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Final CRADA Report - NFE-2008385: Self-Healing Films for Vacuum Insulation Panels

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Buildings Technology Office

FINAL CRADA REPORT - NFE-2008385: SELF-HEALING FILMS FOR VACUUM INSULATION PANELS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Vacuum insulation panels (VIPs) have an extremely high thermal resistance of around R35/inch, which makes them ideal for building envelope retrofits and prefabricated construction with space constraints. However, the barrier film that maintains the vacuum and thermal performance of the panel can be easily damaged during transportation, installation, and service life. Oak Ridge National Laboratory (ORNL) has developed a self-healable barrier film for VIPs that instantly self-heals damages caused by punctures. The multi-layer barrier film is manufactured using roll-to-roll (R2R) methods. The self-healing barrier film prevents loss of vacuum in VIPs and maintains the exceptional thermal insulation performance. Enhanced durability of VIP by self-healable barrier film and establishing the commercialization path will increase the use of VIPs, thus reducing overall energy usage of buildings. This project has fine-tuned the slurry chemistry of the self-healing components and transitioned the R2R manufacturing trials from mid-scale lab equipment to large-scale industrial equipment for de-risking the technology for commercialization with our TCF CRADA partner, FLEXcon.

1. STATEMENT OF OBJECTIVES

Vacuum insulation panels (VIPs) are one of the most efficient thermal insulation materials, achieving extremely high thermal resistance of about R35/inch. In VIPs, evacuation of the core essentially eliminates gas conduction, which is the dominant heat transfer mode in conventional fibrous and foam-based insulation materials. VIPs are attractive due to their extremely low thermal conductivity; however, VIPs are costly and could be easily damaged due to rough transit, improper installation, and service life. When damage occurs to the VIPs, the thermal insulation property significantly goes down to equivalent to that of much cheaper competing insulating materials.

This project advances and de-risk the self-healing VIP technology, which will mitigate the loss in thermal conductivity after external damage, maintain the vacuum within the panel, and yield a product that is more robust and reliable during installation and overall lifetime. The self-healing barrier film consists of two wet chemistry layers sandwiched between three substrate layers (Figure 1). The self-healing mechanism uses a readily scalable two-part chemical reaction, an epoxy and curing agent, which takes place within the multi-layer barrier film upon damage to the separator layer. The project aims to provide a clear path for a commercialized product of self-healable VIPs, that penetrates the current VIP market. The final product with a self-healing high barrier film in a VIP will ensure long lifetime and durability during installation. De-risking this novel technology can only be achieved through maturing the technology by ORNL and FLEXcon Inc. FLEXcon is a leading company for roll-to-roll (R2R) manufacturing, which is the fabrication method used to create uniform coatings of the wet chemistry onto large film substrates and to allow multi-layer film assembly. When a successful self-healing VIP is developed and validated, their commercialization by FLEXcon will make a significant impact on the VIP market.

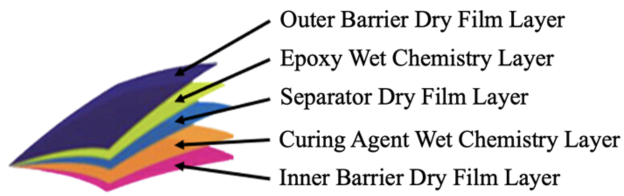

Figure 1. Proposed self-healing barrier film for VIPs.

The goals of the project are to fine tune the slurry chemistry and roll to roll (R2R) methods, develop large-scale self-healing films, develop and test self-healing VIPs, and analyze the techno economics and market for this product. These newly developed self-healing barrier films are also potentially suited for other applications of barrier films, including barrier films for cooling and freezing appliances, storage, packaging, automotive, food, and pharmaceutical applications.

2. BENEFITS TO THE BUILDING TECHNOLOGIES OFFICE MISSION

In alignment with the Building Technologies Office (BTO) mission statement, the self-healing technology developed during this TCF project "enables high-performing and energy-efficient residential and commercial buildings in both new and existing building markets, in support of an equitable transition to a decarbonized energy system by 2050[1]".

Building insulation is a key factor in creating energy-efficient buildings. Among building insulation materials, vacuum insulation panels (VIPs) have thermal resistance values up to about 10 times greater than those of conventional thermal insulation materials, making them the most energy-efficient building insulation on the market.[2] VIPs offer high thermal resistance at a low thickness (25-millimeter) which also allows for cost effective retrofitting of existing buildings. Major barriers to widespread adoption of VIPs are high cost and susceptibility to damage during transit, installation, and service life. The developed self-healing technology addresses the damage susceptibility by enabling VIPs to retain their internal vacuum after external damage, that will significantly enhance the durability and thus penetrate and increase the VIP market. According to the International Energy Agency, wider use of VIPs is likely to reduce CO_2 emissions by approximately 8%.[3]

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

The principal investigators for this CRADA are Tomonori Saito (Contractor) and FLEXcon (Participant).

Meetings were held between Contractor and Participant monthly. Communication between Contractor and Participant will remain steady throughout the duration of the project to ensure proper progress and flow of work.

3.1 TASK 1: TAILOR THE COMPOSITION OF SLURRY AND FILMS

The objective of task one is to fine-tune the slurry composition and overall film structure of the self-healing multi-layered film. Participant advised on roll-to-roll viscosity range for facile manufacturing. Participant provided films for each dry layer and suggested alterations to the dry layers that will be accomplished by the Participant before the Contractor receives the dry film. Contractor used supplied films to make self-healing film prototypes for further testing. Barrier and mechanical properties are defining performance for a VIP barrier film. Both properties were explored herein and compared to industry standards.

The Contractor optimized the slurry compositions for the slot-die machine roll-to-roll method. The compositions of the wet chemistries were not changed during this TCF. The epoxy slurry consists of 10 wt. % MEK and epoxy. The curing agent slurry has 50 wt. % water added to the curing agent solution. Both compositions were determined at the Contractor's facilities and utilized by the Participant during following trials.

Gas impermeability is a key parameter of the base film layers and contributes to the high R-value achieved by commercial VIPs. At least one of the dry layers needed to exhibit ultra-high barrier properties to reach comparably low oxygen transmission rates (OTR) and water vapor transmission rates (WVTR) to the commercially used VIP barrier films. Samples were collected by the Contractor and sent to MOCON Inc. for barrier property testing. The transmission rates tested follow ASTM F1927 and ASTM F1249 for OTR and WVTR, respectively. The Contractor obtained three commercial barrier films from Hanita Avery Dennison, a lead film supplier in the VIP market, and tested for transmission rates for later comparison to the developed self-healing barrier film. The high-barrier commercial laminates come in a range of film types suited for short- to long-term longevity for construction, thermal shipping, and home appliance applications. The Contractor chose three VIP films from Hanita: V085NM3 (a short- to mid-term longevity film constructed of 1 metalized PET film), V08341MN (a mid- to long-term longevity film constructed of 2 or more metalized PET films), and V08621B (a long- to very long-term longevity film constructed of 3 or more metalized PET films). The Contractor used OTR and WVTR of the high-barrier commercial films as a baseline. The Contractor used OTR and WVTR conditions set by the high-barrier film industry. OTR conditions were set to 22°C, 50% RH. WVTR conditions were set to 38°C, 90% RH.

Table 1. OTR and WVTR values for commercial films

Film identification	Film composition	OTR (cc/m^2-day)	WVTR (g/m^2-day)
V08341MN	Multi-laminate metalized PE with Al Foil, Nylon	0.071 ± 0.01 (0.005)	< 0.005 ± 0.00 (0.01)
V085NM3	2-ply PET non-metallic, proprietary surface treatment (PST)	< 0.005 ± 0.00 (0.014)	0.058 ± 0.00 (0.05)
V08621B	3-ply metallized PE	< 0.005 ± 0.00 (0.025)	< 0.005 ± 0.00 (0.015)

The Contractor tested the transmission rates of the chosen dry layers suggested by Participant. The film construction during the first roll-to-roll trials used the MM-050-SILVER film as the inner dry layer and M-050-CLEAR as the separator and outer dry layers. The Contractor determined that a different metalized film was needed to reach ultra-high barrier properties after testing barrier properties of the MM-050-SILVER film. The new MM-150-SILVER yielded a lower OTR at 0.038 cc/m^2-day and a WVTR less than 0.005 g/m^2-day, which was comparable to the current VIP barrier films on the market. The optimized construction consisted of two dry layers of M-050-CLEAR and one dry layer of the M-150-SILVER.

Table 2. OTR and WVTR values for dry films from Participant

Film identification	Film composition	OTR (cc/m^2-day)	WVTR (g/m^2-day)
MM-050-SILVER	Metalized PE with Al	0.636 ± 0.15	< 0.039 ± 0.00
MM-150-SILVER	Metalized PE with Al	0.038 ± 0.00	< 0.005 ± 0.00
M-050-CLEAR	Ceramic coated PET	0.100 ± 0.04	0.700 ± 0.16

After the Participant completed Task 1, several roll-to-roll trials were completed. The three initial trials aimed at mitigating spillage of the epoxy layer over time when the film was stored. The first trial consisted as a baseline and had the following composition: M-050-CLEAR, EPON 160, M-050-CLEAR, PEI-10K, M-150-SILVER. With the guidance of the Participant, two methods to mitigate shifting chemistries included a mesh interlay and embossing the clear dry films. The Participant sent the Contractor samples from the trials. The Contractor tested the transmission rates of the multi-layered films from the three completed trials.

Table 3. OTR and WVTR values for roll-to-roll trials from Participant

Film identification	Film composition	OTR (cc/m^2-day)	WVTR (g/m^2-day)
Trial 1	Baseline	0.033 ± 0.00	0.020 ± 0.00

Trial 2	Mesh interlay placed over wet chemistry	0.028 ± 0.00	N/A
Trial 3	Embossed M-050-CLEAR	< 0.005 ± 0.00	< 0.005 ± 0.00

Trials 1 and 2 showed slightly elevated OTR and WVTR values when compared to the V08621B Hanita film (Table 1, Table 3). Trial 2 had several air bubbles present which resulted in unusable WVTR data. Trial 3 showed a unform coating and promising values when compared to the commercial VIP films (Table 1, Table 3). The Trial 3 embossed M-050-CLEAR films were incorporated to mitigate movement of the wet chemistries over long storage periods. Milestone 1.1 was successfully completed.

The Contractor tested puncture resistance, heat seal strength, and tensile properties to compare the developed films to existing VIP barrier films via mechanical properties. Two Universal Instron machines with varied load cells were utilized to perform all mechanical testing at the Contractor's facility.
Puncture resistance is a common parameter used for high barrier films in the VIP industry. The ASTM D-5748 standard was used to determine the puncture resistance of the commercial films and dry layers listed below.

Table 4. Puncture resistance for commercial and Participant films

Film identification	Film composition	Puncture Resistance (N)
Trial 3	Multi-laminate film with self-healing ability	400
V08341MN	Multi-laminate metalized PE with Al Foil, Nylon layer	290
V085NM3	2-ply PET non-metallic, Proprietary Surface Treatment (PST)	380
V08621B	3-ply metalized PE	370

The high-barrier commercial films shown in the table above (V08341MN, V085NM3, V08621B) were multilayered and included 2-3 layers of metalized PE with a sealing layer. The Participant's film consists of the following composition: embossed M-050-CLEAR, EPON 160, embossed M-050-CLEAR, PEI-10K, M-150-SILVER. The self-healing multi-layered barrier film showed slightly higher puncture resistance values than the commercial films listed.

Along with puncture resistance, heat seal strength is another evaluation, typically listed in commercial barrier film data sheets. The Contractor purchased a custom ultra-high vacuum sealing device from MTI Co. to achieve ultra-low vacuum levels within the fabricated VIP panels (Figure 2).

Figure 2. Custom MSK-115A-L vacuum sealing machine.

The sealing plates were set to 140 °C for the commercial film (V08621B) and 120 °C for the Participant provided heat sealing options. To determine the sealing plate temperatures, a separate temperature sealing study was performed by the Contractor. Each film was sealed for 10 seconds and cut to the ASTM standard before testing. Heat seal strength was tested via ASTM F-88. Within the ASTM F-88 standard, there are three options regarding sample position: unsupported, supported 90° by hand, and supported 180°. For this set of data, the Contractor used the unsupported approach shown in Figure 3.

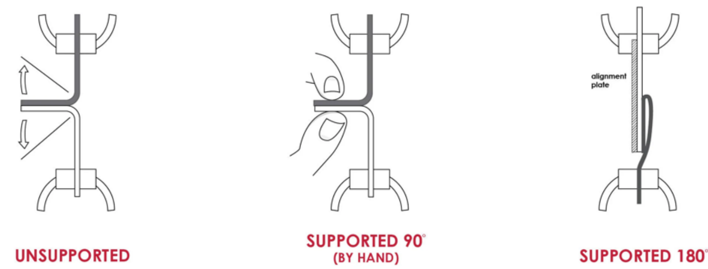

Figure 3. Outlined options regarding sample support during ASTM F-88.
Note: Figure from Instron Website
https://www.instron.com/en/testing-solutions/astm-standards/astm-f88---seal-strength

The commercial V08621B Hanita film with a coextruded LDPE/LLDPE sealing layer showed a heat seal strength of 35.94 N at 165 °C for 2 seconds. The Participant outlined two common sealing avenues in the films industry. The initial sample consisted of a seal coating onto the MM-150-SILVER film. This sample showed a heat seal strength of 49.4 N at elevated sealing temperatures. A secondary sample adding a PE layer to the seal coating allowed for a comparable heat seal strength at 31.79 N. The Participant determined the heat seal strength will increase with a longer sealing time; therefore, reaching a similar value to the commercial film.

Table 5. Heat seal strength for commercial and Participant films

Film identification	Sealing layer	Temperature (°C)	Heat seal strength (N)
MM-150-SILVER	Seal coating	280	49.40
MM-150-SILVER	Seal coating, PE	165	31.79
V08621B	Coextruded LDPE, LLDPE	165	35.94

Mechanical testing of the developed self-healing multi-layered film was completed with tensile measurements by the Contractor. Tensile measurements were completed via ASTM D1708. The tensile strength and strain of the self-healing multi-layered film reached 79 MPa and 243%, respectively. The tensile properties were then compared to the V08621B commercial film, exhibiting stress and strain of 83 MPa and 126%. The tensile strain for the developed self-healing barrier film was much greater than the commercial product, and the stress had a negligible difference, indicating that the fabricated self-healing multi-layered film had a greater toughness. Milestone 1.2 was completed with puncture resistance, heat seal strength, and tensile testing.

Milestone 1.1: Conduct barrier property analysis and self-healing capability of various substrate films from FLEXcon.

Milestone 1.2: Achieve equivalent mechanical strength and puncture resistance of self-healing barrier film to those of the commercial VIP$_S$ films.

3.2 TASK 2: R2R TRIAL FOR MULTI-LAYER FILMS

Several large scale R2R trails were performed to de-risk the technology for commercialization at the Participant’s facilities. Continued discussion occurred between Participant and Contractor to ensure optimized film construction.

The Participant performed several chemistry tests to determine the type of roll-to-roll machine, the need of corona treatment, and the order of the film coating. The order of coating differed from the small roll-to-roll trials conducted at the Contractor's site due to different roll-to-roll machine capability. The Contractor procured wet chemistries needed for both the small and the large trials completed by the Participant.

The Participant ran an initial large-scale trial after optimization on a small hand drawn scale. The parameters determined during this initial trial are as follows: a 6" wide draw down was used on a 10" substrate, therefore 2" on each side remained uncoated for any potential overflow. Overflow was not expected, but keeping the edges were precautionary when using new equipment and materials. The substrates were coated at 6 FPM (feet per minute). This speed was higher than the 1.5 FPM used in previous small-scale trials by the Contractor, as it was the lowest setting available at the Participant's site. Two heating zones were utilized to heat off the water and MEK in the perspective slurries during the trial. The zones were set to 140°F to heat off the water within the curing agent slurry and reduced to room temperature where proper airflow over the film evaporated the MEK in the epoxy slurry. The trial took two runs through the coating machine. For the first run, the MM-200-SILVER was strung through as the first carrier and coated with the epoxy solution. The epoxy has a 2.2 mil coat weight and is applied at a 6" width on an 8" wide film. The prefabricated film was then laminated to the non-ceramic coated side of the M-050-CLEAR barrier film. The second run consisted of stringing the prefabricated film through and coating the ceramic side of the clear barrier film with the curing agent solution. The curing agent was coated at 2.2 mils and applied at a 6" width on an 8" wide film before the film was laminated with a second clear barrier film. The Participant shipped the completed sample to the Contractor after completion. There was spillage on the sides of the film observed from the epoxy coating after storage. The Participant suggested several modifications to control the movement of epoxy after coating. The first modification coated the curing agent first to ensure the epoxy was not being heated at a high temperature after being coated. The second modification included the possible incorporation of a mesh interlay, embossed film, or/and Corona treatment of the substrate films. The next two trials were conducted by the Participant to mitigate wet chemistry spillage from the edges after storage.

The Participant constructed two large-scale films with the suggested improvements. The two trials explored the use of a mesh interlay or embossed film to hold the wet chemistry coatings in place.

Each constructed film took two runs through the coating machine. For the first run, the MM-200-SILVER film was strung through as the first carrier and coated with the curing agent solution with the corona treatment ON. The curing agent solution consisted of equal parts by weight of water and curing agent. The water was evaporated at 135°F. The curing agent had a 2.2 mil coat weight and was applied at a 6" width on an 8" wide film. The prefabricated film was laminated to the non-ceramic coated side of the M-050-CLEAR barrier film. The second run consisted of stringing the prefabricated film through and coating the ceramic side of the clear barrier film with the epoxy solution. The epoxy solution consisted of 10 wt. % MEK in epoxy solution. The epoxy layer was coated at 2.2 mils and applied at a 6" width on an 8" wide film. For this coating the ovens were OFF and the corona treatment was ON.

The constructed film with mesh interlay consisted of 6 layers. The mesh layer was added after the epoxy layer was coated before the film went through the ovens. The coating was uniform upon completion and the slurry did not migrate to the edges of the film after shipment (Figure 4).

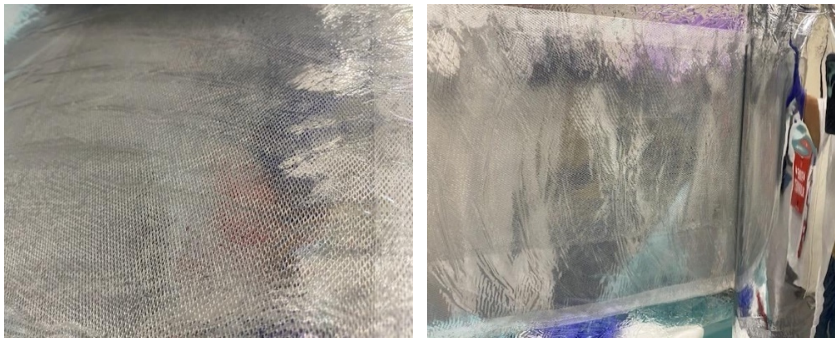

Figure 4. Completed film with mesh interlay.

The constructed film with embossed film consisted of 5 layers. Under guidance from the Participant, the Contractor chose the tile pattern for the embossed film (Figure 5). The pre-made embossed film was adhered to the M-050-CLEAR substrate after the first run. The procedure followed the previously stated outline above other than the embossed film adhesion.

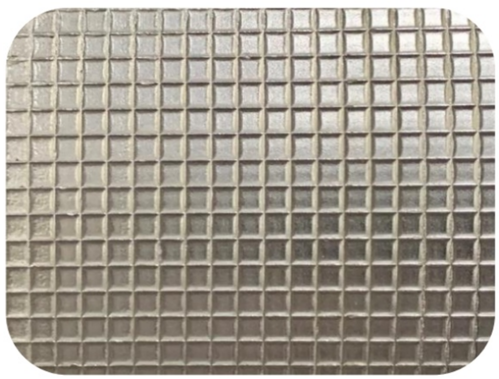

Figure 5. Tile Pattern for embossed film made by Participant.

The construction of this film resulted in some presence of air bubbles and a less uniform coating; however, the coated epoxy did not spill after storage or shipping to the Contractor. The Participant and Contractor assessed the constructions, permeability (Table 4), and the self-healability (Figure 8) before choosing the embossed film construction to optimize. The Participant optimized the embossed film construction by embossing the M-050-CLEAR film directly before film fabrication. This allowed the Participant to keep the roll-to-roll conditions consistent with previous trials while yielding a film with uniform coatings.

Figure 6. Completed large-scale film with embossed film attached to clear film.

The Participant repeated the mesh interlay and embossed film trials with minor changes. Milestone 2.1 and 2.2 were completed with the set of large-scale trials optimized by the Participant.

The Participant completed a final large-scale trial for the TCF with the M-050-CLEAR film embossing. The completed large-scale run resulted in an optimized uniform film structure with no spillage of epoxy observed. The Participant followed the previous procedure for the multi-layered film coatings via slot die machine.

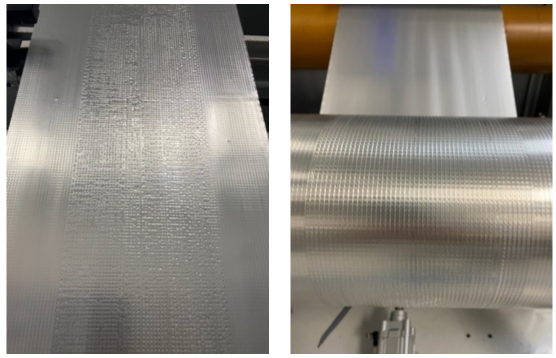

Figure 7. Optimized multi-layered film construction.
Left: Second pass epoxy coating. Right: Final Roll

The Participant optimized the multi-layered film with two major improvements. First, the MM-200-SILVER was replaced by the MM-150-SILVER to achieve lower barrier property values. Second, the M-050-CLEAR film was directly embossed with the tile pattern which resulted in a uniform coating. The optimized film construction on a large-scale successfully meets Milestone 2.3.

After multi-layered film optimization, the Participant explored the addition of an adhesive backing to the constructed film for broader application use within construction. The adhesive layer would allow contractors to apply the film on top of the commercial VIPs to increase the durability of the product. This adhesive layer was added to the outside of the metalized VIP film with a peel-off backing.

<u>Milestone 2.1</u>: *Identify optimal multi-layer film process and conduct at least one large scale trial at FLEXcon*

<u>Milestone 2.2</u>: *Perform large scale R2R trials at FLEXcon*

<u>Milestone 2.3</u>: *Complete uniform large scale R2R trial with optimized multi-layer film construction*

3.3 TASK 3: FABRICATION AND EVALUATION OF SELF-HEALING VIPS

The evaluation of self-healing capabilities of the constructed barrier films were critical to ensure consistent healing, maintained vacuum levels, and successful fabrication of VIP prototypes.

The Contractor completed puncture tests using a custom vacuum puncture apparatus showed that the self-healing films maintained the system vacuum without any discernible pressure increase. The tests were done in a custom vacuum pump assembly, in which the film samples were exposed to vacuum on one side and atmospheric pressure on the other side. The films were punctured using finishing nails (18 gauge), and the system pressure was monitored for several minutes and compared to baseline data generated using intact films.

The Contractor tested the final optimized large-scale trial and the optimized large-scale trial with adhesion. Both films were compared with an intact and damaged commercial VIP barrier film. The backing of the adhesive film was removed for testing and the adhesive side was applied to the sample holder. Figure 8 showed that self-healing occurs, therefore the optimized film was successful in healing and the extra adhesive layer does not alter the healability of the film.

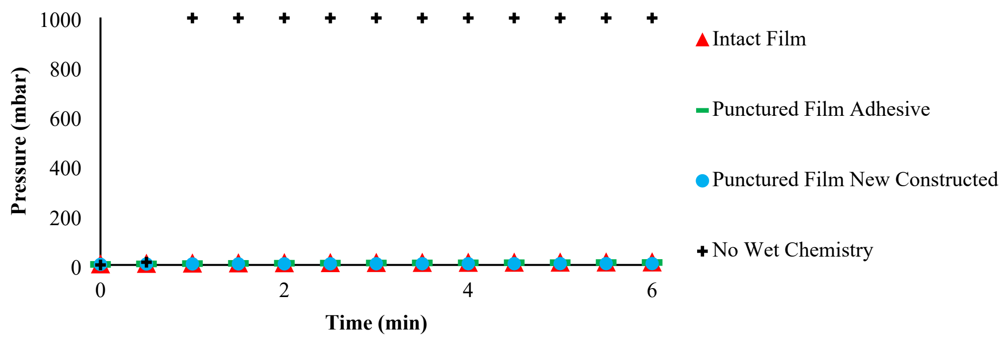

Figure 8. Internal pressure of samples via vacuum puncture apparatus.

Subsequent testing of the self-healing efficacy of the films was completed when a nail is removed after the initial puncture.

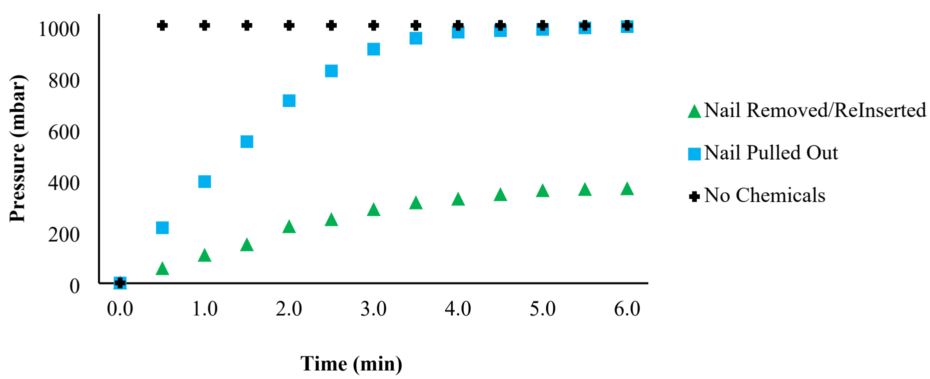

Figure 9. Internal pressure of samples after nail removal via puncture apparatus.

The Contractor completed the nail removal self-healing test. The test showed that the film was able to heal around the nail a second time after reinserting, as shown by the plateau in Figure 9. In addition, the test showed the removal of a nail will result in failure of maintaining the vacuum. The Contractor noted that this failure occurred due to microscopic air bubbles concentrating toward the center of the hole after the nail removal, obscuring proper flow of the wet chemistries.

The Contractor had installed the custom MSK-115A-L vacuum sealing machine to fabricate VIPs in house. A self-healing VIP was constructed with the self-healing multi-layered barrier film inside. A heat flow meter was utilized to measure thermal conductivity measurements. The Contractor was able to show successful self-healing for 24- and 48-hour periods after external damage to the self-healing VIP prototype (Figure 10).

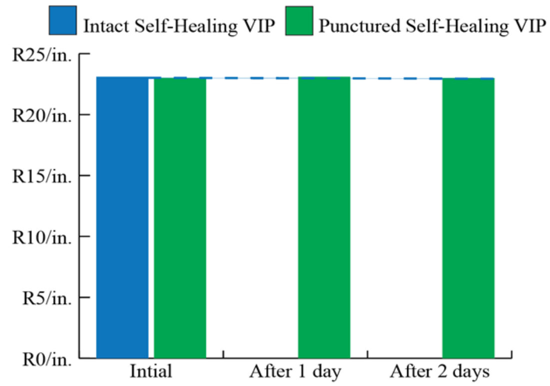

Figure 10. Self-healing ability shown with R-values via heat flow meter.

In addition to the initial results above, the Contactor fabricated a second self-healing VIP to monitor the visual impact after external damage (Figure 12). A baseline was created by damaging a commercial VIP and monitoring for the same timeline (Figure 11).

Figure 11. Damaged VIP without self-healing barrier film

The Contractor showed the effect of vacuum loss visually by the loose barrier film and lack of wrinkles on the surface in Figure 11, which was not observed in the self-healing VIP after external damage (Figure 12).

Figure 12. Left to right: Front of punctured self-healing VIP initial, back of punctured self-healing VIP initial and 7 days after.

Figures 10 and 12 show successful self-healing as mentioned in Milestone 3.2 and continued work between the Participant and Contractor will produce longer extended periods of time.

Milestone 3.1: Evaluate self-healing efficacy of self-healing barrier films by a nail puncture and removal

Milestone 3.2: Fabrication of vacuum insulation panel using self-healing barrier film and maintain R-value over extended time

3.4 TASK 4: TECHNOECONOMIC ANALYSIS

The Participant completed an initial and refined techno-economic analysis using a custom software utilized by the company for in-house product cost estimation. The Participant used standard production quantities for the analysis. The exact numbers will not be included as per the company's request. The Participant showed that thinner coatings will be the biggest impact on cost due to an increase in line speeds as a direct result. Lowering the thickness of the wet chemistry by half will lower the cost of film production by over $2.00 per thousand square inches (MSI). Additional impacts include material and chemistry savings that are assumed with larger runs and scaling of the material. The Participant determined the difference in cost of the films changing with all other layers staying consistent will be $0.03 MSI. Embossing the M-050-CLEAR film increases the overall film production cost by $1.00 MSI. The analysis showed that a decrease in wet chemistry thickness was a valuable pathway for cost reduction. Thus, the manufacturability and film composition were tailored as such during the large-scale trials. The additional cost of embossing is necessary due to the viscosity of chemistry and surface energy of the chosen substrate. This cost associated with the embossing was not expressed as a concern by the Participant. The Participant noted that the product had the ability to vary in cost based on the above analysis conditions and potential pathways for both premium and standard products. The estimated costs via Participant techno-economic analysis were communicated as favorable. Milestones 4.1 and 4.2 were completed successfully.

Milestone 4.1: Initial techno-economic analysis based on screened substrates and reagents

Milestone 4.2: Provide refined techno-economic analysis

3.5 TASK 5: TECHNOLOGY TRANSFER

Continued discussions of technology transfer occur between the Contractor and Participant. The Contractor continues to work with the Participant to complete necessary paperwork and follow the guidelines to allow the Participant to introduce the product to the market. The Participant has licensed the two patents for the developed self-healing films herein toward commercialization.

4. SUBJECT INVENTIONS

Two patents were filed by the Contractor protecting the fabrication process and chemistry used within the developed self-healing barrier film. The Participant shows continued interest in obtaining the patents to the technology.

4.1 PATENT TO PROTECT SELF-HEALING BARRIER FILMS

1. Kaushik Biswas, Pengfei Cao, Tomonori Saito, "Self-healing barrier films for vacuum insulation panels", US Patent No. 11287079, Mar. 29, 2022 ***licensed on November 2023***

A self-healing vacuum insulation panel and a method of manufacture are provided. The vacuum insulation panel consists of a self-healing multi-layer barrier film including a separator between a curing agent and curable resin. Upon damage to the separator, the curing agent penetrates the separator due to pressure differential across the barrier film and reacts with the curable resin to seal cuts and punctures. No external stimuli are needed.

4.2 PATENT TO PROTECT FILM FABRICATION METHOD

2. Kaushik Biswas, David Lee Wood III, Kelsey M Grady, Natasha B Ghezawi, Pengfei Cao, Tomonori Saito, "Roll-to-roll slot die coating method to create interleaving multi-layered films with chemical slurry coatings" US Patent No. 11446915, Sep 20, 2022 ***licensed on November 2023***

An improved method for manufacturing a continuous self-healing barrier film is provided. The method includes slot-die coating opposite sides of a separator substrate with a curing agent slurry and a curable resin slurry using a single-sided coating line or a tandem coating line. The method also includes sequentially interleaving inner and outer protective layers via a continuous roll-to-roll process to create a multi-layered barrier film.

5. COMMERCIALIZATION POSSIBILITIES

Establishing low carbon/energy VIPs in this project with demonstrating equivalent performance and cost to the current state of the art provides a clear path for the industry to switch more sustainable materials' choice for VIP manufacturing. Moreover, the failure of barrier film in the current VIPs directly leads to the loss of the performance, and the incorporation of self-healable barrier films will address the current challenge of VIP durability. The demonstration of high performance and the establishment of detailed manufacturing methods (e.g., formulation, process parameters, materials' choice etc.) are necessary for the industry to commercialize the technology.

Project impact on industry will result in manufactured self-healing barrier films for VIP fabrication. Target customers are VIP manufactures, building/construction companies and refrigeration companies. Self-healing barrier films will be used in multiple VIP thermal insulation systems including building envelopes and coolers. Outreaching to interested companies via Participant, conference presentations, and a journal publication are being conducted. This project had significant industry engagement from the Participant via CRADA and participant received interests in this technology from various companies. The Participant conducted manufacturing trials at their industrial facility and provided highly relevant techno-economic analysis.

6. PLANS FOR FUTURE COLLABORATION

Collaboration efforts between the Contractor and Participant will continue. The Participant reached out to several companies within the buildings market and has continued to discuss the interest of these companies with the Contractor.

7. CONCLUSION

VIPs remain an attractive insulation product due to the panel's extremely low thermal conductivity. Currently, widespread adoption of VIP's is hindered due to high costs and durability issue due to rough transit, improper installation, and service life. The result of this TCF has further de-risked the technology for commercialization of self-healing VIP product that aims to impact the current market. This self-healing VIP product self-heals when damaged, ensuring durability during installation. The developed self-healing VIP barrier film was only possible with the contribution of the Contractor and Participant. The project utilized a collaborative approach between a research institute and a private company to develop and test self-healing VIPs, fine-tune the slurry chemistry and roll to roll (R2R) methods, develop large-scale self-healing films, and analyze the techno economics and market for the product. The Contractor filed two patents (granted) and the Participant has licensed the self-healing barrier film technology (both IPs). The project successfully created scaled industrial R2R manufacturing of the self-healing barrier film achieved by both parties.

8. REFERENCES

1. U.S. Department of Energy. *About the Buildings Technology Office*. https://www.energy.gov/eere/buildings/about-building-technologies-office
2. Alam, M., Singh, H., and M.C. Limbachiya. 2011. "Vacuum Insulation Panels (VIPs) for building construction industry – A review of the contemporary developments and future directions." *Applied Energy* 88(11):3592–3602
3. IEA (International Energy Agency). *Decarbonization Enablers: Innovation*. https://www.iea.org/energy-system/decarbonisation-enablers/innovation#tracking