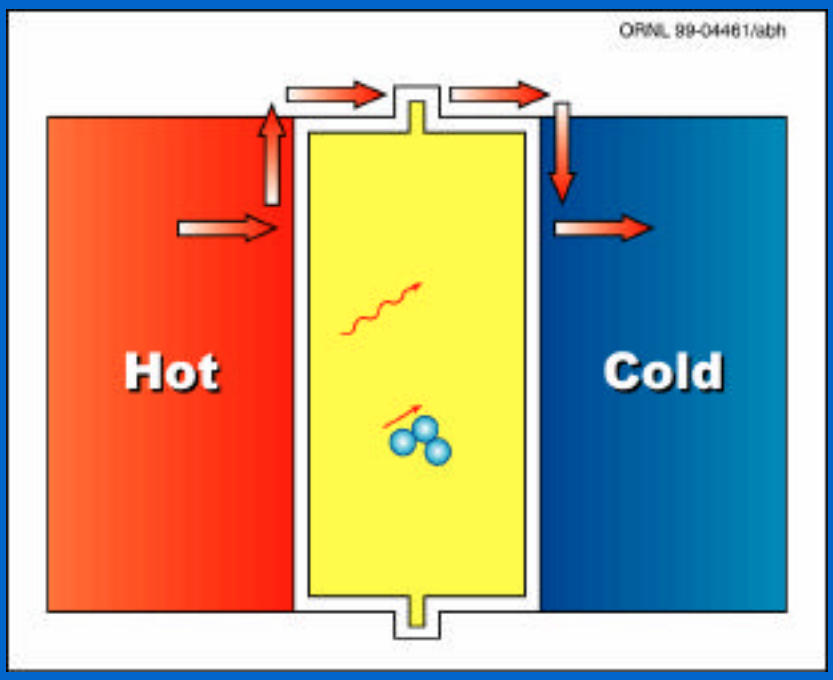
Particle size measurement shows effectiveness of mill



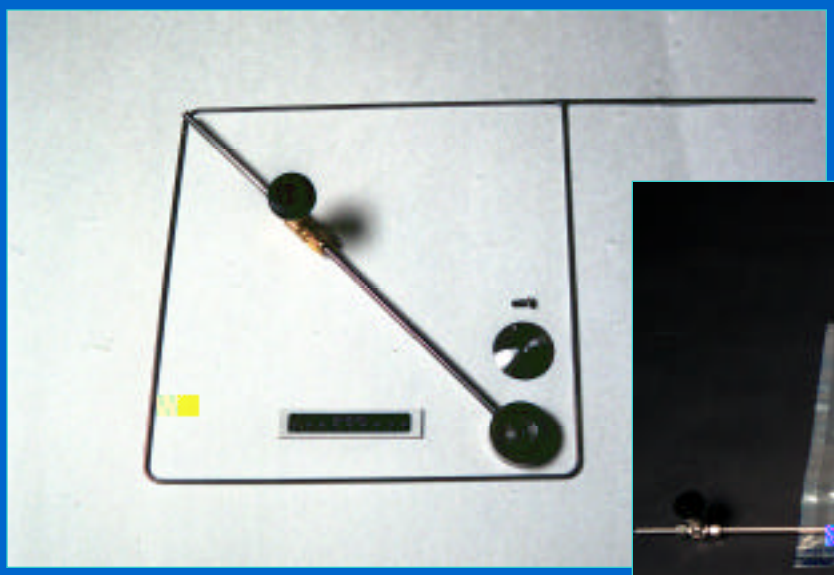
Powder Fillers - alternatives explored



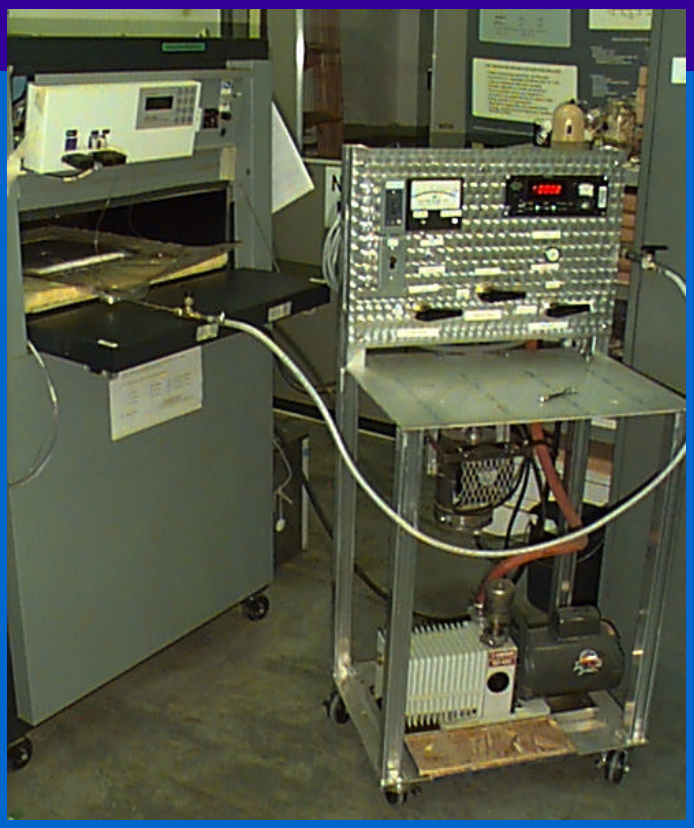
Heat can flow around the edge of a panel



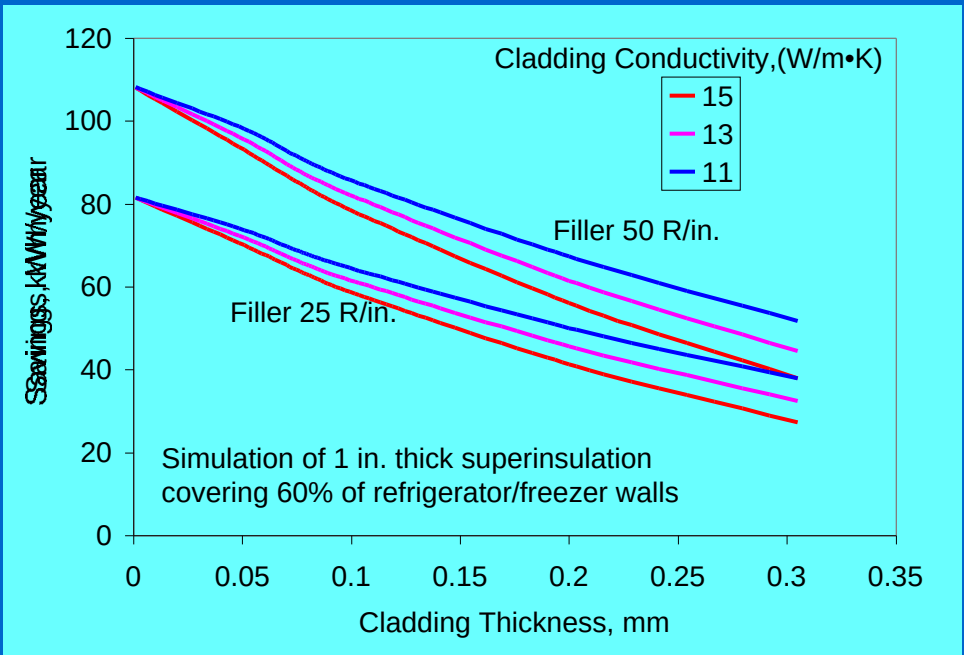
Variable pressure panel allows precise pressure control



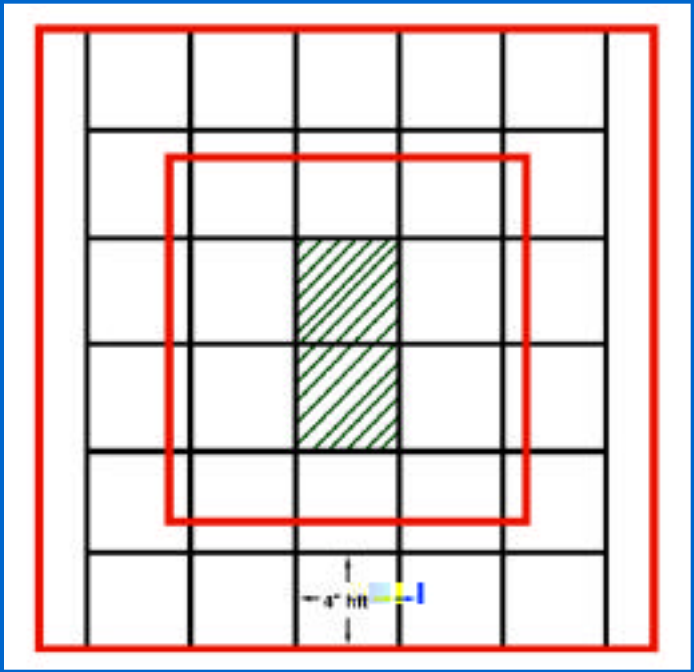
Pressure control system provides pressures as low as 0.03 torr



Barrier material conductivity and thickness effect energy savings



It takes a combination of measuring and modeling to understand panel performance



Aging studies: composite panel construction