Best Management Practices for Tire-Derived Product Development

California Department of Resources Recycling and Recovery

October 2013

Contractor's Report
Produced Under Contract By:

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Publication # DRRR-2014-1509

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Prepared as part of contract number DRR10033 ($1,199,675.46).

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Executive Summary

This report summarizes a project by the California Department of Resources Recycling and Recovery (CalRecycle) aimed at improving the quality of tire-derived products by identifying best management practices, or BMPs, for the selection and use of crumb rubber as a feedstock in manufactured and/or compounded products. The report was prepared by DK Enterprises under subcontract to SAIC as part of CalRecycle's Tire-Derived Product Business Assistance Program. To develop the BMPs, the project team worked closely with several California firms involved in scrap tire recycling. The identification of BMPs and standardization of specifications is intended to help industry participants strengthen their supply chain and product offerings, thereby helping to expand and diversify California's markets for scrap tires.

Overview of Tire-Derived Product Development

While certain standards exist that are pertinent to the tire-derived products industry (see Appendix A and information in this section below), the industry sometimes operates on an informal basis without reference to any established standards or specifications in the development of new products. Developing reliable crumb rubber specifications for TDPs across the industry is a collaborative effort involving information sharing and partnering by stakeholders involved in the fabrication of TDPs including crumb rubber producers, rubber compounders, and TDP manufacturers. In practice, widespread development and adoption of comprehensive standards is a long-term effort that will play out over many years. This report represents one small step toward this goal.

The product development process starts with the assumption that one would work backward from the desired outcome (i.e., finished TDPs that meet customer requirements) to develop crumb rubber specifications. By considering the specific TDP, likely customer needs, and specific applications, it is possible to identify the most essential "Critical to Quality" (CTQ) characteristics. This helps determine the necessary crumb rubber characteristics.

Crumb rubber by its very nature is subject to variability. Tires are made using a variety of different raw materials and technologies, and a wide range of equipment is used for size-reducing rubber. These factors influence the resulting crumb rubber produced. Crumb rubber quality is also influenced by the condition of the equipment, production rates, and even weather conditions. All of these factors may affect TDP consistency and performance.

Another factor to consider is life cycle performance. Will the tire-derived product perform as expected over its intended life cycle? A quality defect might not be easy to spot in a new product. The product may initially demonstrate suitability, but over time it may not perform as expected. These scenarios are realistic, as not all potential means of product failure (i.e., failure modes) can be predicted. It is important to attempt to identify as many failure modes as possible; especially those that are critical to end use performance.

Defining the specification or standard is just the beginning of this process. The process capability (i.e., the capability of a material to be successfully used in different types of manufacturing processes, such as injection molding or compression molding) of materials needs to be compatible with the product specifications and the industry standard requirements. Therefore, the process must include process capability studies. A product specification defined without understanding of process capability may result in increased waste and customer dissatisfaction.

Product manufacturers and end users often feel there is a need for standard specifications for crumb rubber feedstock for specific product applications. For the most part, product development has been carried out on an informal basis with crumb rubber that was readily available. In many cases, crumb rubber is not specifically designed to perform for specific TDP end uses. Instead, the TDPs are adapted to perform by the manufacturer using available crumb rubber.

The main body of this report outlines systematic steps for developing standards and specifications for a particular manufacturer, supply chain, product, customer and product application. The process is iterative and is based on close coordination across these stakeholders.

The terms "standards" and "material specifications" are sometimes mistakenly used interchangeably. A product standard is an established test or guideline for a specific product or raw material. A specification is an explicit set of requirements to be satisfied by a material or product. The American Society for Testing and Materials is a widely cited source for industry standards of all types, and several ASTM standards have been adopted that are pertinent to the production of crumb rubber and/or TDPs, including:

- ASTM D5603: Standard Classification for Rubber Compounding Materials—Recycled Vulcanizate Particulate Rubber
- ASTM D5644: Determination of Particle Size Distribution of Recycled Vulcanizate Particulate Rubber
- ASTM D297: Chemical Analysis (This covers the qualitative and quantitative analysis of the composition of rubber products.)
- ASTM E1131: Standard Test Method for Compositional Analysis by Thermogravimetry
- ASTM D1817: Standard Test Method for Rubber Chemicals—Density
- ASTM D6814: Determination of Percent Devulcanization of Crumb Rubber Based on Crosslink Density

Findings and Recommended Best Management Practices

The following findings and recommendations are based on numerous industry interviews and case studies conducted with two firms and their suppliers that are described in Section 2 of this report.

Companies in a variety of industries have performed independent product testing to understand the quality characteristics of select products made from recycled tire rubber. However, clear CTQ requirements have been developed in writing for only a small number of TDPs, and the industry in large part continues to operate on an informal basis, without reference to established standards or specifications. Developing CTQ requirements for TDPs and implementing quality standards must be done on a product-by-product basis, and must be product-driven, market-driven, and manufacturer-specific.

Industry associations and company alliances may be helpful in expanding understanding and implementation of BMPs to ensure product quality. Stakeholder participation is critical in order to build upon this initial work and continue to establish crumb rubber specifications in a meaningful way that serves the various industries involved. Although ASTM D5603 is an established and useful standard for compounded recycled tire rubber, it appears this standard is not being used

consistently in the development of products. Nor does it appear that there is a general understanding of its usefulness or purpose.

Also, ASTM D5603 is not sufficient in all cases due to the wide variety of TDPs and their many different applications. While it does a reasonably good job of describing crumb rubber characteristics, it may not adequately describe crumb rubber material properties that affect TDP performance in all cases.

Sufficient competency in the product development process is needed by TDP manufacturers to establish crumb rubber requirements, establish appropriate test protocols, evaluate test results, and establish appropriate crumb rubber specifications. While it is certainly possible for new products to be successfully launched without these skill sets, the probability of successfully launching a new product is significantly hampered when basic product development and quality disciplines are not followed.

The project team recommends the following best management practices for improving the consistent quality of new and existing TDPs. All stakeholders have a role in implementing these BMPs, including TDP manufacturers and their suppliers, as well as CalRecycle and industry trade associations.

1. Broad education is needed on basic product quality principles.
2. Focused education on standards and specifications is needed for stakeholders to understand the best route to develop quality standards and specifications for their unique context.
3. In particular, focused education on ASTM D5603, the existing standard that is most relevant to TDPs, is needed.
4. Greater use of ASTM standards in practice is needed.
5. There is a need for stakeholders to determine other material and product performance characteristics that may not be covered by ASTM D5603.
6. Product testing should be conducted to define particular product critical-to-quality requirements.
7. There is a need to compare performance of products made with and without recycled tire rubber.
8. There is a need to use standardized test methods.
9. Multiple product samples and test runs should be conducted.
10. Stakeholders should select only the most valuable CTQs and make them as tangible and specific as possible.
11. Manufacturers should produce only to established specifications.
12. Manufacturers should exclude cost as a product requirement when developing products.
13. Consider the broad market and company context in developing products.

This report has described an ideal approach to developing tire-derived products that emphasizes systems for ensuring quality on an ongoing basis, including identification of recommended best management practices. The approach emphasizes market and customer-based critical-to-quality

requirements, and involvement of crumb rubber manufacturers, compounders, and others in the entire supply chain to systematically define and implement specifications and standards (building on established precedents).

While many TDP manufacturers and suppliers are small, resource-constrained businesses, CalRecycle and industry associations can continue to play a role in educating stakeholders and providing information, tools, and assistance to help the industry steadily move toward adoption of the recommended best management practices. Short of this goal, the industry will continue to operate largely on an informal basis with regard to quality standards and specifications. While the TDP market has grown on this basis, in the long run, the fate of the industry and its ability to diversify and expand may ultimately depend on the extent to which more formalized quality standards and specifications can be adopted.

Section 1
Introduction

This report summarizes a CalRecycle project to identify best management practices for the selection and use of crumb rubber made from scrap tires and/or compounded raw materials as a feedstock for tire-derived products to improve the quality of the final products. The report was prepared by DK Enterprises under subcontract to SAIC as part of CalRecycle's Tire-Derived Product Business Assistance Program (TBAP). To develop the BMPs, the project team worked closely with several California firms involved in scrap tire recycling. Identification of BMPs is intended to help industry participants strengthen their supply chain and product offerings, thereby helping to expand and diversify California's markets for scrap tires.

Section 2 of this report describes current applicable standards and provides general guidance on factors to consider to ensure consistent product performance when producing crumb rubber and TDPs. It is essentially an approach for product development and the refining of specifications for existing products.

Section 3 describes real-world applications of the process described in Section 2, based on several interviews with industry stakeholders and two case studies.

Section 4 provides findings and recommendations for BMPs to enhance quality and consistency of TDPs made from crumb rubber.

A Glossary of Terms and Appendices A Through D provide additional supportive information associated with the report. The appendices include:

- **Appendix A –** ASTM Standards
- **Appendix B** – Sample Specification Sheet
- **Appendix C** – Sample TDP Critical to Quality Requirements
- **Appendix D** – Step-by-Step Process Flow Charts

Section 2
Overview of Tire-Derived Product Development

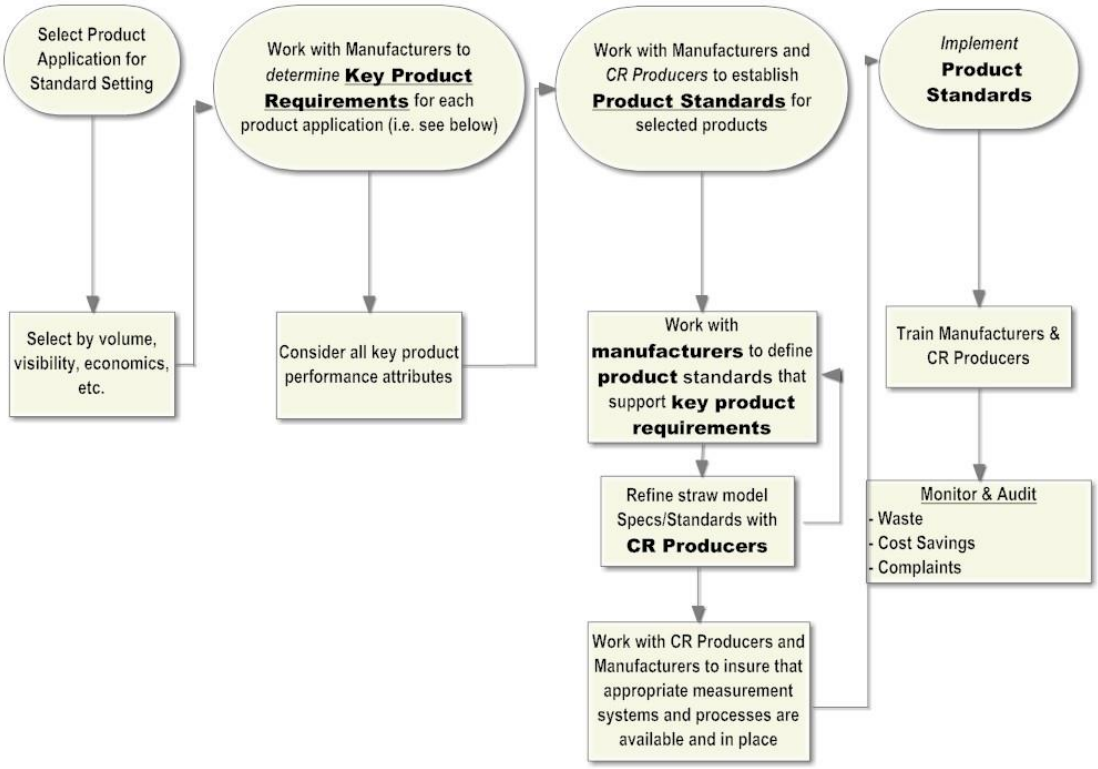
This section provides an overview of how to develop new tire-derived products (TDPs) in a way that systematically integrates appropriate quality standards and specifications. The process can also be used to refine quality standards and specifications for existing TDPs.

The Need for Widely Adopted TDP Industry Standards and Specifications

While certain ASTM standards exist that are pertinent to the TDP industry (see Appendix A and information in this section below), the industry often operates on an informal basis without reference to any established standards or specifications.

Development of reliable crumb rubber specifications for TDPs across the industry requires collaboration by stakeholders involved in the fabrication of TDPs, including crumb rubber producers, rubber compounders, and TDP manufacturers. **Figure 1** presents an overview of a market-driven approach based on input from stakeholders contacted for this study. In practice, this is a long-term effort that will play out over many years.

Figure 1
A Market-Driven Approach to Developing Industry-Wide Standards for Crumb Rubber and TDPs



General Product Development Approach

The product development process starts with the assumption that one would work backward from the desired outcome (i.e., finished TDPs that meet customer requirements) to develop crumb rubber specifications. By considering the specific TDP, likely customer needs and specific applications, it is possible to identify the most essential "critical to quality" (CTQ) characteristics. This then allows for determining the associated critical crumb rubber material characteristics. One methodology that can be used to determine what and how crumb rubber characteristics affect CTQs is to review literature that describes crumb rubber material characteristics, including existing standards and published reports. Because crumb rubber has been used in certain TDPs for more than 20 years, it is possible to glean information from past failures and successes. Literature describes how crumb rubber particle size can affect material properties in plastics and that surface area from particle size, particle size distribution, and grinding method can have a pronounced effect on physical properties. As an example, one source stated in a 2004 review that "ground rubber from tire waste in plastic blends is compatibilized by reducing particle size."[1 2 3 4] It is also known, and supported by published research, that certain grinding processes afford better particle adhesion to the plastic substrate.[5] Although beyond the scope of this project, the final step would be to establish product specifications for crumb rubber.

These three general steps comprise an approach to new product development, as described more fully below:

Step 1: Identify the essential product requirements for the targeted TDP (i.e., CTQ requirements).

a. Define TDP performance characteristics that are critical to customers and to the marketplace by reviewing customer complaints, by asking customers for feedback or by reviewing competitive products.

b. Review current industry standards including pertinent certification standards, both domestic and international. Are there industry or certification standards that apply to the TDP? If so, and based on data, does the current TDP meet requirements?

c. Define current TDP product specifications and determine if they are critical to the customer, based on Steps 1a-b.

d. Define CTQ requirements based on data and discussion during mapping process above in Steps 1a-c.

Step 2: Identify crumb rubber and other raw material characteristics that significantly affect product and process requirements (i.e., critical raw material requirements).

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[1] D. Mangaraj, "Role of Compatibilization in Recycling Rubber Waste by Blending with Plastics," *Rubber Chemistry and Technology*, July 2005, Vol. 78, No. 3, pp. 536-547.

[2] D. Ratna and Ajit K. Banthia, "Rubber Toughened Epoxy," *Macromolecular Research*, July 2002, Vol. 75, No. 3, pp. 429-474.

[3] M. Pittolo and R.P Burford, "Recycled Crumb Rubber as a Toughener of Polystyrene," *Chemistry and Technology*, March 1985. Vol. 58, No. 1, pp. 97-106.

[4] Marvin Myhre and Duncan A. MacKillop, "Rubber Recycling," *Rubber Chemistry and Technology*, July 2002, Vol. 75, Vol. 75, No.3, pp. 429-474.

[5] D. Mangaraj.

a. Determine the crumb rubber attributes that might affect TDP performance benefits. (For example, by consulting Table 1 "Partial List of Material Characteristics and Properties" and Table 5, "Crumb Rubber Material Characteristics," later in this section.) Ask questions such as: Is performance influenced by particle size, particle size distribution, rubber chemistry, surface morphology? Understanding this will help to focus on the critical tests needed to ensure suitability and consistent performance.

b. Define internal manufacturing issues such as scrap, first-time yields, and rework. Analyze how crumb rubber affects or contributes to each issue.

c. Define current raw material requirements/specifications, and consider how each affects the end product. Distinguish between those that establish value in a product versus those that do not. Color, for instance, is a product characteristic that often does not establish value.

Step 3: Establish product specifications for raw materials that establish acceptable quality limits (i.e., product specifications).

a. Review draft product specifications with the raw material provider. In the case of TDPs, this will include reviewing draft crumb rubber product specifications with the crumb rubber producer.

b. Modify draft raw material specifications as needed to ensure reasonable supply and TDP performance.

c. Finalize and publish raw material specifications.

Different industry stakeholders involved in manufacturing various types of TDPs will have different outcomes from this product development process. However, the general process applies to many industries and situations.

Once there is an understanding of which CTQs are affected by incorporating crumb rubber into the TDP, and how TDP performance is influenced by crumb rubber properties, then it is possible to establish crumb rubber specifications. It is important for crumb rubber specifications to be realistic so the material can be incorporated into a manufactured or compounded product at a reasonable cost. Coordination between the TDP manufacturer and the crumb rubber producers about crumb rubber manufacturing capabilities are important to make sure that the requested crumb rubber products can be produced to specification and are suitable and consistent from batch to batch. Periodic testing of crumb rubber is warranted to make certain that it is within specification on an ongoing basis.

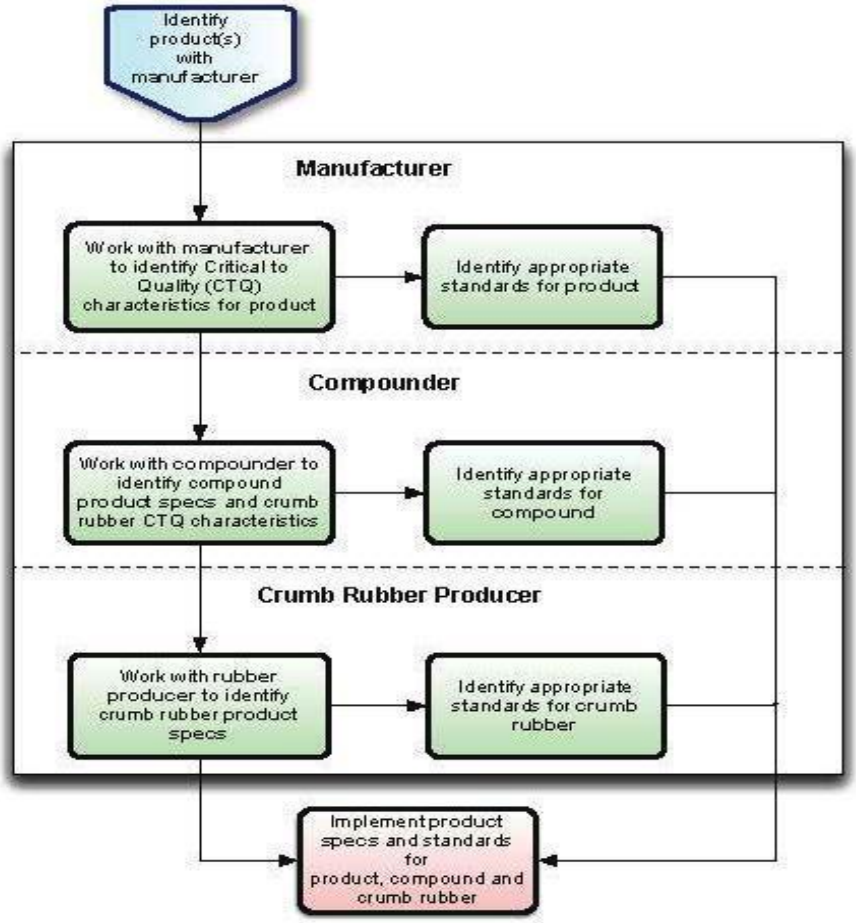
A final product specification sheet should be prepared. This can be tailored to the specific business and to the TDP. See an example of a "CTQ Requirements Specification Form" (Appendix C). This completed form becomes a living document that should be reviewed at least annually to ensure that it remains relevant.

An Approach to Developing Standards and Specifications for a Particular Product

Two important concepts related to developing new products are suitability and consistent performance. It is critical to understand what is required to produce a suitable product and what is required to ensure consistent product performance. Suitability, sometimes referred to as "fitness for use," is the degree to which the product performs as intended. Consistent performance is the degree to which TDP performance is repeatable and predictable.

Figure 2 illustrates the process for developing product-specific specifications and standards for a particular manufacturer and product that can result in suitable and consistent performance. Collaborative, often repetitive communication and coordination among the product manufacturer, compounder, and crumb rubber producer are vital to the process.

Figure 2
Approach to Working with Stakeholders to Develop Product-Specific Specifications and Standards for a Particular Product



Product Development and Quality Fundamentals

The best way to understand and identify CTQ requirements is to interview product users and customers. Another technique that can be used is to study competitive products in order to understand key specifications and benefits that are being offered in the marketplace. This is a worthwhile exercise since it may be necessary to position new tire-derived products against these competitive products.

Crumb rubber is the raw material that is used for the manufacture of TDPs. The physical characteristics of crumb rubber affect the performance of the final product. A considerable amount of technology is required to make certain that the crumb rubber is fit for use and that it performs consistently from batch to batch. Consistent crumb rubber performance directly impacts the degree to which the final TDP will perform as expected over its intended life cycle. Quality

defects in final products may not be evident initially but may present themselves over time. This document outlines a simple approach that can be implemented to enhance TDP quality control in a variety of manufacturing settings. Even though there are several manufacturing methods for crumb rubber and a variety of unique processing approaches, it is still possible for a small manufacturer to ensure that a product is fit for suitable use and that it consistently performs as expected.

As described above, in order to design a quality process, one approach involves "working backward" to first understand the desired outcome (final TDP performance requirements). Once this is done, the required inputs (raw material requirements) can be identified in order to pinpoint the critical CTQs. Another way to describe this in common product development terminology is to obtain the "voice of the customer." Understanding the customer requirements is the first step and is most important in defining the variables that are CTQ. The input specifications (raw material) and the output (product requirements) must be defined together and not independently. Both raw material and product need a roadmap to follow. This begins by identifying what a specification might include. The following are a few examples:

- The objective and scope of the specification and its intended use
- Required certifications
- Safety considerations and requirements
- Quality control requirements (input and output)
- Acceptance criteria
- Test methods for measuring all specified criteria

Table 1 represents a partial list of material characteristics and some properties to be considered.

Table 1
Partial List of Material Characteristics and Properties

• Adhesion/Compatibility	• Fiber Content
• Cleanliness	• Water Content
• Product Consistency	• Natural Rubber Content
• Particle Size Distribution	• Rubber Hydrocarbon Content
• Environmental Documentation	• Carbon Black Content
• Bulk Density	• Ash Content
• Specific Gravity	• Oil Content
• Steel Content	• Dust Levels

To evaluate and implement best management practices for quality, it is important to understand a few quality fundamentals. Product quality is defined as "the collection of features and characteristics of a product that contribute to its ability to meet given requirements."

Product specifications will help to define basic TDP CTQ requirements and identify how these requirements are impacted by crumb rubber attributes. Some of the crumb rubber characteristics that may be important to tire-derived products include particle size, particle size distribution, particle shape, rubber type, and rubber reversion. Identifying crumb rubber attributes that are important for TDP processing and performance will help to improve manufacturing efficiencies by reducing waste, rework, and claims. Early stages of quality discipline will help to ensure long-term industry health and viability.

Customers are the final arbiter of quality since they ultimately decide if the product meets their requirements. It is left to the manufacturer to interpret and translate the customer's expectations into objective performance measures that can be used to manufacture a product that performs reliably and consistently. The customer will also determine whether the product performance is worth the price.

Crumb rubber by its very nature is subject to variability. For example, a variety of tires made using different raw materials and technologies are used, and a range of different equipment and processes for size-reducing rubber are employed. Crumb rubber quality is also influenced by the condition of the equipment, production rates, and even weather conditions. All of these factors may affect TDP consistency and performance.

Another consideration is life cycle performance. Will the tire-derived product perform as expected over its intended life cycle? A quality defect might not be easy to spot in a new product. However, a defect may become noticeable after the product has been in service for a period of time. The initial work may demonstrate suitability, but over time the product may not perform as expected. These scenarios are realistic, as not all potential means of product failure (i.e., failure modes) can be predicted. It is important to attempt to identify as many failure modes as possible, especially those that are critical to end use performance.

Defining the specification or standard is just the beginning of this process. A product specification defined without understanding of material characteristics, product specifications, and processing methods may result in increased waste and customer dissatisfaction. A systematic product design process should be followed both for a product design specification (PDS) and to meet end-use requirements. Process controls must be defined and an effective quality management system utilized to keep production within engineering tolerances.

Product manufacturers and end users often believe there is a need for standard specifications for crumb rubber feedstock for specific product applications. For the most part, product development has been carried out on an informal basis with crumb rubber that was readily available. In many cases, crumb rubber is not specifically designed to perform for specific TDP end uses. Rather, the TDPs are adapted to perform by the manufacturer using available crumb rubber.

The Distinction Between Standards and Specifications

The terms standards and material specifications are sometimes mistakenly used interchangeably. A product standard is an established test or guideline for a specific product or raw material. A specification is an explicit set of requirements to be satisfied by a material or product.

An example of a test standard is an ASTM test method. Recognize that the TDP manufacturer may require additional or tighter specifications than the crumb rubber manufacturer offers. In this case, the TDP manufacturer may need to shop for a suitable crumb rubber or negotiate with a crumb rubber manufacturer to establish the required specification. Additional costs may be incurred by the crumb rubber producer to offer what amounts to a new or different product. If this is case, the TDP manufacturer should expect to pay a premium and possibly to have a minimum order size.

Sieve analyses from multiple crumb rubber producers were examined and compared as part of this project. Product specifications may need to include a precise measure of particle size distribution consistent with ASTM D5603. In addition, specifications on metal content, fiber content, moisture content, rubber hydrocarbon content, carbon black content, inorganic material, and specific gravity may also be required and can be represented on a product specification sheet, as is presented in **Table 2**. **Figure 3** shows industrial sieves used to separate crumb rubber by particle size.

Table 2
Typical Specification Sheet

Specification Sheet					
Product: 40 Mesh				**Date:** 1/1/2012	
Customer(s): ABC Company					
Product Description: Ground rubber from truck tires					
ASTM D5603 Specifications					
Property	**Test Method**	**Units**	**Size**	**Value**	**Tolerance**
Grade	ASTM D5603	NA	NA	1-4	
Particle Size	ASTM D5644	% Retained	30	<1	
			40	<10	
Metal Content	ASTM D5603	%	NA	0.1 max	
Fiber Content	ASTM D5603	%	NA	0.1 max	
Moisture Content	ASTM D1509	%	NA	0.5 max	
Acetone Extractables	ASTM D297	%	NA	8-22	
Ash	ASTM D297	%	NA	8 max	
Carbon Black	ASTM D297	%	NA	26-38	
Natural Rubber	ASTM D297	%	NA	10-35	
RHC	ASTM D297	%	NA	42	
Bulk Density	ASTM D5603	lb/ft^3	NA	22-28	
Other Specifications					

Figure 3
Sieves Used to Separate Crumb Rubber by Particle Size

Industry Standards

Industry standards for crumb rubber have been established by ASTM. ASTM D5603 and D5644 focus on particle size, particle size distribution, and rubber chemistry. In addition to these two standards, there are other material characteristics that may be as important or even more important, depending on how the crumb rubber is being used and on what benefits it is providing to the final product. There are several methods for producing crumb rubber that yield crumb rubber with different material characteristics. See Appendix 1 for additional ASTM supportive documentation.

ASTM D5603: Standard Classification for Rubber Compounding Materials—Recycled Vulcanizate Particulate Rubber

This method covers the compounding material commercially known as recycled vulcanizate particulate rubber. Recycled vulcanizate particulate rubber is the product that results when vulcanizate rubber has been processed by some means to obtain a desired particle size distribution. ASTM D5603 also provides classification recommendations on particle size distribution, polymer type, chemistry, and foreign matter. The guidelines provided by ASTM D5603 are summarized in **Table 3**.

Table 3
ASTM D5603 Crumb Rubber Guidelines

Characteristic	ASTM Test Method	Value (%)
Acetone Extractable	D297	8-22
Ash	D297	8
Carbon Black	D297	26-38
Loss on Heating	D1509	1
Natural Rubber Content	D297	10-35
Rubber Hydrocarbon Content (RHC)	D297	42
Metal Content	D5603	.1
Fiber Content – (Grades 1, 4, 5, 6)	D5603	.5
Fiber Content – (Grades 2,3)	D5603	nil

ASTM D5603 standard particle size designations are presented in **Table 4**. This table defines the acceptable mix of particle sizes within the overall grade of crumb rubber that is defined by a single particle size (i.e., the mesh size). It is up to TDP manufacturers to select the particle size that is most suitable for their applications.

Table 4
Recycled Rubber Product Designation

Nominal Product Designation		Example Classification D5603 Designation[A]		Zero Screen, µm		Percent Retained on Zero Screen	Size Designation Screen, µm		Maximum % Retained on Designation Screen
10	Mesh	Class	10-X	2360	(8 Mesh)	0	200	(10 Mesh)	5
20	Mesh	Class	20-X	1180	(16 Mesh)	0	850	(20 Mesh)	5
30	Mesh	Class	30-X	850	(20 Mesh)	0	600	(30 Mesh)	10
40	Mesh	Class	40-X	60	(30 Mesh)	0	425	(40 Mesh)	10
50	Mesh	Class	50-X	425	(40 Mesh)	0	300	(50 Mesh)	10
60	Mesh	Class	60-X	300	(50 Mesh)	0	250	(60 Mesh)	10
70	Mesh	Class	70-X	259	(60 Mesh)	0	212	(70 Mesh)	10
80	Mesh	Class	80-X	250	(60 Mesh)	0	180	(80 Mesh)	10
100	Mesh	Class	100-X	180	(80 Mesh)	0	150	(100 Mesh)	10
120	Mesh	Class	120-X	150	(100 Mesh)	0	128	(120 Mesh)	15
140	Mesh	Class	140-X	128	(120 Mesh)	0	106	(140 Mesh)	15
170	Mesh	Class	170-X	106	(140 Mesh)	0	90	(170 Mesh)	15
200	Mesh	Class	200-X	90	(170 Mesh)	0	75	(200 Mesh)	15

[A]When specifying materials, replace the X with the proper parent material grade designation code. For example, Class 30-20 would indicate a 600 µm (30 mesh) product made from Grade 2 material, car, truck, and bus tread rubber. Class 100-6 would indicate a 150 µm (100 mesh) product made from Grade 6 material, non-tire rubber.

Classification by parent tire compound per ASTM D5603 should also be considered when creating a specification. ASTM defines six grades of tires that are used to make crumb rubber:

- **Grade 1** — Whole tire recycled vulcanizate particulate rubber is prepared from passenger car, truck, and bus tires from which the fiber and metal have been removed. The rubber is then processed to the desired particle size.
- **Grade 2** — Car, truck, and bus tread recycled vulcanizate particulate rubber is prepared from car, bus, and truck tread only, processed to the desired particle size. This material is commonly referred to as "peel" rubber.
- **Grade 3** — Tread recycled vulcanizate particulate rubber prepared by utilizing tire retread buffings only.
- **Grade 4** — Whole tire recycled vulcanizate particulate rubber prepared by utilizing tire retread buffings only.
- **Grade 5** — Recycled vulcanizate particulate rubber prepared from off road tires, large equipment tires, industrial tires, forklift tires, farm implement tires, and others.
- **Grade 6** — Recycled vulcanizate particulate rubbers are prepared from rubber vulcanizates from non-tire rubber products.

At a minimum, standard particle size designations per ASTM D5603 should always be used when creating a specification for crumb rubber for a TDP.

ASTM D5644: Determination of Particle Size Distribution of Recycled Vulcanizate Particulate Rubber

This test method describes the procedures for determining average particle size distribution of recycled vulcanizate particulate. This method should always be used when specifying particle size distribution.

Additional ASTM standards that are relevant to the industry are described in more detail in Appendix A, and include:

- ASTM D297: Chemical Analysis (impact durability, chemical and water resistance, elastomeric resilience, toughness, strength and conductivity)
- ASTM E1131: Standard Test Method for Compositional Analysis by Thermogravimetry (indicates the volatility of matter, combustibility, and ash content)
- ASTM D1817: Standard Test Method for Rubber Chemicals—Density (to determine density of solid chemicals used as rubber additives during processing and manufacturing)
- ASTM D6814: Determination of Percent Devulcanization of Crumb Rubber Based on Crosslink Density (helps guard against rubber reversion, which can be a potential issue if crumb rubber particles are overheated)

Crumb Rubber Material Characteristics and TDP Performance

Crumb rubber, because of its unique material features, can provide a number of benefits to TDPs. Not every TDP will require every benefit. Therefore it is important to identify the critical benefits, then implement a program to ensure that the appropriate crumb rubber characteristics are managed to produce a suitable and consistent product. Some of the material characteristics that should be considered are summarized in **Table 5**.

Table 5
Crumb Rubber Material Characteristics and TDP Performance

Crumb Rubber Attribute		Crumb Rubber Feature		Potential TDP Performance Benefits
Tire chemistry	➔	Elastomeric Resilience	➔	Abrasion Resistance Impact Resistance Crack Resistance Vibration Damping Sound Damping
		Strength & Toughness	➔	Abrasion Resistance Impact Resistance Crack Resistance Vibration Damping Flexibility Cohesion Crack Bridging Tear Strength Flexural Strength
		Non-conductive	➔	Thermal Insulation Sound Insulation Electrical Resistivity
		Chemical Inertness	➔	Resistant to acids and
		Water Resistance	➔	Moisture and Water Weatherability
		Durability	➔	Aging
Particle Size	➔	Adhesion	➔	Abrasion Resistance Crack Resistance Flexibility Cohesion Flexural Strength Crack Bridging Tear Strength
Particle size distribution	➔	Adhesion	➔	Abrasion Resistance Crack Resistance Flexibility Cohesion Flexural Strength Crack Bridging Tear Strength
Surface morphology	➔	Adhesion	➔	Abrasion Resistance Crack Resistance Flexibility Cohesion Flexural Strength Crack Bridging Tear Strength

Section 3
Case Studies

To help identify BMPs for CalRecycle-affiliated businesses, the project team interviewed and solicited feedback from several crumb rubber producers, rubber compounders, TDP manufacturers, and customers. Based on this initial research, two companies were selected for case studies. The firms and their suppliers were concerned about protecting proprietary product specifications and market context, so the descriptions below do not identify the firms or include company-specific data, but focus on the process employed and the results seen. The process served to reinforce the finding that many TDP manufacturers and suppliers are small, resource-constrained businesses that find it challenging to focus on systematic quality programs in a formal way.

The project team met with the selected companies to qualitatively identify CTQs for a variety of TDPs. The team also researched competing products to better understand product positioning within the commercial marketplace and to determine whether published product specifications exist.

Ideally, testing is used to determine whether the current crumb rubber used is suitable to meet CTQs. However, "cause and effect" testing to determine performance and durability of varying material characteristics was not included in this project scope due to resource limitations. The companies did provide some documented test results that had been performed previously, and/or identified what tests were in the process of being conducted.

Case Study 1 – Rubber/Plastic Manufacturer/Molder (Company A)

In this case study, crumb rubber is used as filler for a thermoplastic molded part. Company A was involved in the development of an injection-molded part using crumb rubber as a filler for a thermoplastic resin. The stated purpose of the crumb rubber was to provide greater resilience and cost dilution versus the standard thermoplastic resin.

Previous development work included multiple trials using different crumb particle size distributions and different lots of thermoplastic resins. Under this project, the team compiled and compared performance characteristics against stated performance expectations. Discussions were held with the compounder, who would provide a compounded resin with crumb rubber filler for injection molding.

A search was done to identify competitive products and to determine CTQs. Eight product requirements were identified. Of these, three were identified as CTQs. These requirements included product characteristics that would be important to the end user and that could potentially be affected by crumb rubber material properties. To protect proprietary information, however, details regarding these CTQs cannot be provided.

Data was collected in an effort to determine the potential effect of crumb rubber material properties on the final TDP properties. Key product characteristics that are directly affected by crumb rubber for this TDP are presented in **Table 6**.

Table 6
Product Characteristic Data Collected for Case Study 1

CTQs	Data Collected On		
	Unfilled Resin	Crumb Rubber Filled Resin	Competitive Product
Flexural Strength	Yes	No	No
Impact Strength	Yes	No	No
Coefficient of Friction	No	No	Yes
Compression Set	Yes	No	Yes
Abrasion Resistance	No	Yes	Yes
Tensile	Yes	Yes	Yes
Hardness	Yes	Yes	Yes
Flammability	Yes	Yes	Yes
Tear Strength	No	No	Yes
Melt Flow	Yes	No	No
Flexibility	No	Yes	No

The intent of the case study was to collect data on the most important CTQs. Comparison against an unfilled resin and against competitive products would have provided indications of performance benefits and of comparative suitability, assuming of course that competitive products performed as intended. Direct interaction with customers and/or users can provide even more useful suitability data.

Suitability comparisons that could be made with available data are presented in **Table 7**.

Table 7
Initial Assessment of Feedstock Suitability for Case Study 1

Test	Test Product Data within Range of Competitive Data	Comments
Flexural Strength	NA	Competitive Data Unavailable
Impact Strength	NA	Competitive Data Unavailable
Coefficient of Friction	No	Values Need to Be Addressed
Compression Set	Not Tested	Testing Needed
Abrasion Resistance	Various ASTM Standards Used for Testing	Additional Testing Optional
Tensile	Yes	Initial Testing Complete – Further Testing Optional
Hardness	Yes	Acceptable
Flammability	Yes, Limited	Additional Testing Optional
Tear Strength	Not Tested	Additional testing Optional
Flexibility	Optional	Additional Testing Optional

The suitability assessment presented in Table 7 does not reflect all of the testing that is required. "Cause and effect testing" is also needed but was beyond the scope of this project. Such testing would determine, for instance, how much the particle size or particle size distribution can vary before there is a noticeable impact on product performance. Aging tests are also needed to determine how the product will perform over its life cycle.

Table 8 provides a summary of cause-and-effect relationships among various crumb rubber attributes. Each row lists an attribute with a "direction of change" (the cause) and the resulting effect on material properties. For example, when examining particle size, as the particle size is reduced, flexural strength and impact strength will increase significantly. At the same time, the coefficient of friction will be substantially reduced. Compression set and abrasion resistance are not affected by particle size. These assessments are relative and are based on material experience and the literature, not on actual test results from this initiative.

Table 8
Predicted Crumb Rubber Attribute Effects Matrix for Case Study 1

Attribute	Dir of Change	Flexural Strength	Impact Strength	Coeff of Friction	Comp Set	Abrasion Resist	Tensile Strength	Hardness	Flammability
Particle Size*	↓	↑↑	↑↑	↓↓	NA	NA	↑↑	NA	NA
Particle Size Distribution	Broad	↓	↓	↑	–	–	↓	–	–
Heat history	↑	↓	↓	–	–	–	↓	–	–
Loading	↑	↓	↑	↑	↑	↑	↓	↓	↑
Surf Area	↑	↑↑	↑↑	↓↓	–	–	↑↑	–	–

* Poor interfacial adhesion is assumed since this is typical in most crumb rubber filled applications.

Product development work for this TDP is ongoing by the manufacturer and its suppliers. Additional testing is needed to determine if the current design with the current crumb rubber raw material is fit for its intended use. Further work is needed to determine the crumb rubber material characteristics that are needed to produce a suitable and reproducible product.

Case Study 2 – Coating Manufacturer (Company B)

Company B is developing a coating using crumb rubber as an aggregate. The process was initiated by interviewing company B about the use and performance expectations for the TDP. A competitive assessment was conducted that identified 14 functionally similar products. Seven products were considered in-kind competitors that also incorporated crumb rubber. Tests were conducted, and performance characteristics were compiled and compared against stated performance expectations.

Key product characteristics that are directly affected by crumb rubber and data collected for the case study are presented in **Table 9**.

Table 9
Product Characteristic Data Collected for Case Study 2

Product Testing	Data Collected On:	
	Crumb Rubber Filled Coating	Competitive Product
Viscosity	No	No
Abrasion Resistance	Yes	Yes
Skid Resistance	Yes	Yes
Adhesion	Yes	Yes
Solids	No	Yes
Tensile Strength / Elongation	Yes	No
Fire Resistance	Yes	No
UV Weathering Resistance	Yes	No
Water Vapor Transmission Rate	Yes	No
Thermal Resistance	Yes	No
Air Permeance	Yes	No
Flexibility (Cracking Resistance)	Yes	No

The intent of this case study was to collect data on the most important CTQs. Comparison against an unfilled coating and against competitive products would provide indications of performance benefits and of comparative suitability, assuming of course that competitive products perform as intended. Direct interaction with customers and/or users can provide even more useful suitability data.

Suitability comparisons could not be made with available data. Reasons are presented in **Table 10**.

Table 10
Initial Assessment of Suitability for Case Study 2

Product Testing	Whether Test Product Data Within Range of Competitive Data	Comments
Viscosity	NA	Not tested
Abrasion Resistance	Yes	The testing was successfully "passed" based on the ASTM standard
Skid Resistance	Yes	Results met ASTM requirements for certain applications
Adhesion	NA	Additional testing may be needed
Solids	NA	Additional testing may be needed
Tensile Strength / Elongation	NA	Additional competitive testing may be needed
Fire Resistance	Yes	Results met ASTM requirements for certain applications
UV Weathering Resistance	Yes	No defects caused by extended weathering cycles
Water Vapor Transmission Rate	NA	Criteria need to be established
Thermal Resistance	NA	Criteria need to be established
Air Permeance	NA	Criteria need to be established
Flexibility (Cracking Resistance)	Yes	Results met ASTM requirements for certain applications; however additional competitive testing may be needed

Table 11 presents a summary of cause-and-effect relationships among various crumb rubber attributes. Each row lists an attribute with a "direction of change" (the cause) and the resulting effect on material properties. Take particle size as an example. As particle size is reduced, viscosity will increase. At the same time, skid resistance will be reduced. Adhesion and solids are not affected by particle size. A wavy line (~) indicates that the resulting effect will be variable. A dash (-) indicates that the resulting effect is unknown. These assessments are relative and are based on material experience and literature, not on actual test results from this initiative.

Table 11
Predicted Crumb Rubber Attribute Effects Matrix for Case Study 2

Attribute	Dir of Change	Viscosity	Abrasion Resistance	Skid Resistance	Adhesion	Solids
Particle Size*	↓	↑	↓	↓	NA	NA
Particle Size Distribution**	Broad	~	~	~	–	~
Heat history	↑	–	–	–	–	NA
Loading	↑	↑	↑	↑	–	↑
Surface Area	↑	↑	↑	↑	–	NA

* Poor interfacial adhesion is assumed, since this is typical in most crumb rubber filled applications.

** The effect of particle size distribution can vary depending on the relative shape, breadth, and location of the distribution.

Section 4
Findings and Recommendations

Findings

Companies in a variety of industries have performed independent product testing to understand the quality characteristics of select products made from recycled tire rubber. However, clear CTQ requirements have been developed in writing for only a small number of TDPs, and the industry in large part continues to operate on an informal basis, without reference to established standards or specifications. Developing CTQ requirements for TDPs and implementing quality standards must be done on a product-by-product basis, and must be product-driven, market-driven, and manufacturer-specific. This report aims to increase the general industry understanding of how crumb rubber raw materials characteristics affect TDP performance. But it will be up to individual manufacturers, crumb rubber producers, compounders, and others in the TDP supply chain to implement quality best management practices going forward.

Industry associations and company alliances may be helpful in expanding understanding and implementation of product-quality BMPs. To build upon this initial work and continue to establish crumb rubber specifications in a meaningful way that serves the various industries involved, stakeholder participation is critical. Also, additional testing will be needed to compare the new product compositions using TDPs to the competitive products, and the resulting comparative data will help guide the process and quantify improvements or identify where trade-offs may exist.

Although ASTM D5603 is an established and useful standard for compounded recycled tire rubber, it does not appear that this standard is being used consistently in the development of products. Nor does it appear that there is a general understanding of its usefulness or purpose. This standard should be used as a minimum in all specifications, while more detailed specifications should be developed to meet the CTQ requirements of specific products.

Also, ASTM D5603 is not sufficient in all cases. While it does a reasonably good job of describing crumb rubber characteristics, it may not adequately describe crumb rubber material properties that affect TDP performance in all cases. For instance, it may be discovered that surface morphology (e.g., changes in the shape of the surface of the material) plays a critical role in TDP performance of a particular product. In such a case, a specific crumb rubber manufacturing method may need to be specified.

It is important for TDP manufacturers and their suppliers to understand TDP performance requirements and how they are affected by crumb rubber material characteristics. The case studies presented in Section 3 demonstrate the need for providing education and assistance to crumb rubber manufacturers and product manufacturers in this regard.

Crumb rubber requirements vary according to how the crumb rubber and the TDP are to be used. The companies involved in this project did not always have a broad understanding of the TDP markets that they intended to sell into, even though this is essential to the product development process.

Crumb rubber producers and TDP manufacturers often do not have the staff resources required to conduct a disciplined product development effort. Ideally, as a new tire-derived product is tested, the same testing data should be available for existing, competing products not made with tire

rubber. While competitive comparisons were being performed for some of the products, other important competitive product testing was not yet complete at the time of this writing. Forgoing testing that compares competitive products is risky. In the case of incomplete testing of the competitive products, CTQs must be established by alternate means.

Sufficient competency in the product development process is needed by TDP manufacturers to establish crumb rubber requirements, establish appropriate test protocols, evaluate test results, and establish appropriate crumb rubber specifications. While it is certainly possible for new products to be successfully launched without these skill sets, the probability of successfully launching a new product is significantly hampered when basic product development and quality disciplines are not followed.

In addition to the two case studies, some firms have conducted independent testing (sometimes with CalRecycle support through its Tire-Derived Product Business Assistance Program) that is sufficient for an initial assessment of TDP performance in certain industries or market areas. These include products such as coatings, primers, fillers, tire compound additives, asphalt coatings, truck bedliners, caulks, and certain building product applications. While technical results and specific details are proprietary, the same process described in this report for prototype testing and performance investigation can be applied across the industry to develop the market requirements for TDPs.

Recommendations for Best Management Practices in Product Development

The project team recommends the following best management practices for improving the consistent quality of new and existing TDPs. All stakeholders have play a role in implementing these BMPs, including TDP manufacturers and their suppliers, as well as CalRecycle and industry trade associations.

1. ***Broad education on basic product quality principles.*** Education on basic quality and product development principles would be helpful for TDP manufacturers and for crumb rubber producers. It is vitally important for the TDP manufacturers to understand both how to develop products that meet specific market needs and how to develop products that are fit for their intended use and that perform consistently over time. Education should be tailored for small businesses and should not be encumbered with technical jargon. It needs to contain "common sense" information with simple-to-follow procedures.

2. ***Focused education on standards and specifications.*** The industry would benefit from education that distinguishes product standards from product specifications. A product standard is an established test or guideline for a specific product or raw material. A specification is an explicit set of requirements to be satisfied by a material or product. Stakeholders must be aware of the established standards and specifications relevant to them, and of the need to implement them and to refine them for specific market situations.

3. ***Focused education on ASTM D5603, the existing standard that is most relevant to TDPs.*** Crumb rubber manufacturers and TDP manufacturers need to be educated about ASTM D5603. Much improvement can be realized and confusion avoided throughout the industry if this standard is used as intended. It should be recognized that this is a broad standard that defines classification standards for crumb rubber, and that additional specificity tied to particular product market needs are required. At a minimum, crumb rubber manufacturers need to be capable of measuring crumb rubber material characteristics per ASTM D5603. It is

recommended that TDP manufacturers require that this testing be conducted by an outside lab.

4. ***Greater use of ASTM standards in practice.*** TDP manufacturers should insist that suppliers adhere to crumb standards per ASTM D5603. End users drive the need for standard test measures, and TDP manufacturers are closest to the end use and in the best position to understand the CTQ characteristics of their product. They should drive crumb rubber specifications and associated standards.

5. ***Need to determine other characteristics that may not be covered by ASTM D5603.*** ASTM D5603 in many instances may not be adequate to fully describe CTQ characteristics for crumb rubber used in certain TDPs. There may very likely be other important material characteristics that should be measured. Likewise, it may be that not all of the ASTM D5603 information is critical for every TDP. Identification of CTQ crumb rubber characteristics is highly dependent on the intended use of the TDP.

6. ***Additional product testing should be conducted to define particular product CTQs.*** Although complete CTQ requirements were not fully defined as a result of this study, some important investigative and developmental testing was completed to start the process. Additional testing is required to determine whether there are additional CTQ characteristics that will affect product performance and to measure the degree to which product performance can be impacted.

7. ***Need for comparing performance of products made with and without recycled tire rubber.*** If practical, manufacturers should produce the developmental product with and without crumb rubber and compare the product with competitive products. This shows the effect of crumb rubber on the TDP. Another way to determine how crumb rubber affects TDP CTQ performance is to prepare a variety of samples that meet different TDP performance standards and to have samples rated by the customer. In this way you can determine what TDP performance level is important to the customer. More than one customer will be needed for the exercise for it to be meaningful.

8. ***Need to use standardized test methods.*** Manufacturers and suppliers should use standard test methods whenever possible. Standard test methods allow objective comparisons and ensure credible and comparable results. Many times a competitive product will list test methods that have been used to collect data. This is a good place to start but may not be the final or best answer. If the performance measure has been identified as a CTQ, then an ongoing testing program will need to be established with the product.

9. ***Need to test multiple product samples.*** Making decisions based upon a single or small number of data points is risky because testing variability is not accounted for. Therefore, tests should always involve multiple samples and test runs. There are always multiple sources of testing variability—measurement variability, sampling variability, manufacturing variability, raw material variability, etc.—that need to be understood. Also, product testing should make use of sound sampling procedures and statistical tools to ensure that variability is accounted for. A good quality or product development professional will be able to assist in designing a sound testing program.

10. ***Select only the most valuable CTQs, and make them as tangible and specific as possible.*** Customers may point to a wide variety of quality concerns that could influence production practices and adoption of specifications. In practice, manufacturers and suppliers should focus on the most critical CTQs that most influence important product performance

characteristics. Specifically, firms should distinguish between the product requirements that establish value in products versus those that do not. Color, for instance, is a product characteristic that frequently does not offer value. As an example, early consumers purchased iPhones even though they were available only in black or white; color was not a CTQ for the iPhone. Also, CTQs should be tangible and specific. For example, impact resistance should be defined by a specific ASTM test standard with specific values.

11. ***Produce only to established specifications.*** Once the product specifications are in place, the crumb rubber producer and compounder should produce only to those specifications if the product meets customer product requirements. If the TDP manufacturer has product failures or customer complaints, it is fairly straightforward to determine the cause if it is specification-related. If a product fails to perform in some way, but still falls within the specifications, then an adjustment to product specifications may be required.

12. ***Exclude cost as a product requirement when developing products***. Cost is a function of product requirements. Price is not a product requirement; it is a function of value and prevailing market conditions. Value is what the market will pay (price) less what it costs to produce and distribute the product (cost).

13. ***Consider the broad market and company context in developing products.*** To develop a winning product, it is important to understand the evolution of the market for the tire-derived product and to meet the needs and requirements of the customer, company, and partners. It is also critical to understand the functionality and usability of the product, its feasibility and economics, and its life cycle benefits and branding implications.

This report has described an ideal approach to developing tire-derived products that emphasizes systems for ensuring quality on an ongoing basis, including identification of recommended best management practices. The approach emphasizes market and customer-based critical-to-quality requirements, and involvement of crumb rubber manufacturers, compounders, and others in the entire supply chain to systematically define and implement specifications and standards (building on established precedents).

While many TDP manufacturers and suppliers are small businesses that are resource-constrained, CalRecycle and industry associations can continue to play a role in educating stakeholders and providing information, tools, and assistance as possible to help the industry steadily move toward adoption of the recommended best management practices. Short of this goal, the industry will continue to operate largely on an informal basis with regard to quality standards and specifications. While the TDP market has grown on this basis, in the long run, the fate of the industry and its ability to diversify and expand may ultimately depend on the extent to which more formalized quality standards and specifications can be effectively adopted.

Glossary of Terms

Following are some terms and their definitions and acronyms (as appropriate) that are used in the industry and/or in this report.

Term	Acronym	Definition
American Society for Testing and Materials	ASTM	Develops international standards for materials, products, systems, and services used in construction, manufacturing, and transportation
Best Management Practices	BMP	Those practices determined to be the most efficient, practical, cost-effective measures to guide a particular activity or to address a particular problem
Critical Raw Materials	CRM	Raw material or natural resources needed to reach desired customer results. Resource supply varies by region and can be critical for businesses.
Critical to Customer	CTC	Measurable standards of performance for a product or service that is essential in order for that product or service to meet the requirements of the customer
Critical to Quality	CTQ	A process characteristic or component that has a direct effect on whether the overall process or product is perceived by the customer to be of acceptable quality
Crumb Rubber[6]	CR	Material derived by reducing scrap tires or other rubber into uniform granules with the inherent reinforcing materials such as steel and fiber removed along with any other type of inert contaminants. Alternate definition: Fine particles of vulcanized rubber resulting from mechanical or cryogenic size reduction of scrap tires or other rubber products
First Time Yield		The number of good units produced divided by the number of total units going into the process. Also identified as First Pass Yield as a tool for measuring the amount of rework in a given process
Fitness for Use		Degree to which the product performs as intended
Granulated Rubber[6]		A material defined by the ASTM D11 Rubber Committee as particulate rubber composed of mainly non-spherical particles that span a broad range of maximum particle dimension from below 30 meshes (400 microns) to 12 mm (0.47 in). The key feature of this type of particulate rubber is the fraction of the material in the maximum particle dimension range greater than 2 mm (0.08 in) and up to 12 mm (0.47 in)
Ground Rubber[6]	GR	A material defined by the ASTM D11 Rubber Committee as particulate rubber composed of mainly non-spherical particles

[6] It is important to note that the current state of practice in the tire and rubber recycling industry uses the terms “crumb rubber” and “ground rubber” interchangeably. Recently, “ground tire rubber” or GTR has become popular and is also used interchangeably with crumb rubber and ground rubber. Crumb rubber material or CRM is also used. Other terms used regularly in the marketplace include granulated rubber or rubber granulate, powdered rubber or rubber powder, micronized rubber powder, micron rubber, and fine mesh rubber or pulverized rubber. In general, crumb rubber is defined by size. However, the method of determining the crumb rubber particle size is the subject of much discussion.

Term	Acronym	Definition
		that span a range of maximum particulate dimension from well below 40 mesh to 2.032 mm (0.08 in) as a maximum particle dimension. The smallest reported mesh size for ground rubber is 450 mesh
Life Cycle of a Product		Relates to the stages of introduction, growth, maturity or stagnation, and decline of a product
Life Cycle Performance		Performance over the lifetime of a product
Micronized Rubber Powder	MRP	Rubber material 80 mesh (180 micron) and smaller 300 mesh (50 microns) that is virtually wire- and fiber-free.
Product Offering		A product offering comprises of five primary elements to include markets, products, processes, people, and economics.
Process Specifications		Defines what must be done in order to transform inputs into outputs
Product Specifications		Explicit set of requirements to be satisfied by a material or a product. A written statement of an item's required characteristics that facilitates its procurement or production and acceptance
Product Standard		Established test or guideline for a specific product or raw material
Pulverized Rubber	PR	Material that has been crushed, pounded, or ground to smaller particles
Quality		The totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied customer or user requirements
Repurpose		To give a new purpose or use
Rework		Revise; reprocess, modify, or remodel
Rubber Hydrocarbon Content	RHC	The percentage of hydrocarbon in a compounded rubber
Rubber Powder	RP	A material defined by ASTM D11 as rubber comprised of finely dispersed particles, less than 40 mesh (425 microns) in size, that are generally characterized as light, dry, and having very high surface areas
Scrap		Amount of something that is left after the greater part has been used; may still be usable for repurposing
Standards		Include terminology, symbols, testing and methods, packaging, or label requirements as they apply to a product or industry
Tire-Derived Product	TDP	Product derived from waste tires after processing such as, but not limited to, chipped, shredded, cut, or sliced tires, crumb rubber, steel/wire, fiber cord material, oil, or carbon black and has been sold or removed from the facility of the waste tire processor

Term	Acronym	Definition
Voice of the Customer		Collective insight into customer needs, wants, perceptions, and preferences gained through direct and indirect questioning.

Appendix A
Listing of Pertinent ASTM Standards

This appendix identifies several ASTM standards that are pertinent to the production of crumb rubber and/or TDPs made with crumb rubber. ASTM is a widely cited source for industry standards of all types. The standards below are available online at: http://global.ihs.com/standards.cfm?publisher=ASTM&RID=Z56&MID=5280&gclid=CKLMneX5_bkCFcZj7AodfhsAAQ.

ASTM Standards for Crumb Rubber and Crumb Rubber TDPs

ASTM D5603 and D5644 focus on particle size, particle size distribution, and rubber chemistry. In addition to these two standards, there are other material characteristics that may be as important or even more important, depending on how the crumb rubber is being used and on what benefits it is providing to the final product. There are several production methods that yield crumb rubber with different characteristics.

ASTM D5603: Standard Classification for Rubber Compounding Materials—Recycled Vulcanizate Particulate Rubber

This method covers the compounding material commercially known as recycled vulcanizate particulate rubber. Recycled vulcanizate particulate rubber is the product that results when vulcanizate rubber has been processed by some means to obtain a desired particle size distribution. ASTM D5603 also provides classification recommendations on particle size distribution, polymer type, chemistry, and foreign matter.

ASTM D5644: Determination of Particle Size Distribution of Recycled Vulcanizate Particulate Rubber

This test method describes the procedures for determining average particle size distribution of recycled vulcanizate particulate. This method should always be used when specifying particle size distribution.

Additional Relevant ASTM Rubber Standards

ASTM D297: Chemical Analysis

This ASTM method covers the qualitative and quantitative analysis of the composition of rubber products. Relevant tests include determination of rubber polymer type and determination of the percentage and type of extractables. This is useful for determination of the type of rubber and the rubber content (rubber hydrocarbon content). These properties will affect TDP properties such as durability, chemical and water resistance, elastomeric resilience, toughness, strength, and conductivity.

ASTM E1131: Standard Test Method for Compositional Analysis by Thermogravimetry

This test method provides a general technique incorporating thermogravimetry to determine the amount of highly volatile matter, medium volatile matter, combustible material, and ash content of compounds.

ASTM D1817: Standard Test Method for Rubber Chemicals—Density

This test method covers the determination of the density of solid chemicals used as rubber additives during processing and manufacture. It is intended to determine the density of the rubber chemical itself rather than the effective density of the chemical in a rubber.

ASTM D6814: Determination of Percent Devulcanization of Crumb Rubber Based on Crosslink Density

This test covers the procedure for determining percent devulcanization from crosslink density measurements of devulcanized rubber and control crumb rubber in the laboratory. While it is primarily used for devulcanized materials, it is also useful to establish an acceptable level of crosslink density. This will help to guard against rubber reversion, a potential problem if the crumb rubber particle has been overheated.

Appendix B
Sample Specification Sheet

The sample specification sheet below provides a framework for recording testing data.

Specification Sheet					
Product: 40 Mesh				**Date:** 1/1/2012	
Customer(s): ABC Company					
Product Description: Ground rubber from truck tires					
ASTM D5603 Specifications					
Property	**Test Method**	**Units**	**Size**	**Value**	**Tolerance**
Grade	ASTM D5603	NA	NA	1-4	
Particle Size	ASTM D5644	% Retained	30	<1	
			40	<10	
Metal Content	ASTM D5603	%	NA	0.1 max	
Fiber Content	ASTM D5603	%	NA	0.1 max	
Moisture Content	ASTM D1509	%	NA	0.5 max	
Acetone Extractables	ASTM D297	%	NA	8-22	
Ash	ASTM D297	%	NA	8 max	
Carbon Black	ASTM D297	%	NA	26-38	
Natural Rubber	ASTM D297	%	NA	10-35	
RHC	ASTM D297	%	NA	42	
Bulk Density	ASTM D5603	lb/ft^3	NA	22-28	
Other Specifications					

Appendix C
Sample TDP Critical to Quality Requirements

The sample form below provides a framework for stipulating and describing attributes of a product that are CTQ, as well as to identify testing methods. This form becomes a living document for the specific product.

Critical to Quality Requirements			
Product:		Date:	
Customer(s):			
	CTQ	**Group***	**Test Method**
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
* End Use Performance, Raw Material, Process, Health & Safety, Environmental			

Appendix D
Step-by-Step Process Flow Charts

Appendix D provides several flow charts that illustrate processes that would occur in developing product specifications. They include:

1. Figure D-1—Engage TDP Manufacturer in Drafting TDP Specification
2. Figure D-2—Engage Compounder in Defining Draft Product Specifications for Tire-Derived Product
3. Figure D-3—Engage Crumb Rubber Producer in Defining Draft Product Specifications for Tire-Derived Product
4. Figure D-4—Finalize Product Specifications for the Tire-Derived Product

Figure D-1
Process of Developing Product Specifications with a Manufacturer

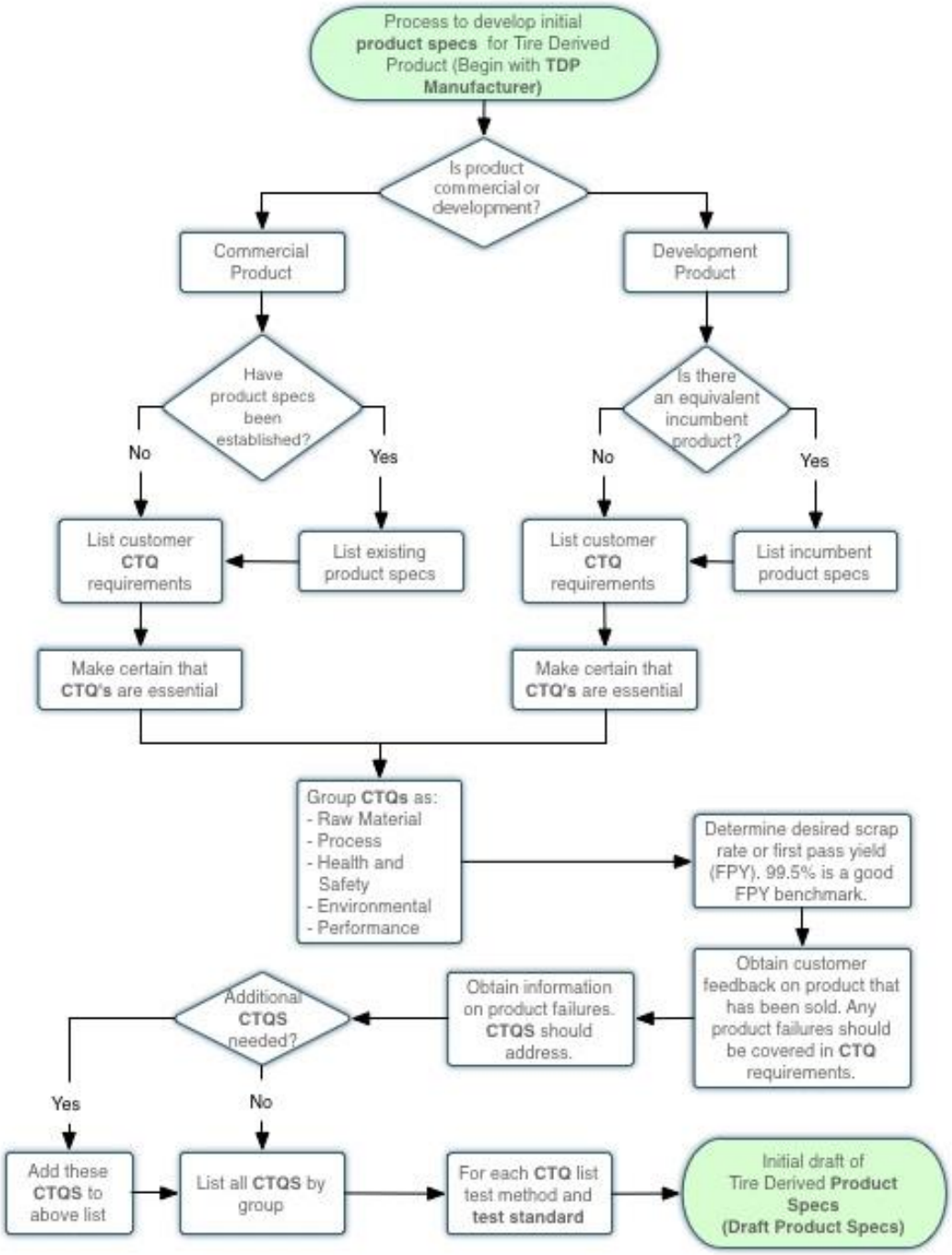


Figure D-2
Process of Defining Draft Product Specifications with Compounder

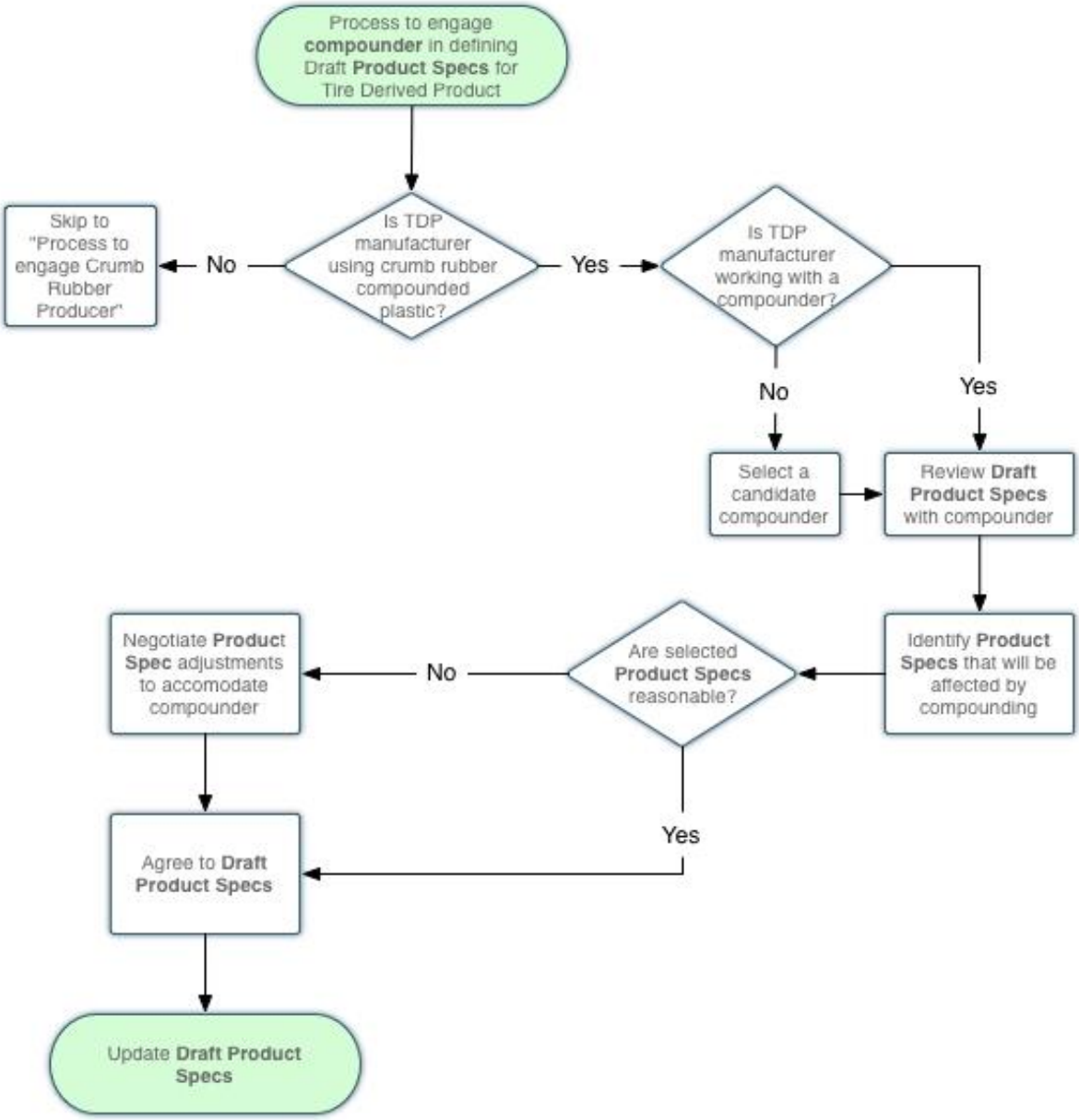


Figure D-3
Process of Confirming Product Specifications with Crumb Rubber Producer

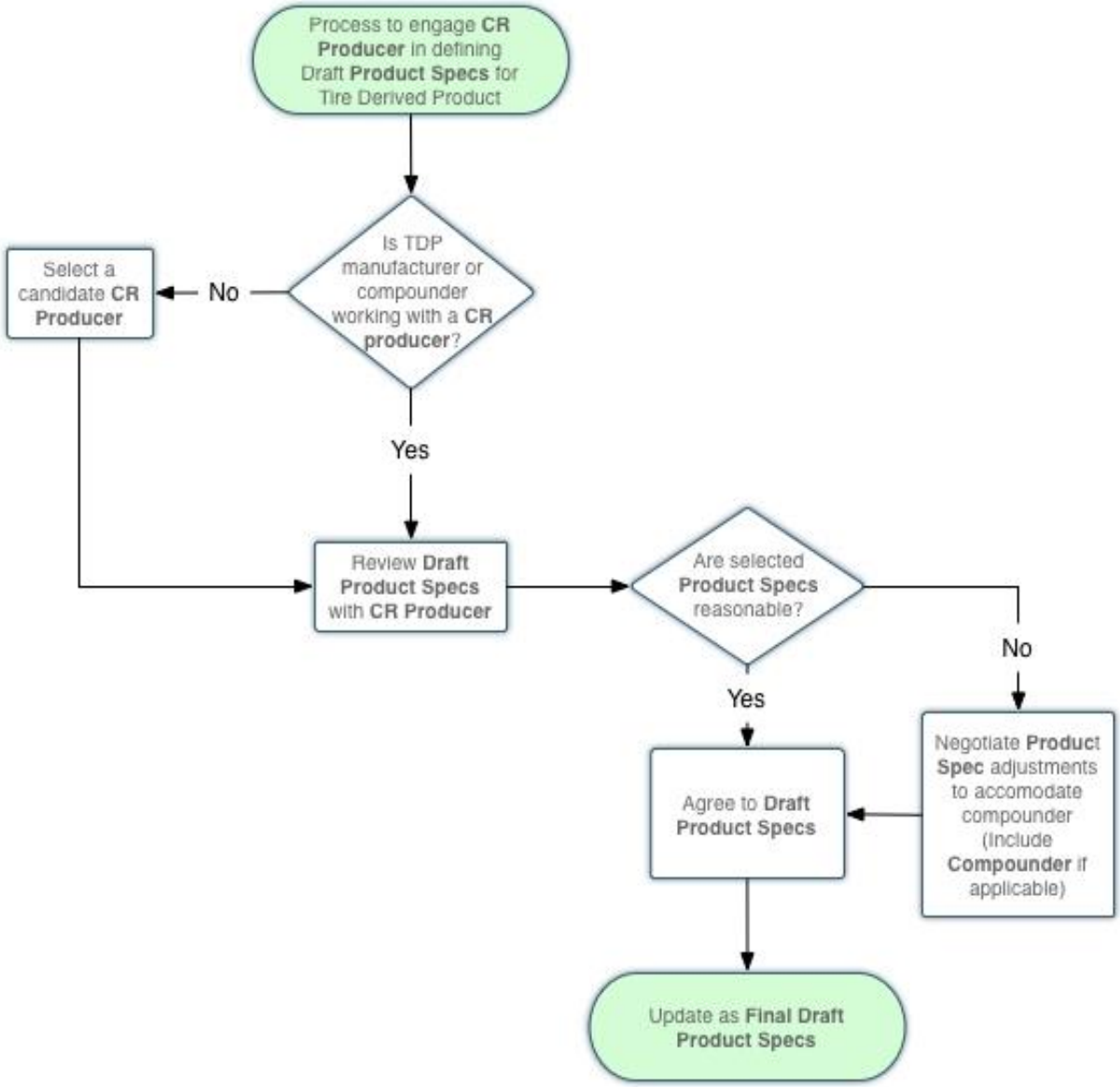
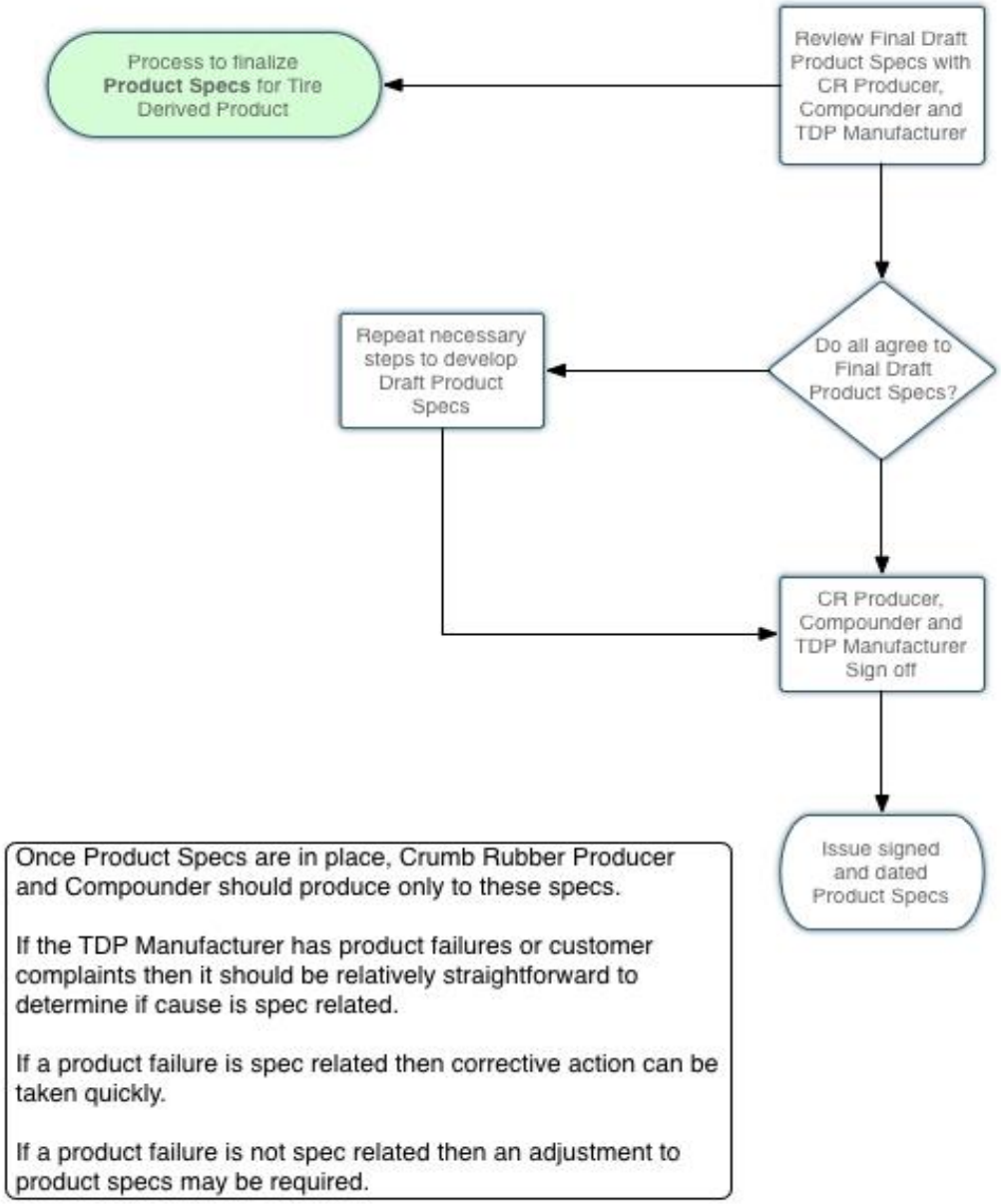


Figure D-4
Process to Finalize Product Specifications



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