Thermal Insulation; past, present, and future?

- Every 30-50 years, there has been a new generation of thermal insulation:
  - Foams such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane and poly-iso board insulation. Nice rigid boards that are easily processed and which have R/inch = 3.5-6.
  - Before that, fibrous materials such as fiberglass, mineral wool, cellulose, asbestos, etc. with R/inch of 2.5-3.5.
  - Before that, closed-cell natural and synthetic materials such as cork and porous rubbers.
  - Before that, wadded up newspaper or dried seaweed!
- So how to make a step-change improvement in thermal insulation performance?

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How does insulation work?

- Energy is transferred through insulation from a hot to a cold surface via:
  - Gas phase conduction: Warm gas molecules colliding with colder molecules and transferring energy
  - Gas phase convection: Bulk gas movement as a result of density differences (hopefully suppressed by the insulation)
  - Solid phase conduction: A solid's material property and related to the insulation's density
  - Radiation: Infrared radiation is emitted from every surface
- For most conventional insulation, the dominant heat transfer mode is gas-phase conduction.
- Foams have improved performance over fibers because they have lower thermal conductivity gases such as pentanes trapped in the cells

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How to improve thermal insulation over the present state-of-the-art?

- Gas phase conduction is the problem, how to lower?
  - Exotic low conductivity gases/vapors such as CFC's, HCFC's, and rare gases such as Xenon and Krypton (expensive and they will escape)
  - The Knudsen effect. When the mean free path (MFP) of a gas approaches cell/pore dimensions, gas/wall interactions begin to dominate and gas conductivity is reduced. When MFP>>cell/pore size, the gas conductivity goes to zero.
  - The MFP of ambient air is ~60 nanometers
  - Ambient pressure and very small pores (aerogels)
  - Vacuum insulation panels (VIPs) and modified atmosphere insulation (MAI)

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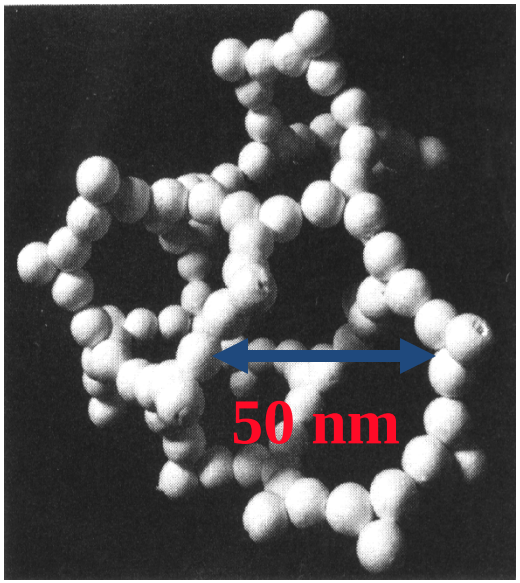
VIP's and NanoPore MAI Insulation

- 7 to 12 times improvement over conventional thermal insulation.
- Why?
  - 93% porous and 30-70 *nanometer* pores
  - Vacuum packed under mild vacuum
  - Opacified for infrared radiation
- VIP's have high cost (even on a R value basis) and MAI yields a ~50% cost reduction over a VIP



Relative insulation thickness for the same thermal resistance

Fiberglass

Expanded Polystyrene

Polyurethane

NanoPore MAI

History of advanced thermal insulation

- Dewar's (2 rigid shells with a deep vacuum and MLI in between) have been used for decades for cryogenics (liquid nitrogen, oxygen, etc.)
- Aerogels produced by Monsanto in the 50-60's and more recently by Cabot and Aspen. R/inch values better (~10/inch) than foams but expensive & hard to handle.
- In the 90's, VIP's developed by a range of companies (GE, Whirlpool, Owens Corning, Dow, ICI, Degussa/Evonik, NanoPore) using various core (silica, fiberglass, foams) and barrier materials (plastic, metallized plastics, Al foil laminates, stainless steel foil)
- After 2010, VIP's become commonplace for packaging and refrigerators (US), packaging, refrigerators, and buildings (EU), and refrigeration (Asia)
- But how to reduce cost (MAI?) and integrate into a building system?

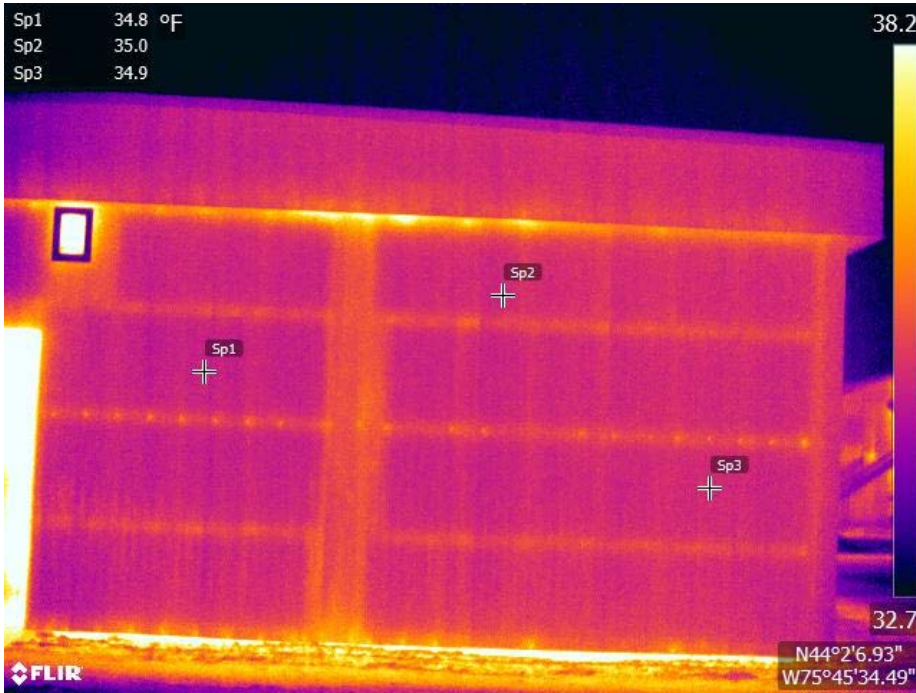
Approaches for integrating advanced insulation into buildings

- **External retrofit with individual MAI panels**
- **Encapsulation in poly-iso boards**
- **Insulated vinyl siding**
- **Metal wall panels**

- **How to make the job site the same as today (or better), reduce retrofit costs, and ensure theoretical performance is achieved?**
- **Remember that there are other insulation attributes such as flammability, mechanical strength, etc..**

Retrofit with MAI at a Fort Drum Building

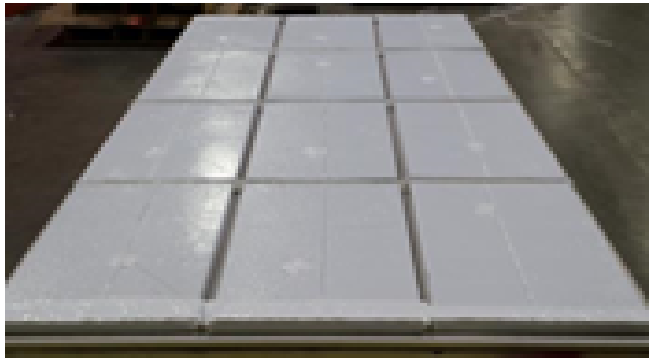
- External retrofit with individual MAI panels
- ~4,000 ft^2 building. External metal panels removed and ~400 1” thick MAI panels were installed using 1” poly-iso spacers. After sealing, external panels were reinstalled.
- 20 man-days to complete (i.e., how not to do a retrofit!)



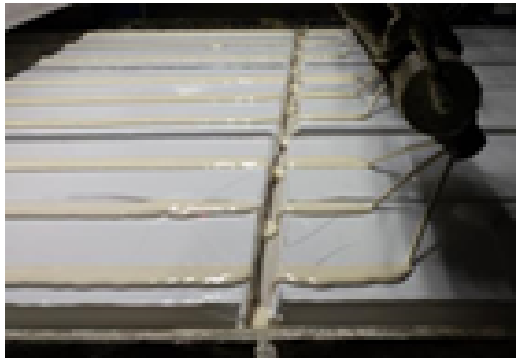
Encapsulation in Poly-iso board

Progress and Accomplishments

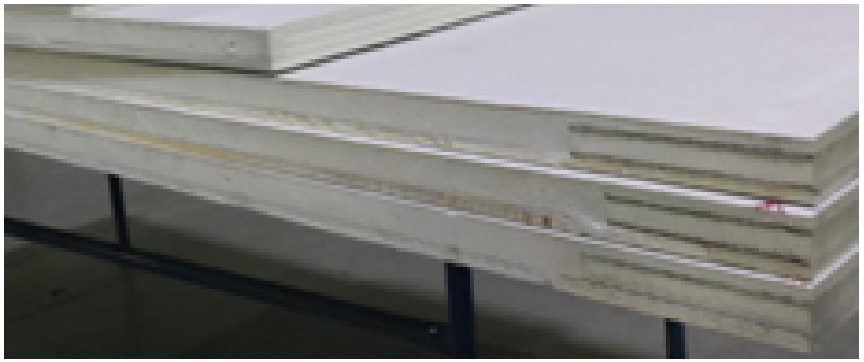
- July 2015: First-generation composites produced in a manufacturing plant.
  - *No major changes needed to the assembly line; critical consideration with respect to cost premium of the new composite insulation*.



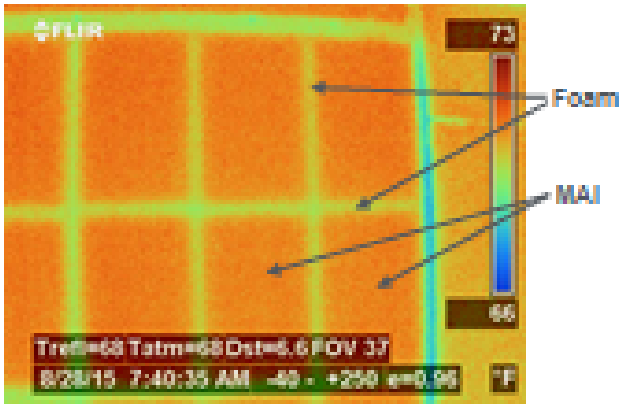
MAI panels attached to high-density (HD) foam substrate



MAI-HD board fed through foaming line**



Finished composite insulation boards



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Encapsulation in Poly-iso board

Progress and Accomplishments

- Sep 2015: Guarded hot box tests (ASTM C1363) yielded R21.6 for the 2 inch composites (*R10.8/inch*).
  - Year 1 Go/No-Go target: R10/inch
- Autopsy of one board performed after the hot box test.
  - No discernible changes in MAI shape and dimensions
  - One area had poor foam fill, with implications on measured R-value.

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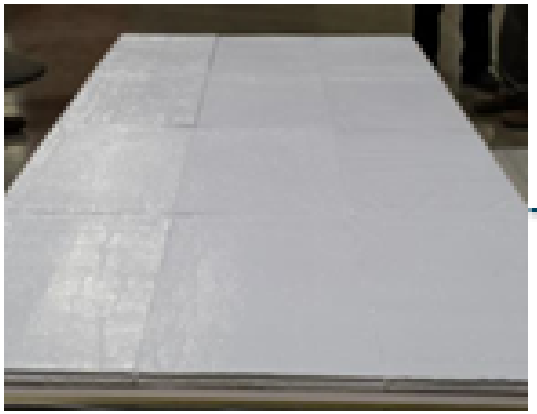
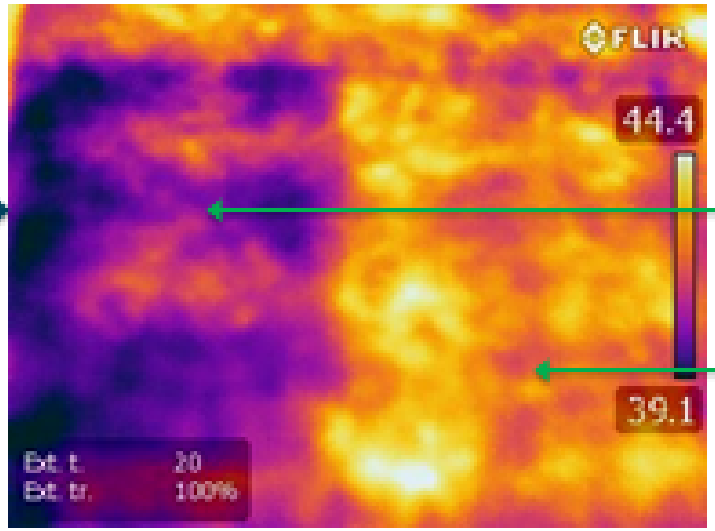
Encapsulation in Poly-iso board

Progress and Accomplishments

Second-generation composite production (March 3, 2016)





Damaged MAI panel

Intact MAI panel

- Potential online quality control using IR imaging
- Thermal diffusivity ($k/\rho c_p$): Damaged MAI >> Intact MAI
  - Cools the 'warm' spray-applied foam faster.

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Other approaches for MAI retrofit in buildings?

- DOE workshop identified vinyl siding as a primary target:
  - ~2 million homes have new siding every year
  - Insulated vinyl siding (~1/2" of EPS) provides minimal insulation improvement and thus, has had minimal market penetration.
  - ½" of MAI could give significant insulation improvement with little change for the installers as the insulation would be installed at the vinyl siding factory
  - Current DOE-funded feasibility project is underway
- Other approaches?

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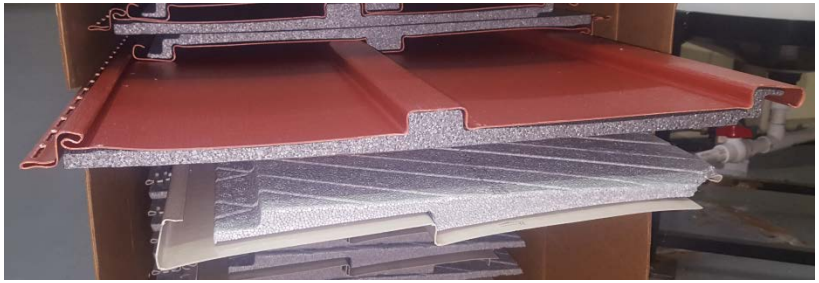
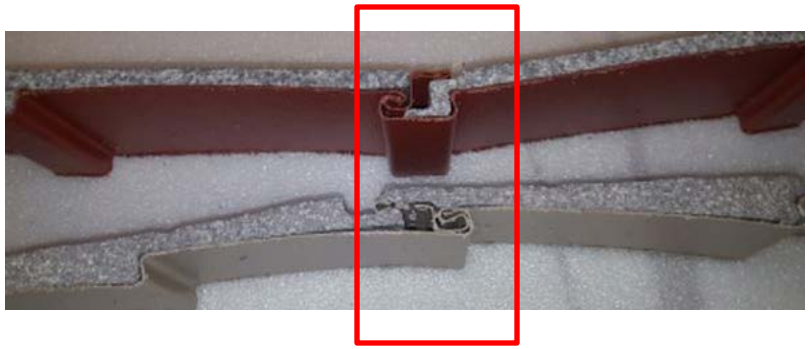
Vinyl siding 2’x2’ test sections

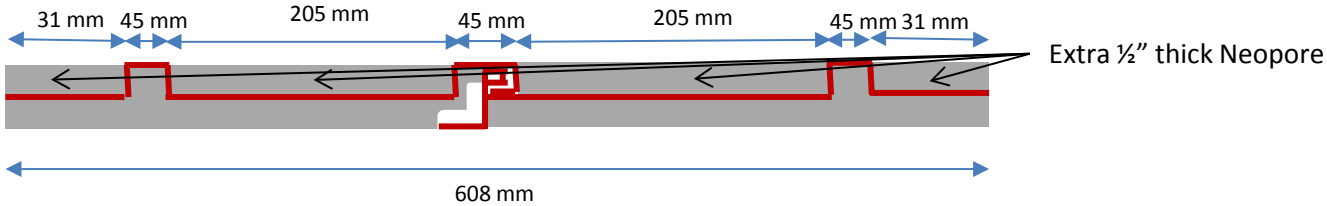
2 different cross-sections



Joint regions
Very different thermal bridging



Test Panel #1



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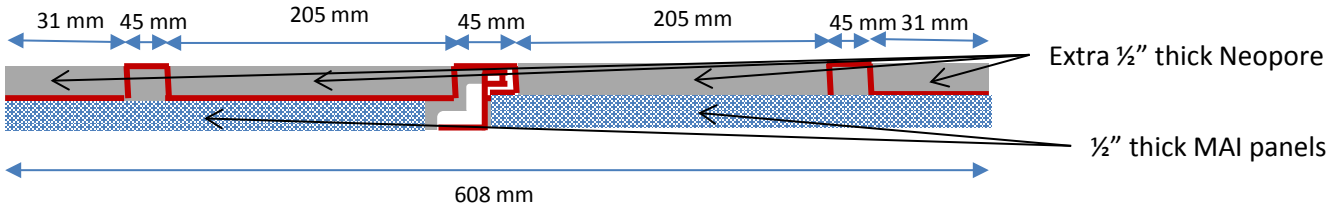
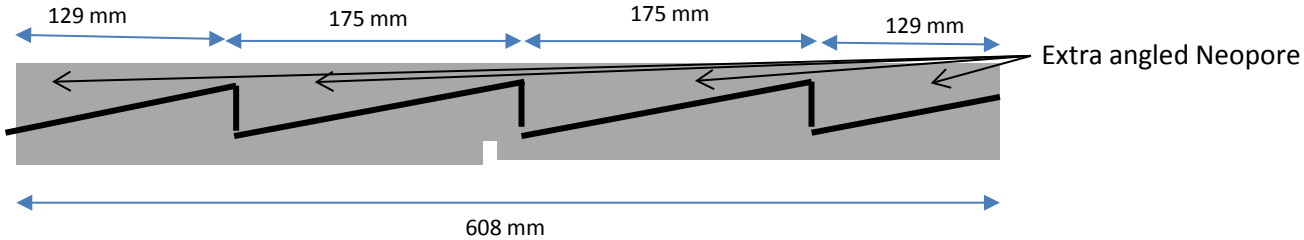
Test Panel #3