



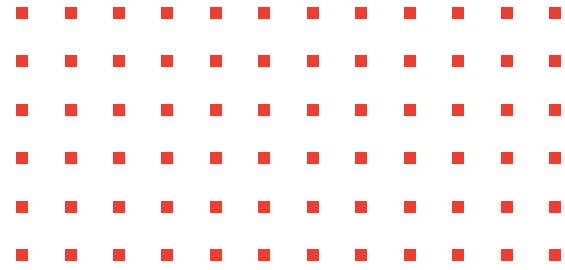
RETHINKING WASTE

How Fujipoly Is Turning Scrap Into Sustainability



WHITE PAPER

Thermal interface materials improve energy efficiency, support system reliability, and help extend the operating life of electronic products. However, producing these highly engineered materials can generate silicone scrap, thermally conductive filler waste, and used PET liners that are difficult to recover through conventional recycling methods. Fujipoly is developing new technologies designed to separate, recover, and reuse these materials while maintaining the thermal, mechanical, and electrical performance required by demanding applications.



SUSTAINABILITY BEYOND THE FINISHED PRODUCT

Thermal management plays an important role in the development of more efficient and reliable electronic systems. As power densities increase, effective heat transfer can reduce operating temperatures, improve energy efficiency, and extend equipment life.

These benefits allow thermal interface materials, or TIMs, to contribute indirectly to sustainability. A product that operates efficiently and remains in service longer may consume fewer resources over its lifetime and require less frequent replacement. However, the sustainability of a finished electronic system is only part of the equation. Manufacturers are also being asked to examine the environmental impact of the materials, production processes, and supply chains used to create it.

OEMs increasingly seek information related to:

- Material composition and traceability
 - ▶ Carbon dioxide emissions
 - ▶ Recycled material content
 - ▶ Manufacturing waste
 - ▶ Life Cycle Assessment performance
 - ▶ Scope 3 supply-chain emissions
 - ▶ End-of-life and recycling options

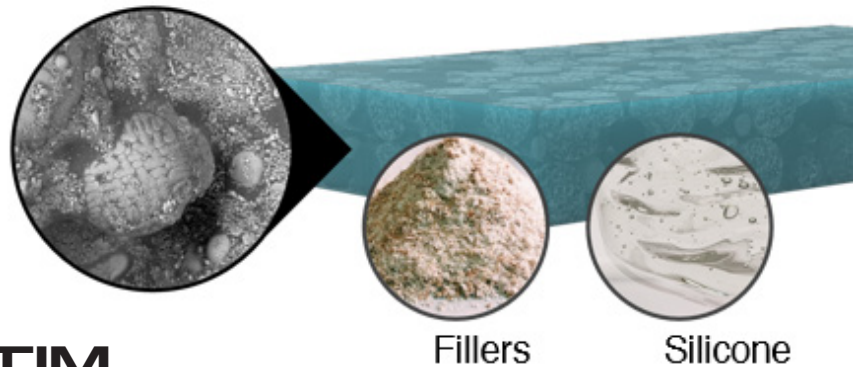
For thermal interface material manufacturers, these expectations present a complex challenge. Many high-performance TIMs are made from thermosetting silicone polymers that are intentionally engineered to remain stable under heat, pressure, and long-term environmental exposure. Once cured, these polymers cannot simply be melted and remolded like conventional thermoplastics. The same durability that makes silicone valuable in demanding applications also makes it difficult to recycle. As global demand for thermal management continues to grow, the industry must consider not only how TIMs improve the environmental performance of electronic products, but also how the materials themselves are manufactured and managed.

A Growing Thermal Management Market

Electrification, renewable energy, artificial intelligence, data centers, advanced automotive systems, and power electronics are increasing the need for higher-performing thermal solutions. Greater production volume also means greater potential for production waste. Without new recovery methods, manufacturing scrap may continue to increase alongside the market.

Fujipoly has therefore begun examining how waste generated during TIM production can be treated as a recoverable resource rather than an unavoidable byproduct.

The Sustainability Paradox Thermal interface materials can improve the efficiency and operating life of electronic products, yet the thermosetting materials used to manufacture many TIMs are inherently difficult to recycle.



UNDERSTANDING TIM MANUFACTURING WASTE

Fujipoly specializes in silicone-based thermal interface sheets and converted thermal components. These materials are manufactured to provide specific combinations of thermal conductivity, softness, electrical insulation, durability, and dimensional stability. Fujipoly works to minimize material usage at the customer level by supplying finished components in the sizes and shapes required for the application. This can reduce the need for customers to cut or convert thermal material during assembly. Nevertheless, scrap is still generated during manufacturing.

Where Scrap Is Created

The production of pad-type thermal interface materials generally includes four primary stages:

1. Mixing
2. Molding
3. Cutting or converting
4. Installation in the customer's assembly

Scrap may be generated during both molding and cutting. Molding operations can produce excess material around the perimeter of a sheet or component. This material, often called flash, is necessary to ensure complete mold filling but does not become part of the finished product. Additional scrap is created when sheets are cut

into application-specific shapes. Depending on the geometry and arrangement of the finished components, the unused material surrounding the parts may represent a significant percentage of the original sheet. For some product configurations, more than 40 percent of the material may become production scrap.

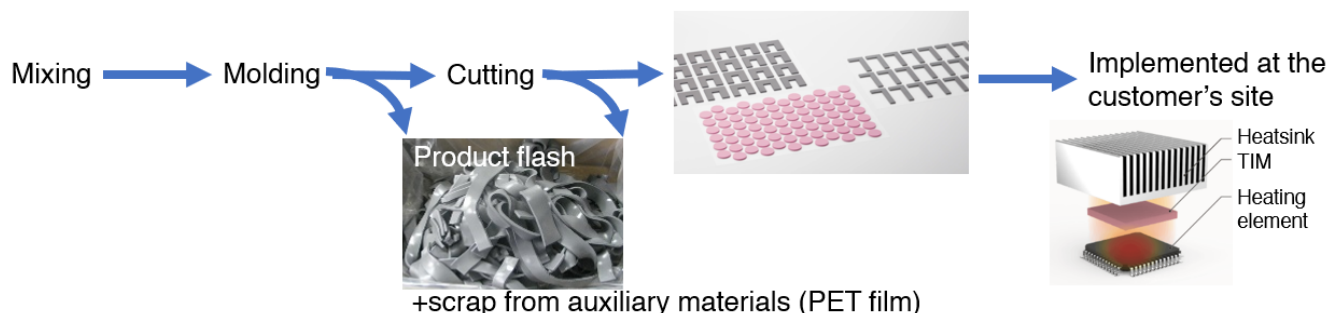
Auxiliary Material Waste

Waste is not limited to the TIM itself. Silicone thermal gap fillers are commonly supplied with PET film liners that protect the material and support handling, packaging, converting, and installation. These liners perform an essential function, but they also add to the total volume of manufacturing waste. Recovering the PET film can be complicated by several factors:

- ▶ Silicone residue may remain on the film.
- ▶ Release coatings may be present on the film surface.
- ▶ Multiple PET grades may be used.
- ▶ Different film types must be identified and separated.

These challenges mean that conventional recycling streams may not accept the material without additional processing.

Pad-type TIME Manufacturing Process



WHY CONVENTIONAL RECYCLING METHODS FALL SHORT

Silicone-based thermal interface materials differ significantly from common plastics and elastomers. A typical TIM formulation may contain a relatively small amount of silicone polymer and a much larger proportion of thermally conductive inorganic filler. In some formulations, approximately 90 percent of the material by weight may consist of filler.

For that reason, recovering the silicone alone is not sufficient. An effective recycling process must also address the valuable aluminum oxide, aluminum nitride, or other thermally conductive fillers contained within the material.

Fujipoly evaluated three potential recycling approaches.

Chemical Treatment

Chemical recycling can break silicone polymers into lower-molecular-weight materials. However, conventional chemical treatments may require highly alkaline solutions and other processing steps that create additional environmental concerns. The inorganic fillers remain as residue and may require:

- ▶ Separate recovery equipment
- ▶ Cleaning or neutralization
- ▶ Additional waste treatment
- ▶ Verification of surface condition
- ▶ Testing before reuse

Chemical treatment may recover part of the silicone content while leaving the much larger filler fraction difficult to reuse.

Mechanical Treatment

Mechanical recycling commonly involves grinding a material and incorporating the resulting particles into a new product.

This method is difficult to apply to soft, gel-like TIMs. Thermoset silicone materials do not remelt, and mechanically processed scrap may be difficult to handle or disperse consistently. The addition of irregular scrap particles can also affect:

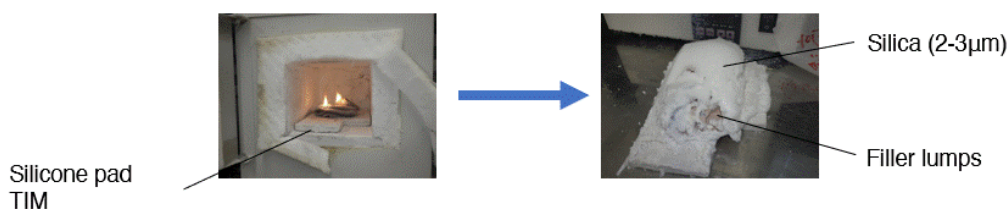
- ▶ Material flow
- ▶ Filler distribution
- ▶ Hardness
- ▶ Dimensional stability
- ▶ Thermal performance

For high-performance thermal products, these variations can make reliable property control difficult.

Thermal Treatment

Fujipoly identified thermal treatment as the most promising approach for separating silicone from inorganic fillers. Conventional heating in the presence of oxygen can burn silicone and generate silica. This can contaminate recovered fillers and damage processing equipment. Thermal decomposition can also create low-molecular-weight siloxanes that must be collected and managed. By carefully controlling the treatment environment, however, it becomes possible to suppress combustion, separate silicone-derived materials, and recover the inorganic filler for potential reuse.

HEATING TEST IN ATMOSPHERIC CONDITIONS



FUJIPOLY'S RAW MATERIAL RECOVERY TECHNOLOGY

Fujipoly's proposed recovery process begins with collected TIM scrap. The material is crushed and subjected to controlled thermal treatment, separating the silicone component from the inorganic thermally conductive filler.

The recovered filler initially forms hardened agglomerates. These agglomerates must then be carefully reduced to fine particles without damaging the original primary particle structure.

Three technologies are central to this process.

1. Controlled Thermal Conditions

Oxygen concentration, temperature, and heating rate must be carefully managed. If too much oxygen is present, the silicone may combust and form silica. If the treatment conditions are not properly controlled, the surface characteristics of the inorganic filler may also be altered.

Fujipoly's process is designed to suppress combustion while preserving the properties required for the filler to be reused in thermal interface materials.

2. Gas Recovery

Thermal decomposition produces low-molecular-weight siloxanes. These materials must be effectively collected rather than released or allowed to accumulate within the equipment. A dedicated recovery mechanism, combined with careful temperature control throughout the piping system, helps collect these silicone-derived materials while reducing the risk of clogging. The recovered silicone material may then be reused externally as silicone oil.

3. Filler Deagglomeration

Following thermal treatment, the inorganic filler particles are clumped together.

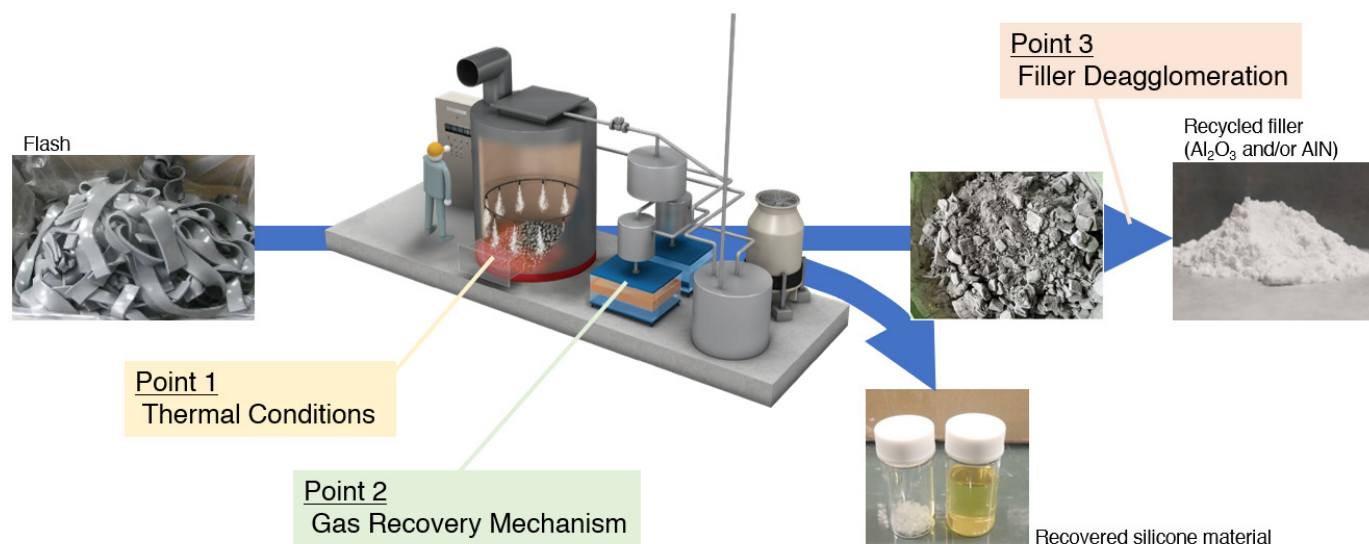
A controlled deagglomeration process breaks these clusters apart and restores the filler to a fine-particle condition similar to the original raw material. This step must be performed without damaging the primary particles or substantially changing their particle-size distribution.

The recovered filler can then be evaluated for use in new TIM formulations.

Material Limitations

Not every filler responds to thermal treatment in the same way.

Aluminum hydroxide, which is often used in lower-thermal-conductivity products, may dehydrate and undergo structural changes during heating. These changes can make the material more difficult to recover and reuse. Fujipoly continues to investigate recycling methods for aluminum hydroxide and other materials that require different recovery conditions.



CAN RECYCLED FILLER MAINTAIN TIM PERFORMANCE?

Recycled material is only practical if it can meet the performance and reliability requirements of the finished product. Fujipoly evaluated recycled aluminum oxide filler recovered through its thermal treatment process. The testing examined whether the material could be incorporated into new thermal interface materials without introducing unacceptable changes. The recovered filler demonstrated several important characteristics:

Comparable Thermal Conductivity

The recycled filler maintained thermal conductivity comparable to virgin filler. Test samples containing recycled filler achieved the same reported thermal conductivity as the original material.

Preserved Particle-Size Distribution

The recovery and deagglomeration processes maintained the original particle-size distribution. Preserving this distribution is important because particle size influences packing density, material flow, and thermal performance.

Suitable Surface Characteristics

The recycled filler remained hydrophobic and did not cause the curing inhibition that can occur when incompatible materials are introduced into platinum-catalyzed silicone systems.

Good Filling and Packing Behavior

The recycled material demonstrated suitable flow and packing properties, allowing it to be incorporated into highly filled TIM formulations.

Comparable Electrical Properties

Testing indicated that dielectric breakdown strength and volume resistance remained comparable to the original material.

Heat Resistance

Samples containing recycled filler demonstrated heat-aging performance suitable for practical application.

Replacement-Level Testing

Fujipoly produced TIM samples with recycled filler replacing 0, 10, 20, 30, 50, and 100 percent of the original filler.

All samples achieved a reported thermal conductivity of 4.2 W/m-K. Samples containing up to 50 percent recycled filler maintained hardness comparable to the original material. At 100 percent replacement, hardness increased more significantly. This increase may be related to differences between the recovered filler surface and virgin filler treated with silane coupling agents. In a practical closed-loop process, however, partial replacement is expected to be more common than complete replacement. The testing demonstrates that recovered filler can be incorporated into TIM formulations while maintaining key thermal, electrical, and reliability properties.



Collection at Fujipoly



Blend with virgin material at a fixed ratio and pelletize.

Used in fiber products and reused in markets

BUILDING A MORE CIRCULAR MANUFACTURING PROCESS

Fujipoly's proposed manufacturing model addresses both the TIM and the auxiliary materials used to produce it. TIM waste is collected and separated into inorganic filler and silicone-derived material. The recovered filler is evaluated and reused in new formulations, while the silicone component may be recovered for use as silicone oil.

PET film is collected separately and sent to a recycling partner. The material is processed, blended with virgin resin at a controlled ratio, pelletized, and reused in other markets. Fujipoly reports that its PET recycling initiative has already reduced scrap by more than one ton per month.

Three capabilities are necessary to make this circular process practical:

1. Formulation

New formulations must be designed to incorporate recycled filler while maintaining thermal, electrical, mechanical, and processing performance.

2. Collection and Traceability

TIM scrap must be separated by product type and collected under controlled conditions. Traceability is necessary to maintain material quality and prevent incompatible formulations from being combined.

3. Material Separation and Recovery

Dedicated recovery technology is required to separate silicone from inorganic filler and restore the filler to a condition suitable for reuse.

Together, these capabilities create a potential closed-loop process in which valuable materials remain within the manufacturing system rather than being discarded after a single use.

Benefits for Customers

Improved Life Cycle Assessment Performance

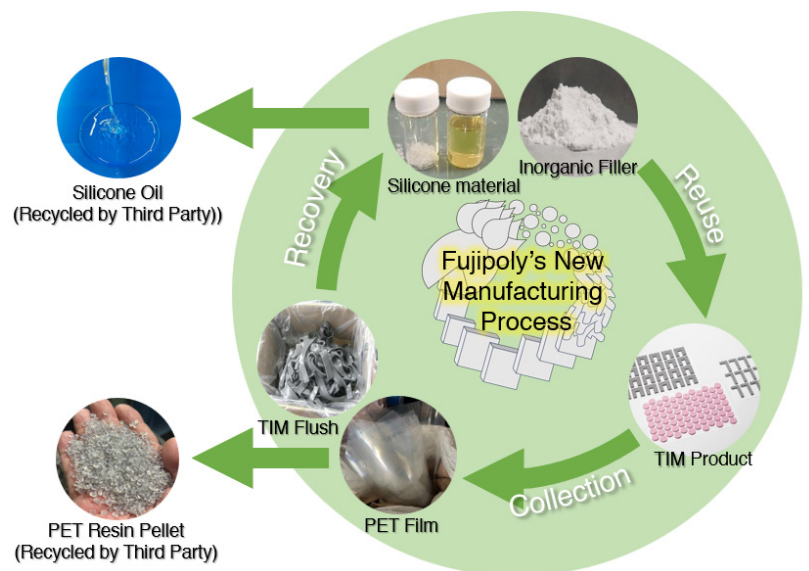
TIMs containing recovered filler may help customers reduce the environmental impact associated with raw material production while maintaining required product performance.

Reduced Carbon Emissions

Fujipoly's evaluation indicates that recovered filler may reduce carbon dioxide emissions by more than 90 percent compared with virgin filler production. The exact benefit will depend on material type, transportation, energy sources, and the boundaries used for the calculation.

Potential Cost Benefits

Recovering thermally conductive filler may reduce dependence on newly produced raw materials. This is particularly relevant for high-performance fillers such as aluminum nitride, which can be more expensive than aluminum oxide.



Support for Sustainability Goals

Materials incorporating recovered production scrap may qualify as post-industrial recycled, or PIR, content. These materials can help manufacturers address environmental reporting, responsible sourcing, and recycled-content objectives.

LOOKING AHEAD

At the time of the webinar, Fujipoly had completed feasibility studies and established the key technologies required for the recovery process.

The development roadmap included:

- ▶ Installation of mass-production recovery equipment
- ▶ Introduction of closed-loop products
- ▶ Expansion into additional TIM formulations
- ▶ Collection of scrap from customer operations
- ▶ Potential collection of materials from the broader market
- ▶ Continued development of aluminum hydroxide recovery technology

These initiatives represent a shift from reducing waste at isolated points in production toward designing a more circular thermal-material supply chain.

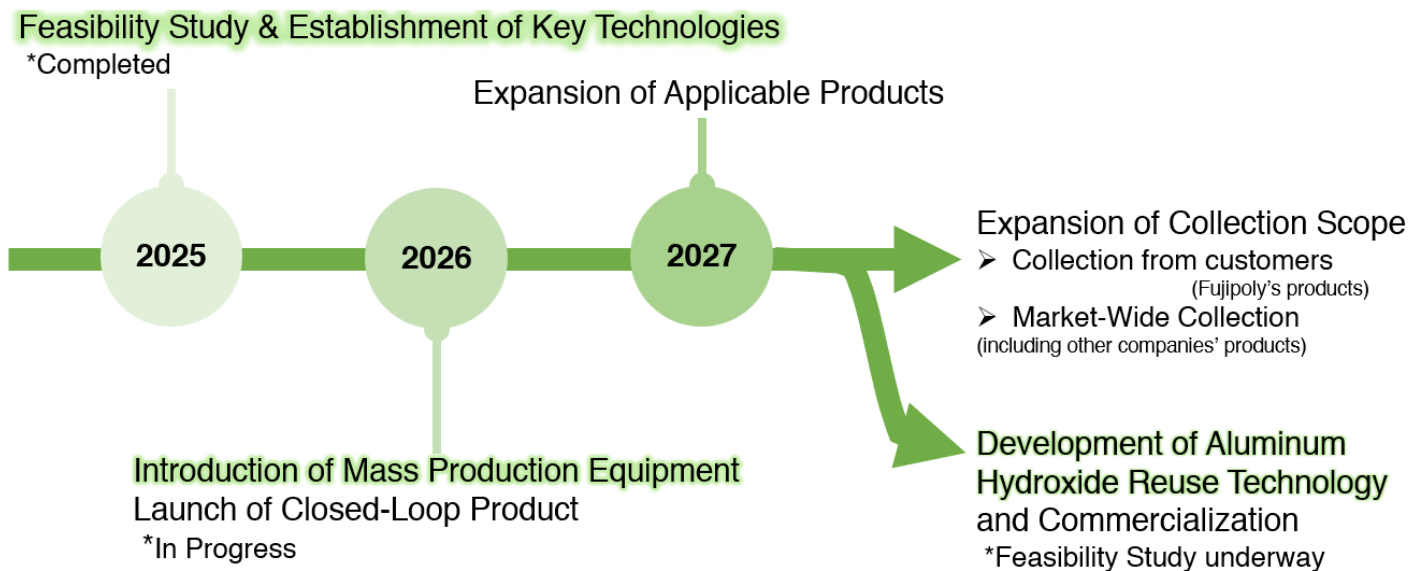
Conclusion

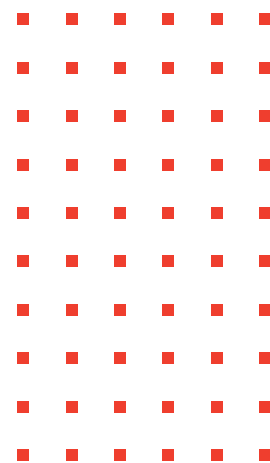
Thermal interface materials will continue to play an important role in making electronic systems more efficient, reliable, and durable. However, the industry must also address the environmental impact of manufacturing the materials themselves.

Silicone-based TIMs are difficult to recycle because they combine thermosetting polymers with high concentrations of inorganic fillers. Conventional chemical and mechanical recycling processes are not well suited to these complex formulations.

Through controlled thermal treatment, gas recovery, filler deagglomeration, PET recycling, and closed-loop formulation development, Fujipoly is exploring a practical path toward recovering valuable materials without sacrificing thermal performance or product reliability. The transition to more sustainable thermal management will not come from a single material or process. It will require coordinated improvements in product design, manufacturing, collection, traceability, recovery, and reuse.

By treating production scrap as a potential raw material, Fujipoly is taking meaningful steps toward a more efficient and circular future for thermal interface materials.





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LEARN MORE

Interested in advancing sustainability throughout your thermal-management supply chain?

Contact Fujipoly to discuss material selection, application requirements, custom thermal solutions, and emerging recycling technologies.

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