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Recyclable Polyolefins: How Plastic Additives Can Enable a Circular Economy

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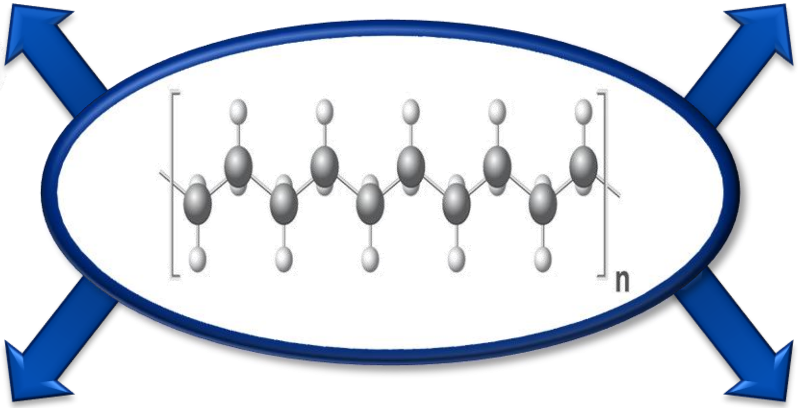
Plastics: The Benefits

Lower Emissions:
Light-Weight Automobiles/Airplanes, Batteries

Lower Infections:
Medical Packaging, Antimicrobial Materials



Energy Efficient & Durable Buildings:
Insulation & Building Materials

Less Food Waste & Easier Transport:
Light Weight Food Packaging

Plastics: The Problem

Only **14%** of the 141 million tonnes of plastic packaging waste was recycled in 2015[1]

Nearly 50% of the plastic waste generated globally in 2015 was **plastic packaging[1]**

Of the 14% recycled, 4% was **lost in process[1]**

By 2050, the plastic in the ocean will **outweigh the fish[1]**

The world generates at least **3.5 million tons of solid waste a day**, 10 X the amount a century ago[1]

600+ Marine Species are harmed by ingestion of microplastics[1]

Barge taking recyclables from NYC to Brooklyn Recycler (NY Times)

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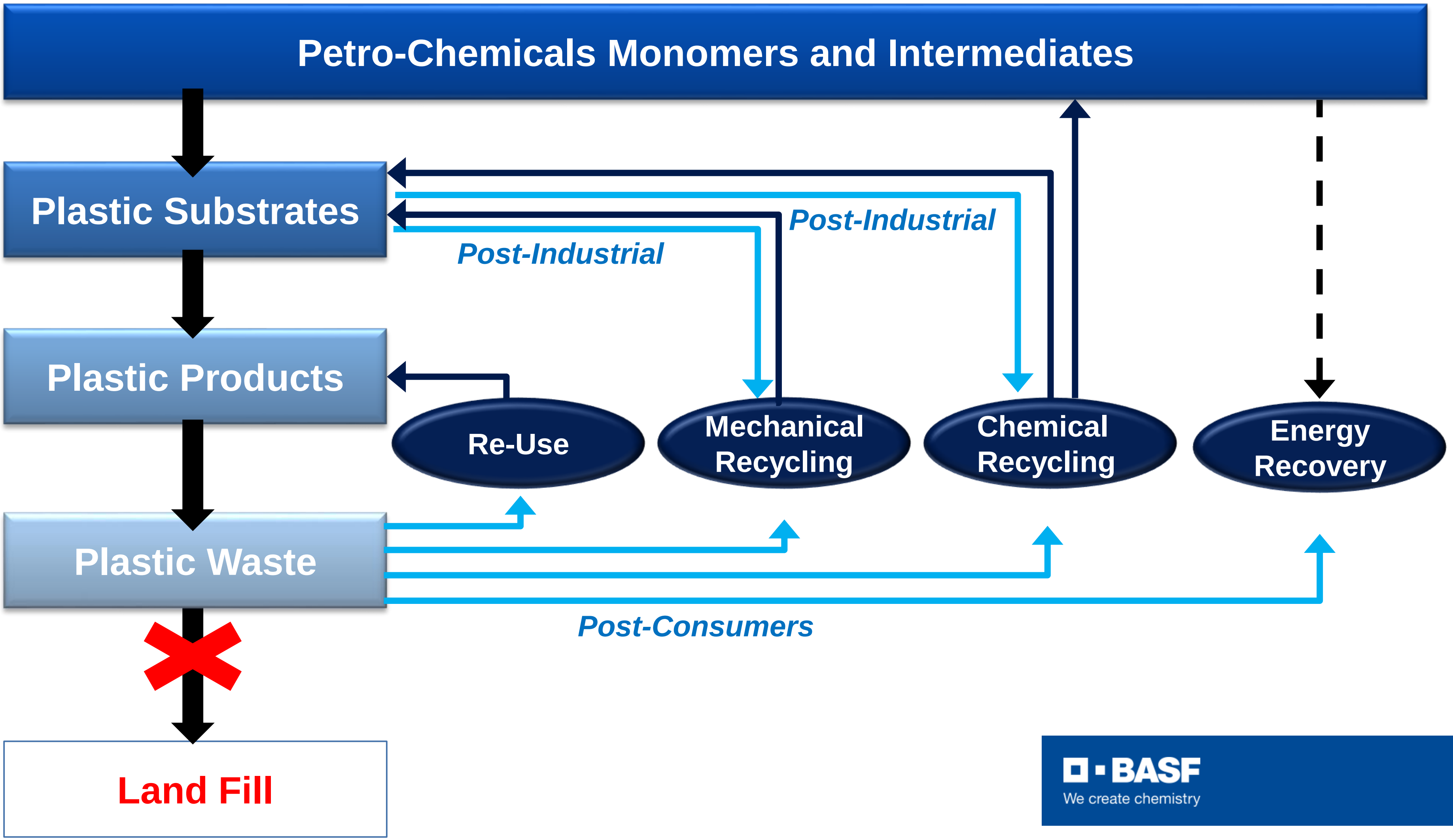
[1]*All statistics from the 2017 UN Sustainability Report: Copyright © United Nations Environment Programme, 2018*

The Solution – A Circular Economy for Plastics

A circular economy promotes closing loops in industrial systems, minimizing waste, and reducing raw material and energy inputs



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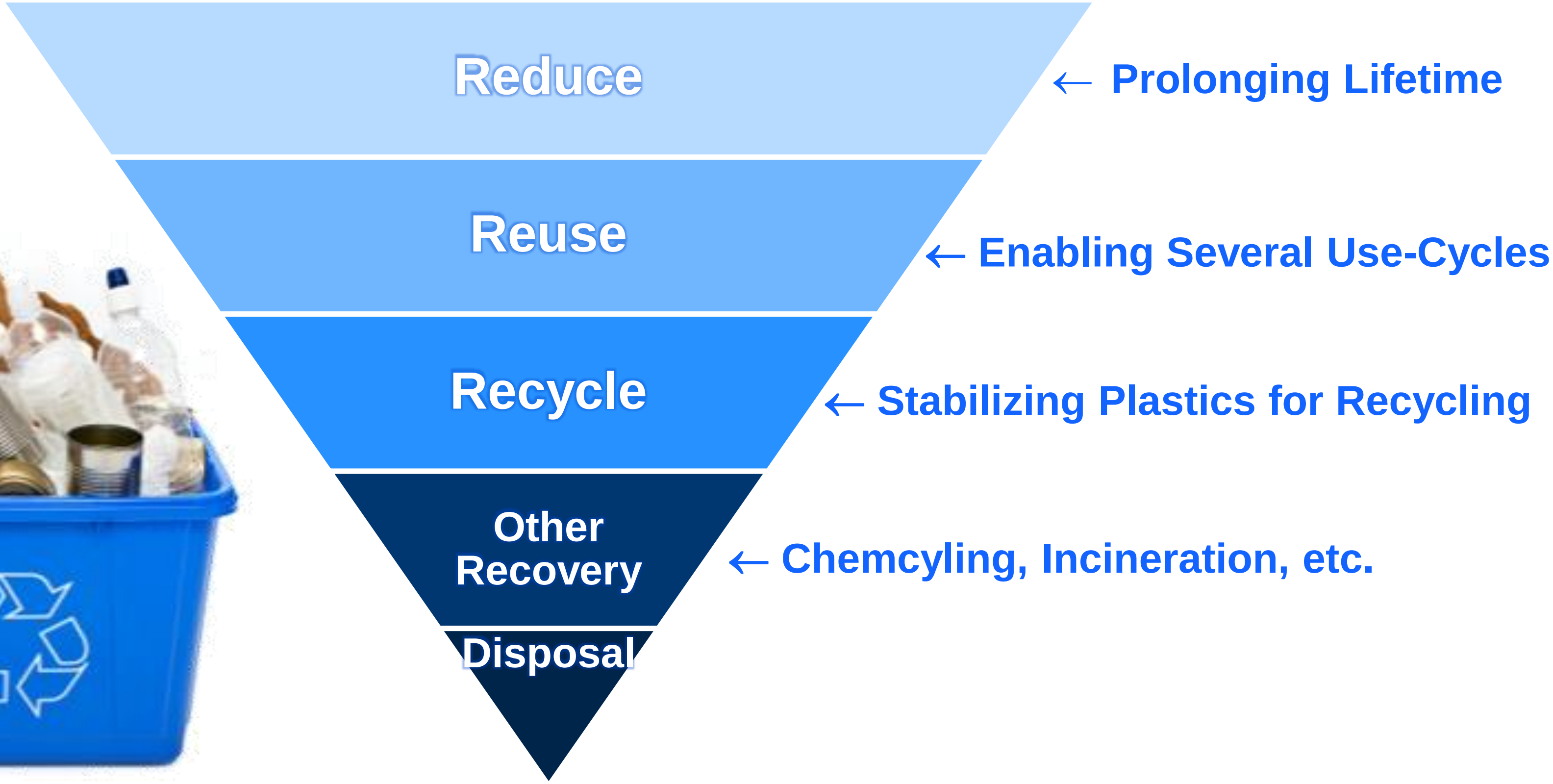
BASF Plastic Stabilizers

The sustainable management of plastic waste



BASF plastic stabilizers prolong lifetime, yield reusable materials, and stabilize the polymer through recycling

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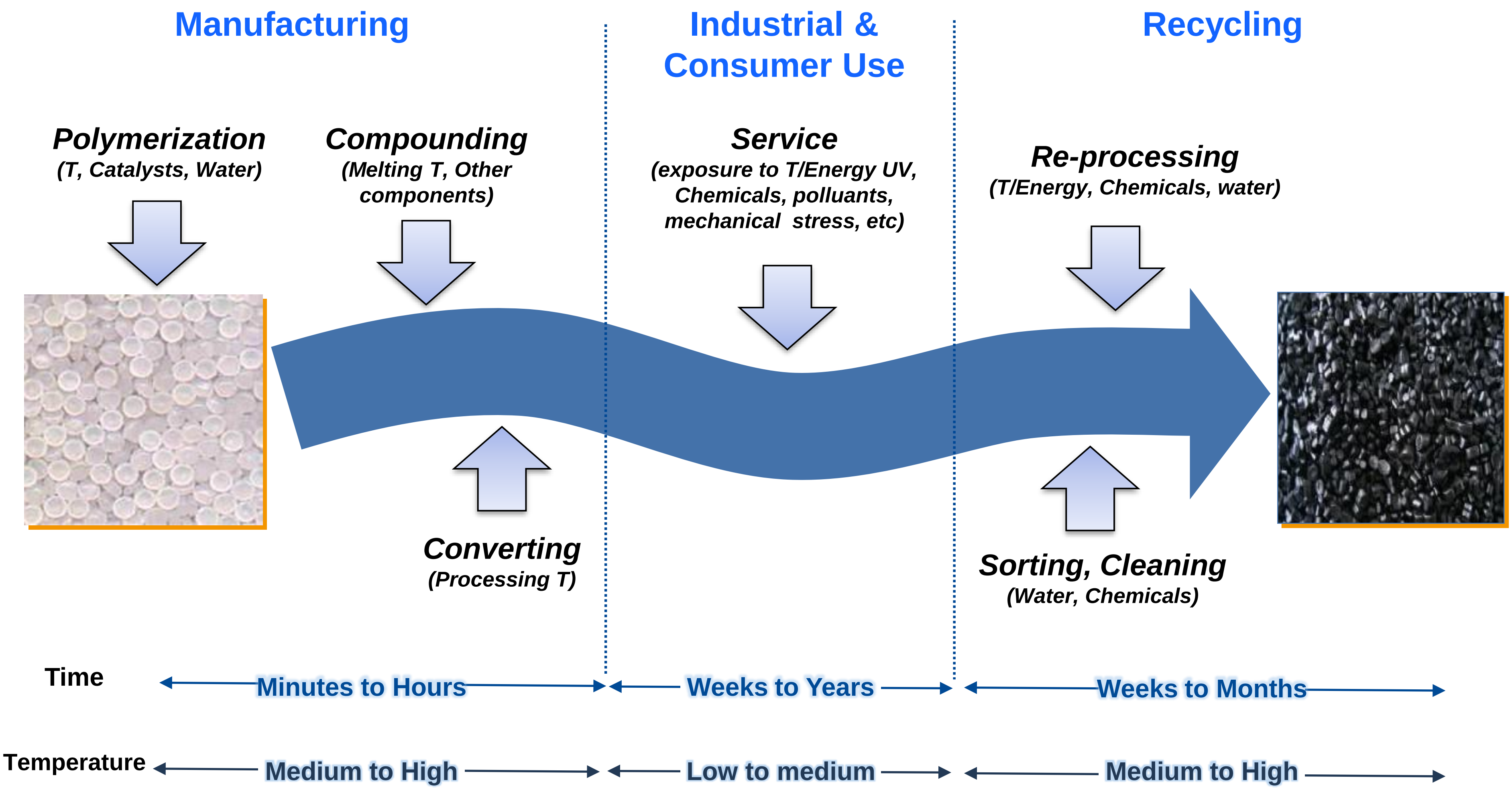
Polyolefins Service Life

The polymer is exposed to harsh conditions during entire lifecycle



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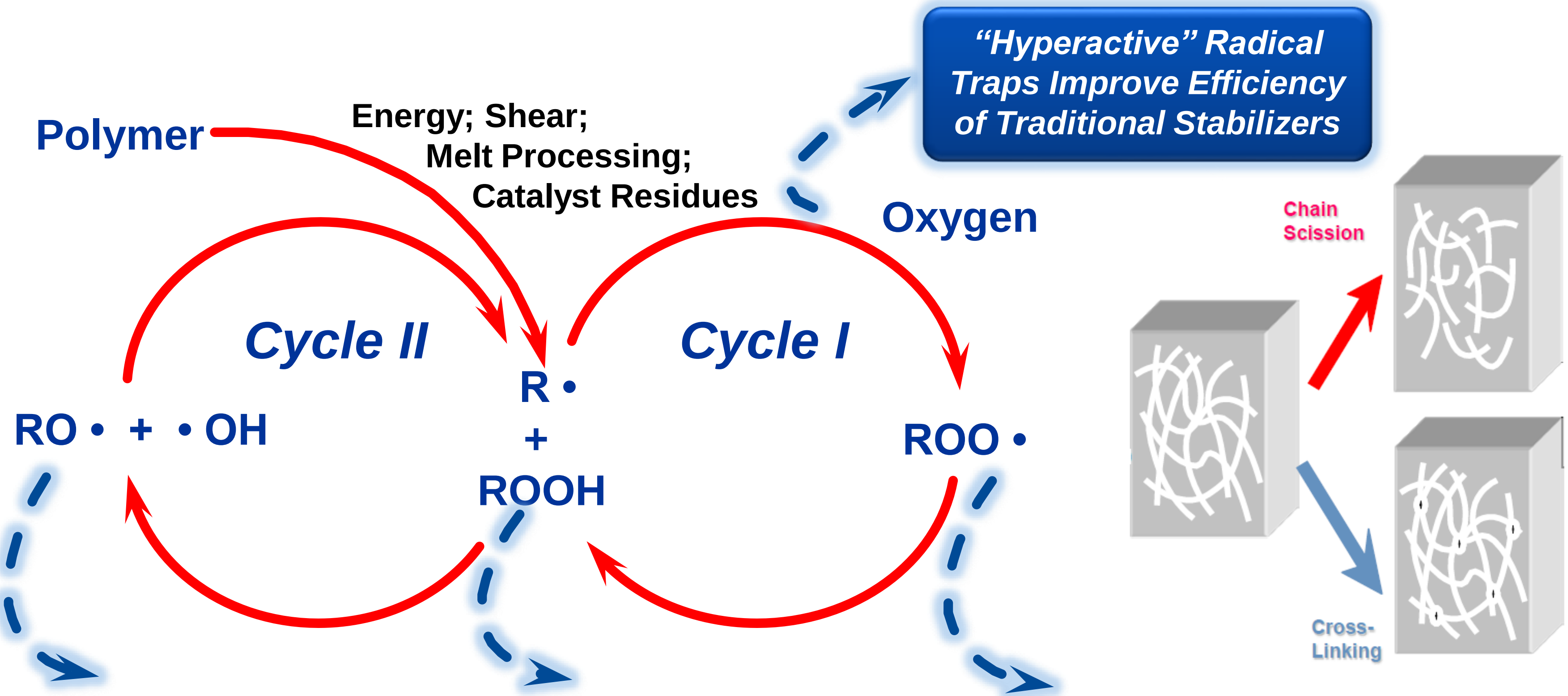
Why do we need plastic stabilizers?

Low concentrations (≤ 0.2%) of stabilizers can yield more recyclable polyolefins



Phenolic AOs react with oxygen centered radicals to yield less active products (ROH and H_20)

Phosphites react with hydroperoxides to yield inactive products (ROH)

Phenolic AOs react with oxygen centered radicals to yield less active products (ROH and H_20)

Path of Degradation

Path of Stabilization

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The Circular Economy of Polyolefins

Where do BASF plastic stabilizers play a role?

"Ready for Recycle"
Virgin HDPE

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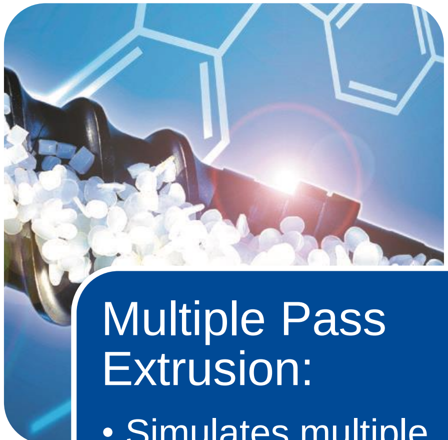
“*Ready for Recycle*” Virgin HDPE

Formulations:

- Blow molding grade HDPE copolymer*
- Varied phenolic AO chemistry
- Varied hyperactive stabilizer chemistry



Multiple Pass Extrusion:

- Simulates multiple “recycles” of polymer
- Six extrusion passes total (zero pass on twin screw, 1^{st}-5^{th} on single screw)

Recyclability was Measured by:

- Melt flow retention
- Color retention
- Oxidative induction time (OIT)
- Gas fade discoloration

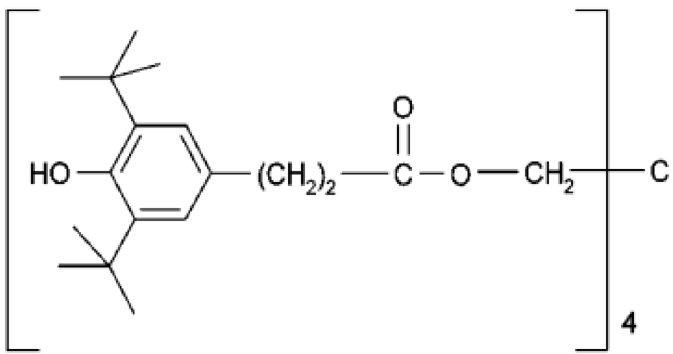
**density=0.954 g/cm^3, MI=0.2 g/10min (190°C/2.16 kg)*

Note: Refer to paper for full description of experimental conditions

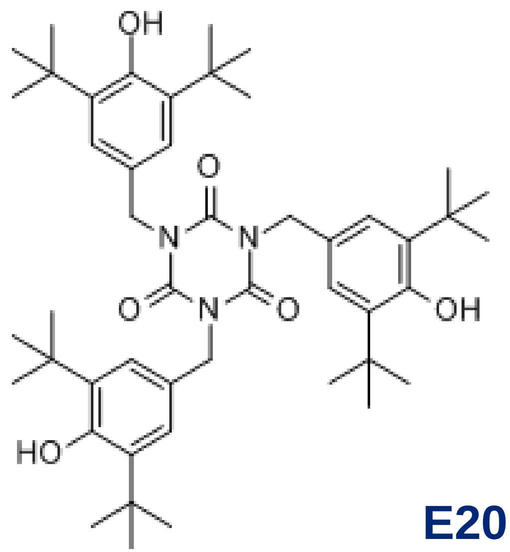
Chemical Structures of Antioxidants

Varying the chemistry to target specific performance

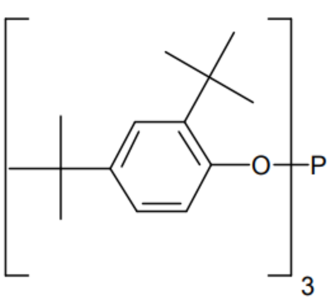
AO1: Phenolic AO
Irganox® 1010



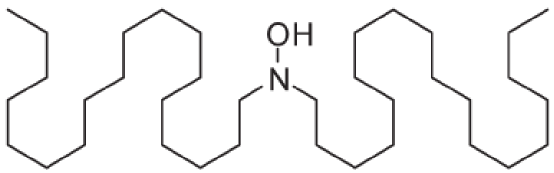
AO2: Phenolic AO
Irganox® 3114



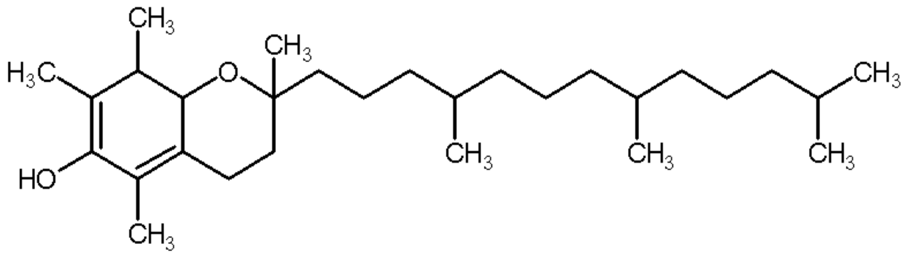
P1: Phosphite AO
Irgafos® 168



NOH: Hydroxylamine
Irgastab® FS-042



E201: Vitamin E
Irganox® E201



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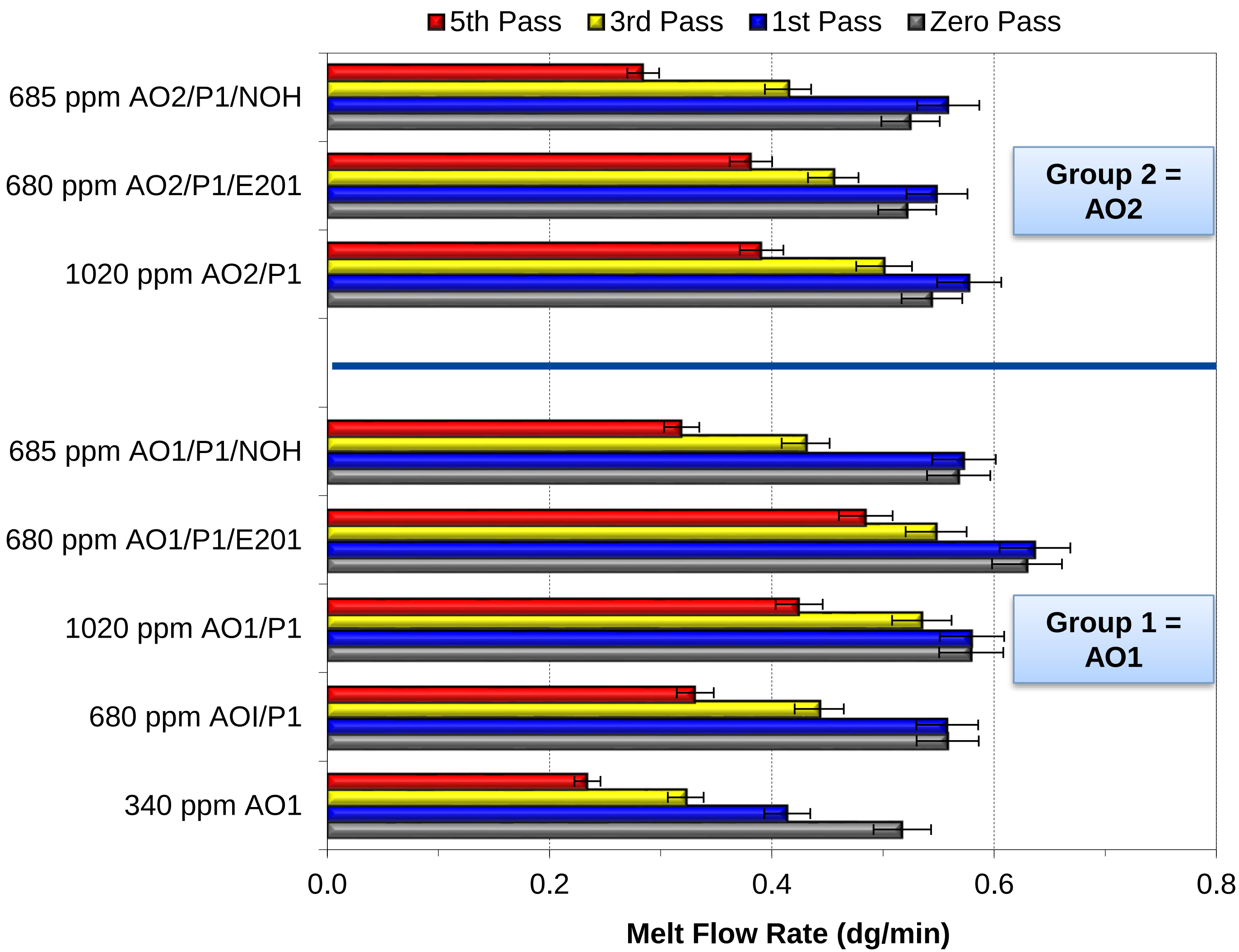
Melt Flow Rate Retention

Effective stabilization preserves the MW during recycle



- Recyclability is improved by either increasing the concentration of stabilizers or changing the components
- Formulations containing AO1 yield better MW retention when compared to formulations with AO2
- 680 ppm AO1/P1/E201 yields the best MW control (**recyclability**)

Note: The predominant degradation mechanism for this HDPE is molecular weight (MW) enlargement and MW distribution (MWD) broadening

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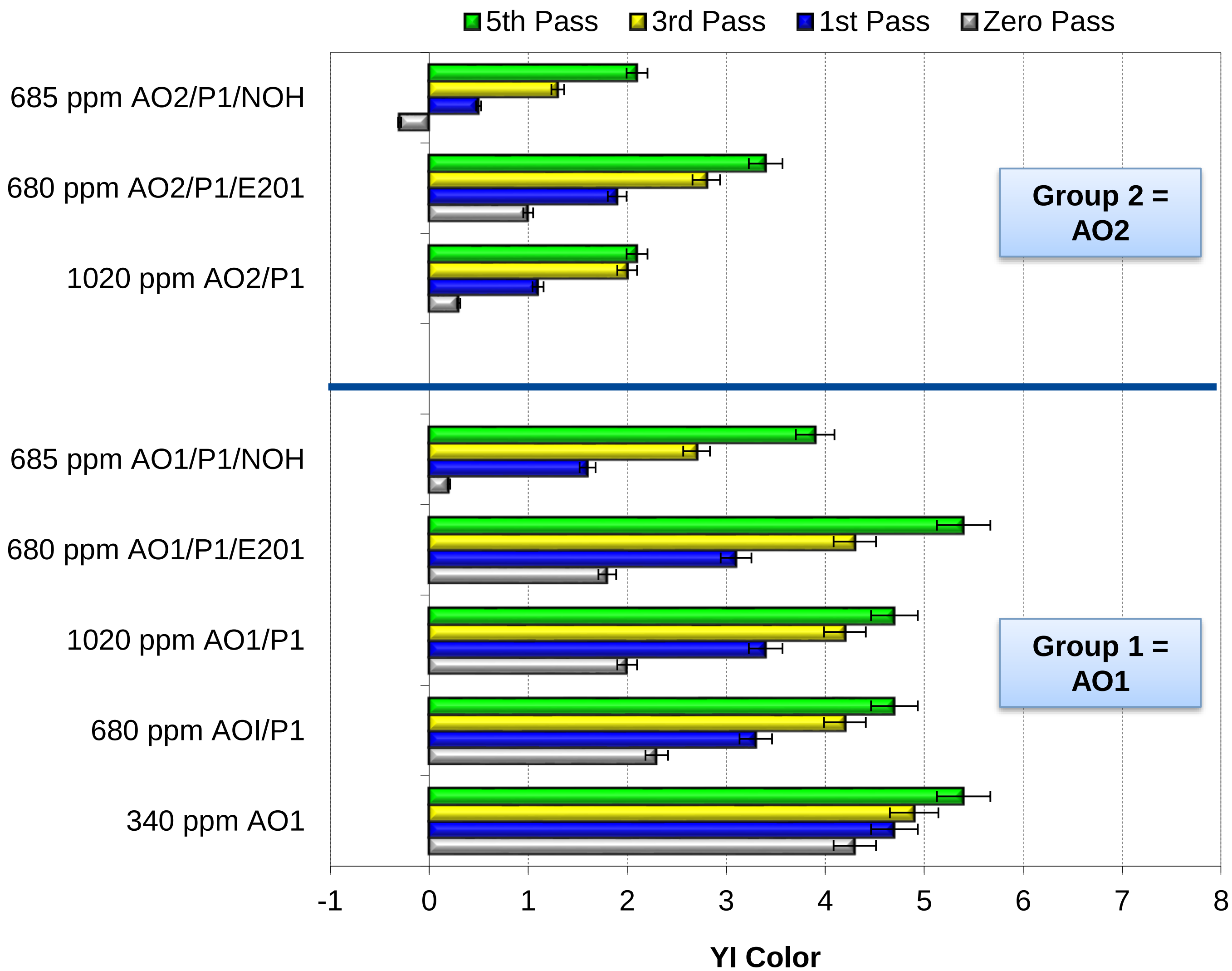
Color Retention

Selection of stabilizers depend on the critical-to-quality properties



- Switching from AO1 to AO2 significantly improves color retention
- Typically, formulations that provide the best melt flow control, tend to be slightly more discolored
- Best color retention is achieved in formulations containing NOH hyperactive

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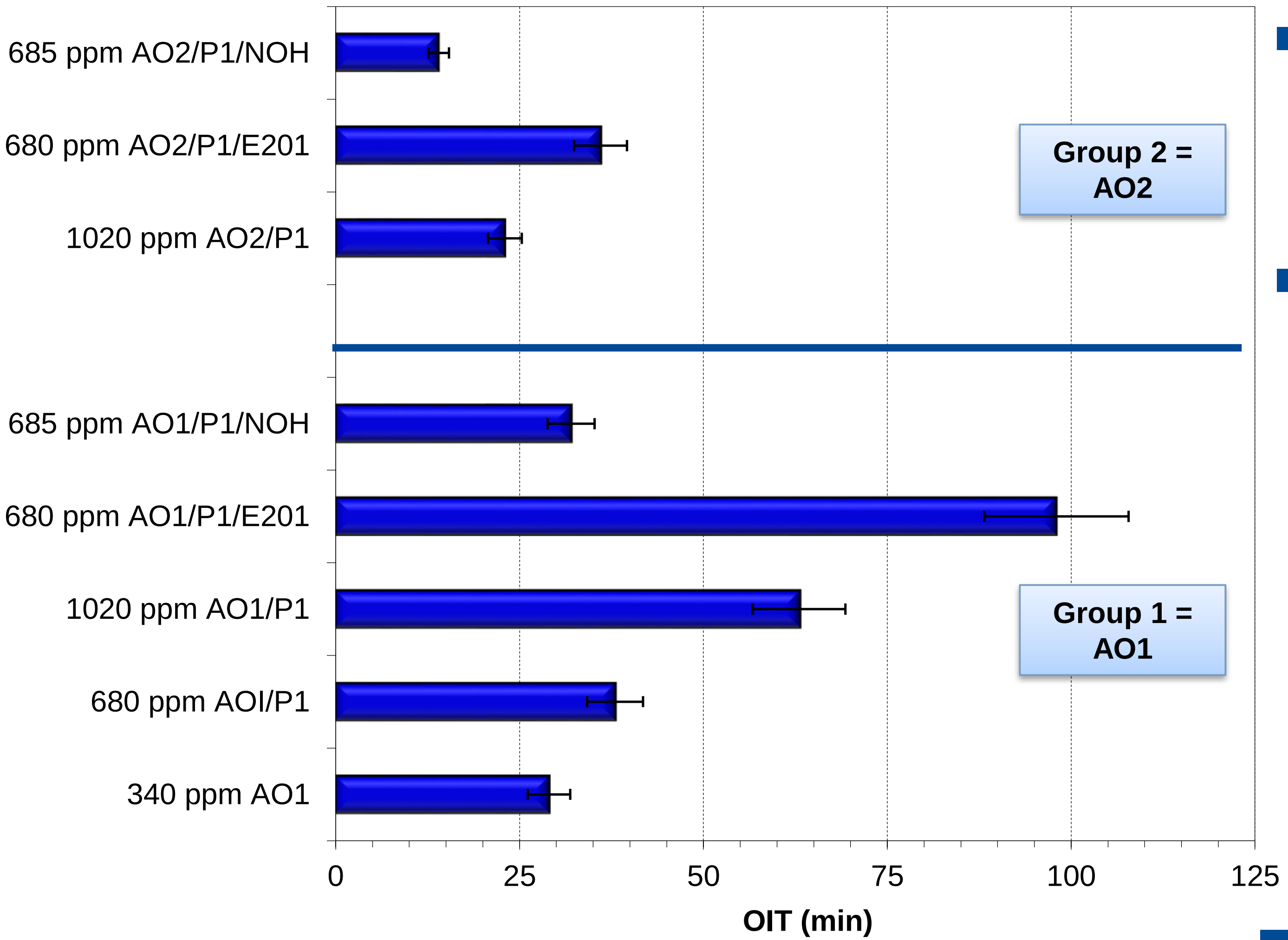
Oxidative Induction Time (OIT)

Trends in oxidative stability match melt flow rate retention



- There is a significant trade-off in oxidative stability when using AO2 instead of AO1
- E201 is an incredibly efficient stabilizer for preserving the MW and MWD of the polymer but has the potential disadvantage of discoloration

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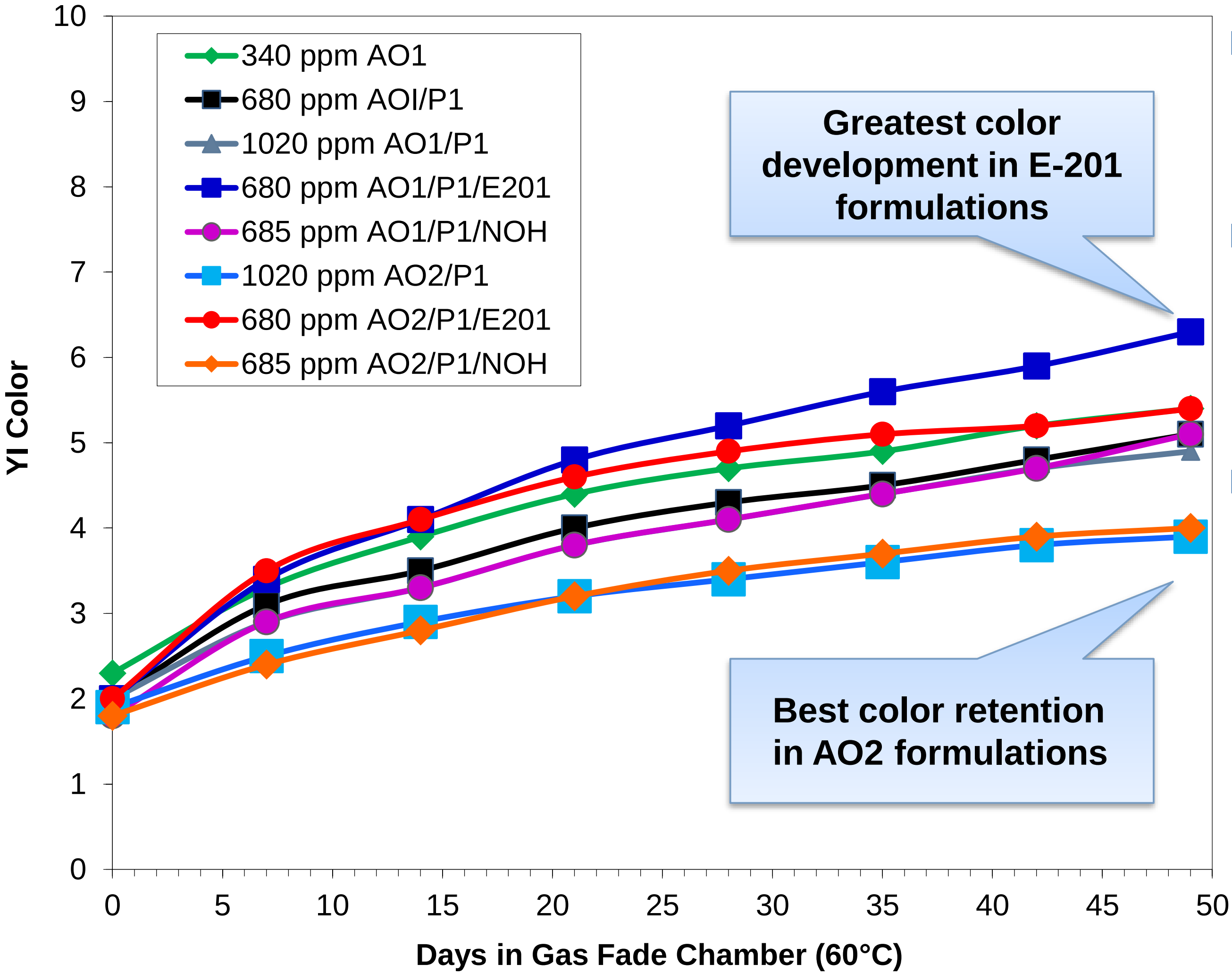
Gas Fade Discoloration

Stabilizers ensure the polymer structure remains stable in storage



- Gas fade discoloration simulates long term storage stability
- AO1 and AO2 formulations with E201 yield the highest overall color development
- AO2 formulations (without E201) yield the lowest gas fade discoloration

Summary: “*Ready for Recycle*” Virgin HDPE

Plastic stabilizers enable longer lifetimes and recyclability

- This HDPE co polymer undergoes MW enlargement and MWD broadening when not properly stabilized
- Dosing in a phosphite (P1) or hyperactive stabilizer (E201) with a phenolic antioxidant results in improved MW retention of the polymer (i.e. **improved recyclability**)
- Better color retention (during multi-pass extrusion and gas fade) is achieved when substituting AO1 (Irganox® 1010) with AO2 (Irganox® 3114) with a consequential loss in MW control
- E201 (Irganox® E201) is an incredibly efficient stabilizer for preserving the MW and MWD of HDPE but has the potential disadvantage of discoloration → ***Color is not typically critical in recycled resin***

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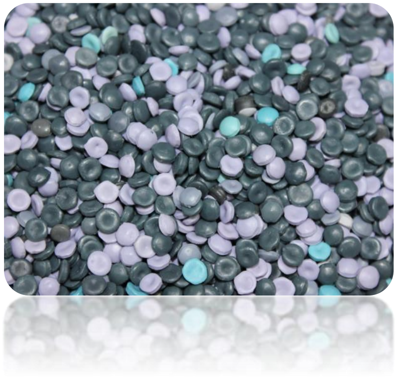
The Circular Economy of Polyolefins

Where do BASF plastic stabilizers play a role?

Re-Stabilization of Recycled HDPE



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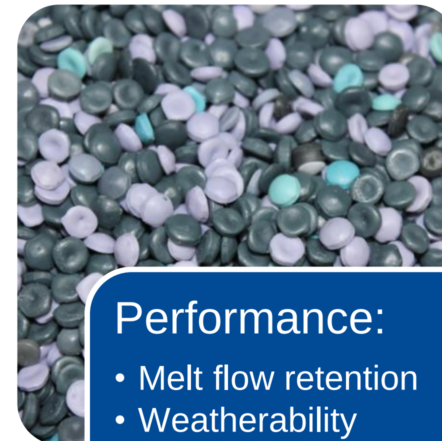
Re-Stabilizing Recycled HDPE

Formulations:

- Used HDPE bottle crates were washed, crushed, and ground*
- Varied loadings of phenol, phosphite, and light stabilizers

Recycling:

- Ground crates were extruded with and without stabilizers (zero pass, twin screw)
- Multiple pass extrusion (1^{st} – 5^{th} pass) done on single screw extruder



Performance:

- Melt flow retention
- Weatherability

**2-16 years in age from manufacturing*

Note: Refer to paper for full description of experimental conditions

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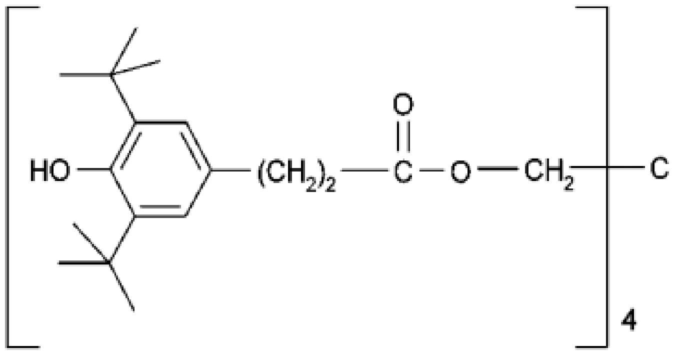
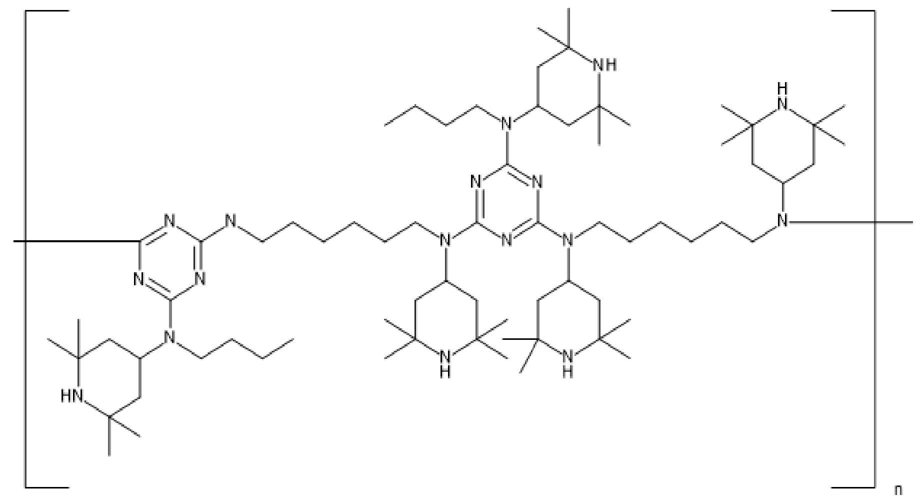
Structures of Antioxidants & Light Stabilizers

Varying the chemistry to target specific performance

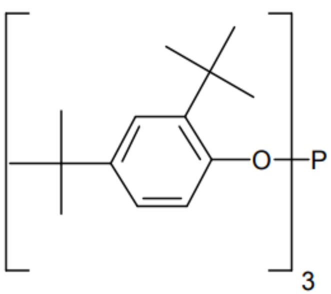
AO1: Phenolic AO
Irganox® 1010



LS: Hindered Amine Light Stabilizer
Chimassorb® 944



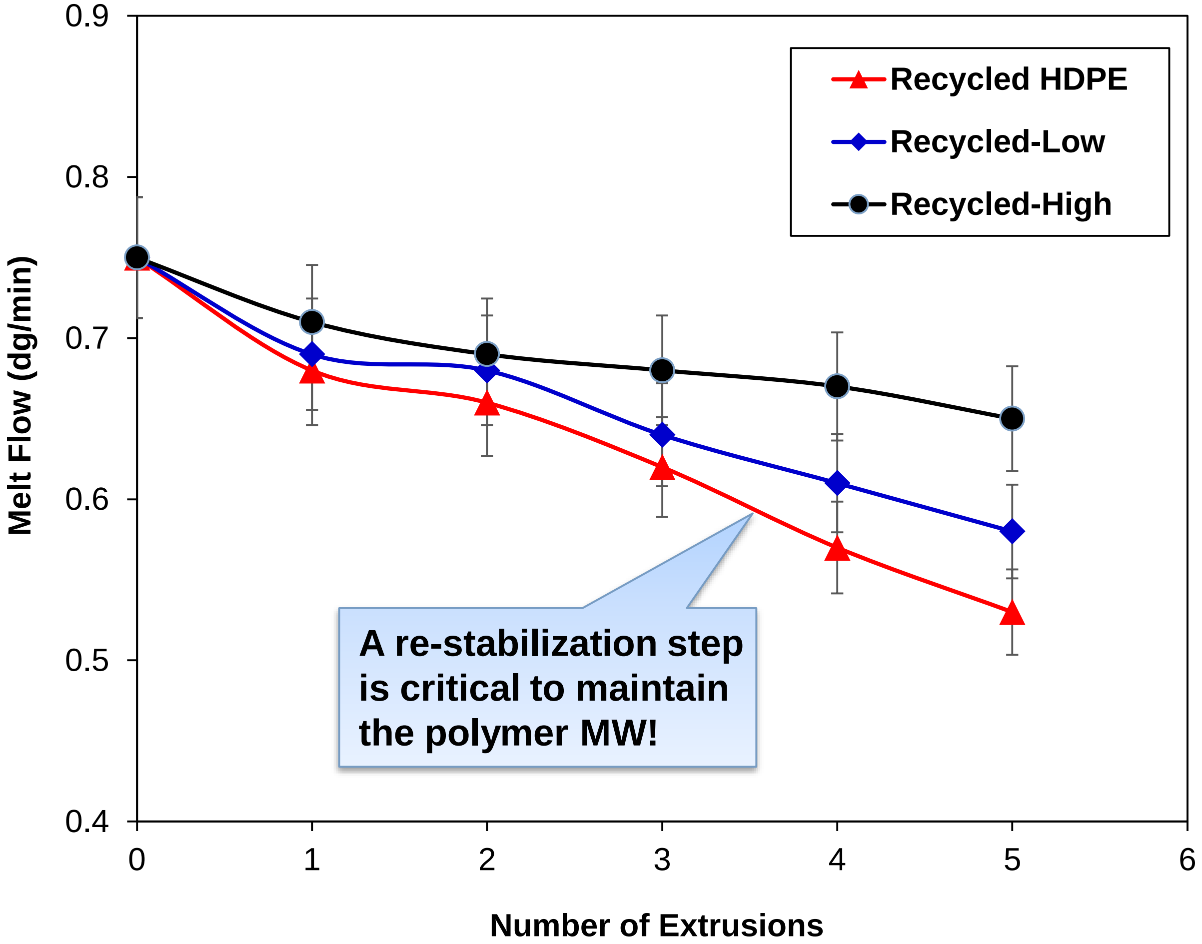
P1: Phosphite AO
Irgafos® 168



Formulation Name	Components
Recycled HDPE	None
Recycled-Low	200 ppm AO1 400 ppm P1 1000 ppm LS
Recycled-High	400 ppm AO1 800 ppm P1 2000 ppm LS

Melt Flow Rate Retention

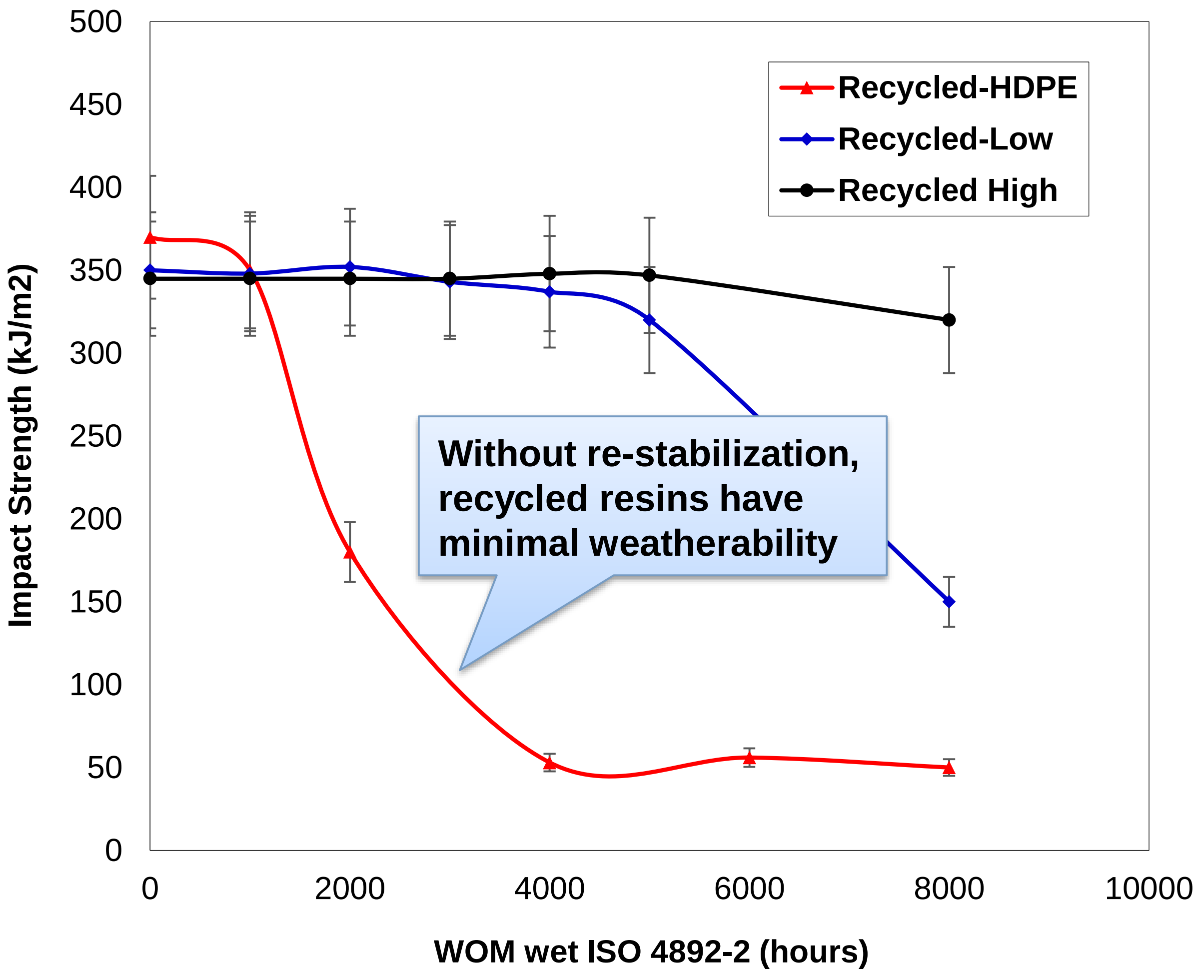
Re-stabilizing recycled HDPE preserves MW & limits microplastics



- Recycled resin that was **not re-stabilized** underwent significant MW enlargement during multiple pass extrusion
- Recycled resin that was re-stabilized with 1200 ppm AO1/P1 and 2000 ppm LS (Recycled-High) yielded excellent melt flow retention

Impact Strength

Re-stabilizing recycled HDPE improves weatherability



- Recycled HDPE that was **not re-stabilized** underwent *complete failure* after 2000 hours of exposure
- Re-stabilizing with 600 ppm AO1/P1 and 1000 ppm LS extended the lifetime to 5000 hours (Recycled-Low)
- Increasing the LS to 2000 ppm further extended the lifetime to 8000 hours (Recycled-High)

Note: Samples were exposed to xenon-arc light in the presence of moisture for 8000 hours to simulate weathering (ISO 4892-2)

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Summary: Re-Stabilizing Recycled HDPE

Re-stabilizing recycled HDPE yields longer lasting materials

- A re-stabilization step is critical to yield reprocessed resins that meet the same quality standards as their virgin counterparts
- Re-stabilizing the recycled HDPE resin results in a significant improvement in MW retention and weatherability when compared to recycled HDPE without stabilizers
- Stabilizing additives will play a major role in preserving the MW of plastics that enter the waste stream and the prevention of microplastics

Proper stabilization of virgin resins: "*Ready for Recycle*"

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Re-stabilization in recycling processes: *Recycled Polyolefins*

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Circular Economy for Polyolefins

BASF Circular Economy Initiatives for Plastics

- **Alliance to End Plastic Waste (AEPW)**
  - BASF co-funded global Alliance to End Plastic Waste January 2019
- **Chemcycling**
  - Chemical recycling of plastic waste to create new chemical products
- **Biodegradable Plastics**
  - Ecoflex® and Ecovio® are 100% compostable plastics, an ecological innovation within the BASF plastic portfolio

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