Bio-sourced aromatics for virgin plastics and fuels

The Bio-TCat™ Process --- Thermal Catalytic Biomass Conversion

B-T-X

Benzene
Toluene
Ortho-xylene
Meta-xylene
Para-xylene

Catalyst + Heat

Bio-Plastics

C9+ aromatics

Naphthalenes
Indanes
Indenes
Alkylbenzene

March 2022
Developed with $85 million cash and in-kind support from industrial R&D and brand owner partners

- Program Management
- Research & Development
- Pilot Plants

- Process Development
- Modeling & Hydrodynamics
- Scale-Up

- Catalyst Technologies
- Formulations
- Catalyst Supply

- Process & Plant Design
- Technology Licensing & Marketing
- Start-Up & Operations Support
7,500 hours of pilot plant testing

- Commercial yield and catalyst life
- Regularly completing sustained 24/7 runs; 7,500+ hours on stream operations since Feb’18
- Demonstration of major continuous process operations, recycle loops
- Feedstock -- loblolly pine SE USA forests
- Operates inside OSHA PSM compliant commercial chemical facility
Bio-TCat Development Completion Milestone
100% bioPET Bottle made by Suntory from Bio-TCat Paraxylene

Georgia-grown loblolly pine → TCat-8 Pilot Unit (Silsbee, TX) → BTX Product → Prototype 100% bioPET bottle with PX from TCat-8
1st Commercial Plant Planning Underway

Anellotech Technology Deployment

TCat-8

BEP*

Construction

First commercial plant (FCP) production

BEP

construction

Second commercial plant (SCP) production

TCat-8

1st Plant

Feed: 500 tpd
Products: 40 KTA BTXN (860 BPSD) & 30 KTA CO

2nd Plant

Feed: 2,500 - 3,000 tpd
Products: 200 – 250 KTA BTXN (4,000–5,000 BPSD) & 150 KTA CO

( ) BEP = Basic Engineering Package

Basic engineering work for the 1st Plant completed; site, funding TBD
1st Commercial Plant Planning

Process Design Study performed by Axens
(500 TPD)

- Basis of design
- Unit description, Operating Conditions
- Heat & Material Balances
- Catalyst & Chemical Specifications
- Utility Summary
- Effluent Summary
- Material specifications
- Sized equipment list
- Drawings (PFD, PID)
- Data Sheet of main equipment
- Cost estimate
- Pre-Hazop
Anellotech

Plas-TCat™
Huge, Growing Plastics Recycling Challenge
400+ million tons/year production by 2030

Production Growth by Plastic Type
Total AAGR Projected at ~ 3.5 to 4%
Plas-TCat™

Olefins

ethylene

propylene

B-T-X

benzene
toluene

ortho-xylene
meta-xylene
para-xylene
Anellotech aims to convert large volumes of mixed waste plastics...

...directly into valuable chemicals (using new technology Plas-TCat)... not fuels!

ANELOTECH’S VISION
Efficient, economic, large-scale recycling of mixed waste plastics

...widely used today in packaging and other products.

...that are the same ones that manufacturers buy to produce the plastics...

Plas-TCat™

OLEFINS

• Polystyrene
• Polyethylene
• Polypropylene
• Polycarbonate
• Nylon
• PET
• ...and many more
Plas-TCat reactor outlet products from Polyethylene feed can be controlled to give High Yield Olefins or High Yield BTX.

For illustrative, qualitative use only. These lab results are to be validated in long-duration studies in a fully integrated TCat-8 Pilot Plant. Detailed review of experimental conditions, catalyst and other factors can be shared to fully assess this data.
Plas-TCat reactor outlet products from Polyethylene feed can be controlled to give High Yield Olefins or High Yield BTX

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Global plastics demand by type of polymer

- **Total Demand 300 MMT 2019**
- **PP** 27%
- **LDPE** 11%
- **LLDPE** 9%
- **PS** 4%
- **EPS** 3%
- **PVC** 16%
- **PET** 9%
- **HDPE** 17%
- **Other (Nylons, PC)** 4%

**Total Demand 300 MMT 2019**
Plas-TCat Development: Design Window

• Addresses a Broad Range of Plastic Solids Waste (PSW) Composition

• Based on the analysis of composition of Plastic Solid Wastes in different regions, a window of PSW composition has been selected.

• Plastic mixtures with high and low polyolefin (PO) concentration define the operational window.

• The midpoint of the window is the Base Case
Plas-TCat Base Case Feedstock Composition

- PE: 38%
- PP: 16%
- PS: 17%
- PET: 10%
- Nylon: 7%
- Biomass: 2%
- PC: 3%
- PU: 3%
- ABS: 2%
- Acrylic: 2%
Plas-TCat Product Yield vs H/C\textsubscript{eff} Ratio

- H/C\textsubscript{eff} ratio can be used to predict the yield of valuable products: BTX+Olefins+Paraffins

- In general, the higher the H/C\textsubscript{eff} ratio, the higher the product yield.

- Poly-olefins such as polyethylene and polypropylene contain only H and C and their H/C\textsubscript{eff} ratio is 2.

- Product yield from poly-olefins is higher than plastics containing heteroatoms because hydrogen reacts with oxygen to make water, hydrogen combines with nitrogen to make nitriles and ammonia and hydrogen reacts with chlorine to make hydrochloric acid. These side reactions reduce H/C\textsubscript{eff} ratio.
Heteroatoms (N, O, S, Cl, etc.) rejected by Plas-TCat mainly in Gas Phase for easy separation. Potential positive LCA impact (vs. thermal pyrolysis)

**Example: PET**

<table>
<thead>
<tr>
<th>Plas-TCat</th>
<th>Thermal Pyrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td></td>
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</table>

### Plas-TCat Advantage

- Low Upgrading Cost: Minimal hydro treating is required to remove heteroatoms from the liquid phase.
- Favorable LCA: Overall CO2 footprint is low because of small amount of fossil hydrogen is required to remove heteroatoms from the liquid phase as they are rejected in the gas phase.

*Anellotech Lab Data


Plas-TCat converts No. 7 plastics (including nylon, ABS, polycarbonate, polyurethane) directly into valuable chemicals

- Most No. 7 plastics contain heteroatoms such as nitrogen and oxygen in their chemical structure
- Plas-TCat converts these heteroatom containing plastics (such as PET, Acrylic, Nylon, Polyurethane, ABS, Polycarbonates, etc.) directly into BTX, olefins and paraffins.
- Due to the process wide tolerance of waste plastic feedstocks, minimal upfront sorting is needed.

![Graph showing H/Ceff for different feedstocks]
Contrast Plas-TCat with non-catalytic pyrolysis, which produces predominantly waxes needing further upgrading.

For illustrative, qualitative use only. These lab results are to be validated in long-duration studies in a fully integrated TCa-t8 Pilot Plant. Detailed review of experimental conditions, catalyst and other factors can be shared to fully assess this data.
While Non-Catalytic Pyrolysis of polyethylene produces a broad mix of waxes and olefins\(^1\)(\(^2\))

**Requires upgrading in a steam cracker to yield upgraded valued product**

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\(^1\) Dongting Zhao, Xianhua Wang, James B Miller, George W Huber, “The chemistry and kinetics of polyethylene pyrolysis: A feedstock to produce fuels and chemicals.

Plas-TCat Catalytic Pyrolysis yields mainly BTX, ethylene, propylene, paraffins **directly** in one reactor

*Products ready for purification and use to make virgin plastics*

1. Dongting Zhao, Xianhua Wang, James B Miller, George W Huber, “The chemistry and kinetics of polyethylene pyrolysis: A feedstock to produce fuels and chemicals."

Plas-TCat is highly scalable – limited only by feedstock supply

Industrial Fluid Bed Catalytic Reactor Technology

- Plas-TCat Reactor
- Waste Plastic Feed
- BTX Olefins Paraffins +
- Regenerator Flue Gas
- Regen Cat Stripper
- Coked Cat + Char
- Steam
- Regen Air Blower

Scalable Heat Transfer Solution

- Plas-TCat
  - Circulating catalyst provides heat to reactor

Thermal Pyrolysis

- Heat provided by external heating of reactor walls
- Limits reactor diameter and overall process scale
- Multiple reactor trains required for scale up
Thermal Pyrolysis Heat Transfer Scale up Dilemma

Thermal Pyrolysis (numbering-up)

Scale-up potential has inherent limitations

Numbering-up required to reach comparative single system scale for Plas-TCat

Plas-TCat (single system scale-up)

Capex and Opex significantly improved by ability to utilize single reactor larger scale systems
Plas-TCat Hi-Olefin Case vs Thermal Pyrolysis – PE:PP:PS = 3:2:1

Non-Catalytic Pyrolysis*

Plastic Waste → Pyrolysis & Primary Separation → Pyrolysis Oil** 86% → Steam Cracking Unit → BTX 7%, Olefins (<C5) 42%, Others: Lights, Heavies 37%, Gases 14%

Plas-Tcat***

Plastic Waste → Plas-TCat Unit → Olefin Rich Gas 62% → Steam Cracker Cold Section → <C5 Paraffins 7% → Olefins (<C5) 4%, Lights, Heavies 3% → Steam Cracker Furnace → BTX 13%, Other C5+ Liquids, Heavies 25%

Yields as % of Plastic Waste Feed

Thermal Pyrolysis

BTX + <C5 olefins = 49%
7% 42%

Plas-TCat Catalytic Pyrolysis

BTX + <C5 olefins = 65%
13% 52%

** Assume pyrolysis oil has same avg steam cracker yields as naphtha
***Anellotech Lab data

March 2022
Plas-TCat Hi-Olefin Case vs Thermal Pyrolysis – 100% Polyethylene Feedstock

Non-Catalytic Pyrolysis*

Plastic Waste → Pyrolysis & Primary Separation → Pyrolysis Oil** → Steam Cracking Unit → BTX 7%

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Yields as % of Plastic Waste Feed</th>
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<tbody>
<tr>
<td>Thermal Pyrolysis</td>
<td>BTX + &lt;C5 olefins = 48%</td>
</tr>
<tr>
<td></td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>41%</td>
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</tbody>
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Plas-TCat***

Plastic Waste → Plas-TCat Unit → Olefin Rich Gas 69% → <C4 Paraffins 7% → Steam Cracker Furnace → Olefins (<C5) 4%

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<td>Plas-TCat Catalytic Pyrolysis</td>
<td>BTX + &lt;C5 olefins = 70%</td>
</tr>
<tr>
<td></td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>57%</td>
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Plastic Waste → Plas-TCat Unit → Olefin Rich Gas 69% → Steam Cracker Cold Section → Olefins (<C5) 53%

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**Assume pyrolysis oil has same avg steam cracker yields as naphtha**


**Assume pyrolysis oil has same avg steam cracker yields as naphtha**

***Anellotech Lab data***
New Joint Venture Company with 12 Japanese Cross-Industry Partners
to Develop Innovative Anellotech Plas-TCat Plastics Recycling Technology

June 30, 2020
R Plus Japan JV Partners
As of Feb. 2022

Crude Oil → Basic Chemicals → Intermediate Material → Packaging Material → Consumer Goods

Sorting / Pretreatment

Retailer
With the engagement of various industries throughout the supply chain,

- from raw materials manufacturers, and packaging suppliers to brand owners,

- the newly established R Plus Japan,

- together with Anellotech,

- will advance the development & commercialization of this eco-efficient plastic recycling technology by 2027.
Plas-TCat Development Program

**Laboratory Fluid Bed Reactors**

**TCat-8 Pilot Plant (VIDEO LINK)**

**Future Commercial Plant**

- **Completed**
- **2022-2023**
- **2027**
6 Reasons that Plas-TCat is a Game Changer

1. Plas-TCat process is a new, direct route to olefins and aromatics from low value plastic waste feedstock

2. Competitive economics (double digit IRR%) using market price feedstock; no tipping fees or product price premiums.

3. Makes valuable products from range of feedstocks at attractive yields
   - Can feed all major plastics due to proprietary catalyst and fluid bed reactor-regenerator system design.
   - Product slate can be controlled to maximize aromatics (BTX) or olefins (ethylene, propylene)
   - Composites, mixed plastics can be used with minimal presorting of feedstocks (other than PVC reduction)
   - Yields can be predicted based on plastic’s chemical composition
   - Heteroatoms (O, N, S, Cl) mostly rejected in the form of gases CO, CO2, H2S, N2 to nitriles, Cl removed in pretreatment
4. **No major chemical upgrading** of Plas-TCat products is required
   - Aromatics, C2-C4 olefins and paraffins ready for purification and sale or direct feeding into the downstream steam crackers purification trains.
   - No upgrading is required in ethylene furnaces -- as for thermal pyrolysis output.

5. **LCA assessment** (preliminary): potential to reduce CO2 emissions up to 50% vs. monomers from steam crackers.

6. **Scalable.** Anticipated commercial plants should exceed 200,000 metric tons/year of olefins and/or BTX production from a single reactor system processing majority polyolefin plastic waste.
   - Reactor scaling is not limited by heat transfer (multiple reactors, in parallel, are not required to scale as in liquid thermal pyrolysis). Hot, regenerated Plas-TCat catalyst serves as a carrier to provide the heat to the reactor.
Plas-TCat Catalytic Pyrolysis vs. Thermal Pyrolysis

Catalytic pyrolysis directly yields high value products
- BTX
- Olefins (mainly ethylene, propylene, butylene)
- Paraffins (mainly methane, butane, propane)

Thermal pyrolysis products have oligomeric structure (waxes) and need to be upgraded to make commercial products (Olefins, BTX)
- in steam crackers furnace to produce olefins (and some BTX)
- in FCC unit to make BTX
- Furthermore, heteroatoms contained in the pyrolysis oil might be critical for steam cracker processing (since can promote coking), and must be removed prior to feeding.
- And..... steam cracker (or FCC) upgrading of pyrolysis oil generates a significant yield loss
- Naphtha cracking yields as proxy for pyrolysis oil:
  - Ethylene 25–35 %
  - Propylene 14 – 18%
  - Butadiene 4–6 %
  - Methane 14%
  - BTX 5 – 10%

Naphtha conversion in Steam Cracker: 44% to 63% wt. Olefin+BTX Yield (on feed)
Plas-TCat Vs Non-Catalytic Pyrolysis - Graphic

Product Value
- Waxes
- BTX Olefins

Scale
- 10-20 KTA
- 175+ KTA

Carbon Yield to Olefin BTX, etc.
- 50% (after SC upgr'd)
- 90% (Direct from Plas-TCat)

Feedstock Restrictions
- No PVC
- PET
- Nylon PC (29%)
- No PVC (16%)

Additional Processing Required
- Pyrolysis
- SC Furnace / Refinery
- Purific'nt & Sep
- Plas-TCat
- Purific'nt & Sep

Features
- Value of Products
- Additional Processing
- Highest Carbon Yields (after SC upgrade for pyrolysis)
- Practical Scalability
- Limited Feedstock Restrictions

Plas-TCat Overall Winner

March 2022