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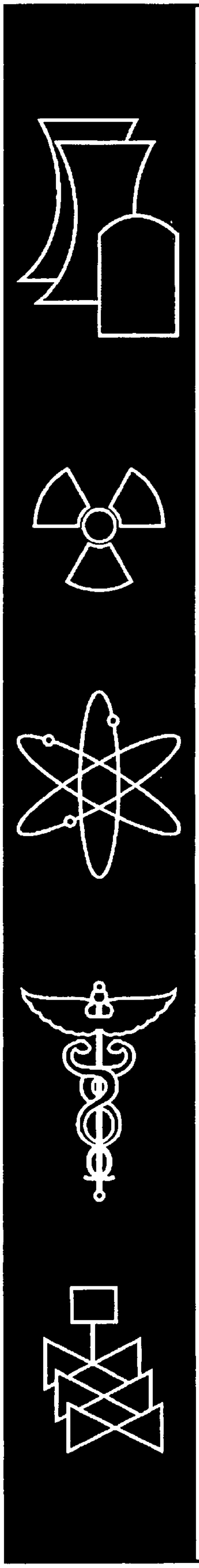

Hydraulic Transport of Coating Debris

A Subtask of GSI-191

Naval Surface Warfare Center,
Carderock Division

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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Hydraulic Transport of Coating Debris

A Subtask of GSI-191

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ABSTRACT

Generic Safety Issue (GSI)-191 "Assessment of Debris Accumulation on PWR Sump Performance" raised the concern of debris transport to pressurized-water-reactor (PWR) sump screens following a loss-of-coolant accident (LOCA) and subsequent impact to emergency core cooling systems (ECCS) and containment spray systems (CSS) during ECCS sump recirculation. Failed coatings debris is one potential source for debris transported to the ECCS sump screens. This document describes a limited number of tests conducted to study the transportability of coatings debris (chips) in ambient temperature water, at specific conditions of uniform flow. It is intended that the transport parameters observed in these tests could be used as the basis for the evaluation of coating chip transport under plant specific conditions. The transport characteristics of coatings particulates were not examined in these experiments as fine particulate are assumed to transport.

Five coating systems, typical of coatings applied to equipment and structures located in the contaminant buildings of PWR plants, were tested. The effects of chip size, shape, density, thickness, stream velocity, water saturation, and thermal curing on transportability were examined through two types of tests – quiescent settling and transport within uniform flow. The quiescent settling tests were conducted in a 0.3 m wide by 0.3 m long by 1.2 m deep (one foot wide by one foot long by four foot deep) acrylic tank. The goals of the quiescent water tests were to determine: (1) the time necessary for coating chips dropped onto the water surface to break the surface and begin to sink (time-to-sink tests), and (2) to determine the terminal settling velocity of submerged coating chips (terminal velocity tests). The transport tests were conducted in a 0.91 m wide by 0.91 m deep by 9.1 m long (three foot wide by three foot deep by thirty foot long) acrylic flume suspended in a large circulating water channel. The goal of the transport tests was to characterize the behavior of coating chips in moving water. The tests consisted of a tumbling-velocity test to study the behavior of coating chips placed on the flume floor and a steady-state velocity test to study the behavior of coatings debris released into the moving stream below the water surface. A statistically meaningful number of data tests were conducted for each coating type, chip size and chip shape in each test category in order to more accurately quantify observations.

The quiescent tests demonstrated that, when dropped onto the water surface, coating chips with a density close to that of water tended to remain on the surface indefinitely and heavier chips tended to sink almost immediately. The tumbling velocity tests demonstrated that all but the lightest chips and curled chips remained in their initial position at stream velocities in excess of 0.09 m/s (0.3 ft/s). The steady-state velocity test demonstrated that, at a uniform water velocity of 0.06 m/s (0.2 ft/s), all but the lightest chips settled to the bottom before reaching the end of the flume.

FOREWORD

The U.S. Nuclear Regulatory Commission (NRC) is engaged in activities associated with resolving Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on PWR Sump Performance." GSI-191 raised the concern that debris, generated by a loss-of-coolant accident (LOCA), could be transported to the emergency core cooling system (ECCS) sump screens during sump recirculation, thereby blocking flow area and reducing the ability of the ECCS and containment spray system (CSS) to cool the reactor core and containment building.

Failed coatings have been identified as one potential source of debris that may transport to the ECCS sump screens. Therefore, the NRC sponsored research at the Carderock Division of the Naval Surface Warfare Center to assess the potential for coatings debris to transport to the sump screens. The primary objective of these tests was to examine the buoyancy (time-to-sink), terminal settling velocity, tumbling velocity, and steady-state transport velocity of the coating chips.

This study involved the following two distinct types of tests to examine the behavior of coating chips in water:

1. Settling tests in a quiescent water tank, 0.3 meter long by 0.3 meter wide by 1.2 meter deep (1 foot x 1 foot x 4 feet). The purposes of these tests were to (1) examine the time required for coatings chips to break the surface of the water and begin to sink when dropped onto the surface from a height of 0.3 meter (1 foot), and (2) to record the terminal settling velocity.
2. Hydraulic transport tests in a flume, 9.1 meter long by 0.9 meter wide by 0.9 meter deep (30 feet x 3 feet x 3 feet). The purposes of these tests were to (1) determine the water velocity required to lift coating chips and tumble them along the floor, and (2) observe the transportability of coating chips submerged in water moving at a constant velocity of 0.06 meter (0.2 foot) per second and at the tumbling velocity specific to the coating chip sample-lot being tested.

The coating systems selected for testing were a single-coat alkyd, a two-coat epoxy, a zinc primer/epoxy top coat, a six-coat epoxy and a three-layered all-epoxy concrete system. These coatings were selected from the large number of containment coating system/supplier combinations because it was not feasible to test every coating system from every supplier. Moreover, the selected coating systems are considered to be representative of the range of chemical formulations, coating thicknesses, densities, and weights of coatings used in nuclear power plants. Further, to ensure that suppliers of the original coating systems were represented in the tests, the supply of samples was distributed among the three remaining major nuclear coating suppliers. The coatings were received at the test facility in sheets and were prepared for testing by breaking them into smaller pieces (by hand or using a commercial blender) to replicate the random shapes and sizes observed in failed coatings. The chips were further classified into three size groups — 0.4 mm to 0.8 mm, 3.2 mm to 6.4 mm, and 25 mm to 51 mm ($^1/_{64}$" to $^1/_{32}$", ⅛" to ¼", and 1" to 2") — for testing. Samples of 25 mm to 51 mm (1" to 2") chips were also curled and heat treated to study the effect of curling and exposure to elevated temperatures, respectively, on transport characteristics. In addition, in the quiescent water tests, some chips were pre-soaked to study the effect of water saturation due to containment sprays or the pipe break on coating chip buoyancy and terminal velocity.

To more accurately quantify observations, a statistically meaningful number of tests was conducted for each coating type, size, and shape (flat or curled) in each test category. Nonetheless, because the tests were engineered to replicate the random, jagged outline of in-situ coating debris, a comprehensive correlation of the observed transport properties with the physical properties of the tested coating chips could not be developed. However, the observations can be generalized as follows:

- Light-weight coating chips (specifically alkyd chips) dropped onto the water surface tended to remain on the surface indefinitely.
- A large percent of the heavy coating chips (six-coat epoxy and epoxy system for concrete) sank immediately.
- A lower percent of the medium-weight coating chips (two-coat epoxies and zinc/epoxy systems) sank initially.
- Chips that did not sink immediately remained on the surface indefinitely.
- The highest bulk tumbling velocity, approximately 0.43 m/s (1.4 ft/s), was associated with the heaviest flat coating chips.
- The curled and light chips had the lowest tumbling velocities, with the bulk of the chips tumbling at 0.08 m/s (0.27 ft/s) and 0.14 m/s (0.46 ft/s) for curled two-coat epoxy and one-coat alkyd coating systems, respectively.
- At a uniform water velocity of 0.06 m/s (0.2 ft/s), all but the lightest chips came to rest at the bottom of the flume within a short distance of the release point.
- A small percent of the medium-sized alkyd chips transported to the end of the test flume, floating on the surface.

The research described in this contractor-prepared NUREG-series report is intended to examine a number of physical coating properties that are believed to influence the transportability of coating debris. Nonetheless, the limited number of coatings tested and the various test limitations make it necessary for users of this report to verify the applicability of the reported observations to their plant-specific conditions. With that understanding, the observed transport properties could be used as a basis for evaluating the potential for coating chips to transport to the ECCS sumps under plant-specific conditions.

Brian W. Sheron, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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EXECUTIVE SUMMARY

A series of coating chip transport experiments were performed in support of the resolution of Generic Safety Issue (GSI)-191, "Assessment of Debris Accumulation on PWR Sump Performance." The concern raised by GSI-191 is the transport and accumulation of debris to pressurized water reactor (PWR) sump screens following a loss-of-coolant accident (LOCA) and subsequent impact to emergency core cooling systems (ECCS) and containment spray systems (CSS). During the recirculation phase of a PWR design basis LOCA, the (ECCS) and CSS circulate cooling water from the containment sump pool, through heat exchangers, to the reactor core and containment spray header. During the LOCA, there is a potential for debris accumulated in the containment building to transport to the recirculation sump and inhibit the flow of water necessary for ECCS and CSS operation.

To determine if failed coatings can be a potential source for debris transported to the ECCS sump screens, the United States Nuclear Regulatory Commission (NRC) sponsored research to characterize the transportability of coating debris (chips). The research is intended to support the evaluation of the effect of coating chip accumulation on ECCS performance. The experiments were performed between September 2005 and January 2006 at the US Naval Surface Warfare Center, Carderock Division in the facility's Specialized Research and Advanced Development Laboratory and the Circulating Water Channel. The transport of coatings particulates was not investigated in this research project as the particulates are assumed to remain in suspension and, therefore, transport.

The transportability of chips from five different coating systems was examined. They were: a single coat alkyd, an inorganic zinc primer with epoxy topcoat, a two-coat epoxy, a six-coat epoxy and an all-epoxy sealer/surfacer/ top-coat concrete system. These coatings were selected from an extensive list of coatings used at nuclear power plants and are considered to represent the physical properties of the bulk of the coatings used. When possible, coating materials were obtained from the original major coatings suppliers.

The experiments examined the effects of chip size, chip shape, chip density, chip thickness, and fluid velocity on chip transportability through quiescent settling testing and transport testing. The goals of the quiescent settling tests were to (1) determine the time necessary for floating coating chips to break the water surface and begin sinking (time-to-sink tests), and (2) determine the steady-state settling rate of submerged coating chips (terminal velocity tests). The transport tests were performed to characterize the behavior of coating chips in flowing water. The specific objective was to measure the stream velocity required to initiate and sustain chip movement along the floor of the test channel (tumbling velocity) and the tendency of chips to transport when placed in a stream moving at a velocity of 0.06 m/s (0.2 ft/s).

The quiescent settling experiments were conducted in a 0.3 m wide by 0.3 m long by 1.2 m deep (one foot wide by one foot long by four foot deep) clear acrylic tank. For each coating sample type, the motion of 100 chips was observed in groups of 5 for large chips and 10 for small chips. The transport experiments were conducted in a 9.1 m (30 ft) long, open ended, acrylic flume having a 0.91 m (3 ft) by 0.91 m (3 ft) cross-section. The flume was suspended in a larger circulating-water channel capable of developing a range of steady velocities from zero to 4.6 m/s (15.2 ft/s). The tank was submerged so that the depth of water in the tank was 0.76 m (30 in.). To collect chips that transported, a filter was placed at the down-stream end of the flume. The filter consisted of three sections to allow capture and segregation of chips that transported at the surface (top 0.08 m (3 in.)), in suspension (middle 0.6 m (24 in.)), and along

the bottom of the tank (bottom 0.08 m (3 in.)). Coating chips were released into the water at a point 2.44 m (8 ft) downstream of the flume entrance and chip motion was recorded with cameras positioned along the length of the flume. The transport tests were repeated until 50 chips of each sample category were recorded.

The quiescent tests demonstrated that (1) light-weight coating chips, specifically alkyd chips, dropped onto the water surface tended to remain on the surface indefinitely, (2) a large percent of the heavy coating chips (six-coat epoxy and epoxy system for concrete) sank immediately, and (3) a small percent of the medium-weight coating chips (two-coat epoxies, zinc/epoxy systems) sank immediately. The tumbling velocity tests demonstrated that the highest bulk tumbling velocity (approximately 0.43 m/s (1.4 ft/s)) was associated with the heaviest flat coating chips. The curled and light chips had the lowest tumbling velocities with the bulk of the chips tumbling at 0.08 m/s (0.27 ft/s) and 0.14 m/s (0.46 ft/s) for curled two-coat epoxy and one-coat alkyd coating systems, respectively. In the steady-state velocity test, at a uniform water velocity of 0.06 m/s (0.2 ft/s), all but the lightest chips came to rest at the bottom of the flume within a short distance of the release point. Only a small percentage of the medium sized alkyd chips transported to the end of the test flume by floating on the surface.

ABBREVIATIONS

ADV – acoustic Doppler velocimeter
ALK –low density alkyd, single layer coating
ANSI – American National Standards Institute
ASTM – American Society for Testing Materials
CSS - containment spray system
CWC – circulating water channel
DFT – dry film thickness
DBA – design basis accident
E2 – coating system of all-epoxy two-layered coating system
E3C – all-epoxy three-component concrete coating system
E6 - all-epoxy six-layered coating system
ECCS - emergency core cooling system
HELB - high-energy line break
LOCA - loss-of-coolant accident
NPSH - net positive suction head
NRC – Nuclear Regulatory Commission
NSWCCD – Naval Surface Warfare Center, Carderock Division
PNNL – Pacific Northwest National Laboratory
PWR – pressurized water reactor
ZE - inorganic Zinc primer, epoxy topcoat coating system

1 INTRODUCTION

1.1 Background

During the recirculation phase of a design basis loss-of-coolant accident (LOCA) at a pressurized water reactor (PWR) nuclear power plant, the emergency core cooling system (ECCS) and containment spray system (CSS) provide cooling water from the containment sump to the reactor core and containment spray header. However, a potential impediment to proper cooling water recirculation has been identified. The accumulation of debris generated during a LOCA may adversely affect the flow paths necessary for ECCS and CSS recirculation. Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on PWR Sump Performance," was established in 1996 to determine if the transport and accumulation of debris in containment following a LOCA would impede or prevent ECCS and CSS operation during recirculation mode of operation.

A technical assessment of GSI-191 was performed by the NRC. The assessment confirmed that chips blockage is a generic concern for PWRs, and that plant-specific analysis should be performed to address this concern. As the regulatory strategy for resolving GSI-191 was developed and interaction with industry on the sump evaluation methodology progressed, the NRC identified several additional research tasks necessary for the resolution of GSI-191.

One of the research tasks is to evaluate the transport characteristics of coating chips in the containment pool. A high-energy line break (HELB), including a LOCA, could introduce quantities of coating chips into the containment pool. Subsequently, if the ECCS or CSS pumps take suction from the containment ECCS sump, the coating chips could be transported to the sump and either accumulate--along with other types of debris--on the sump screen or be transported through the system. The accumulation of coating chips on the sump screen could increase the head loss across the screen. If a sufficient amount of coating chips accumulated on the sump screen, the debris bed could reach a critical thickness beyond which the head loss across the debris bed could exceed the net positive suction head (NPSH) margin required to ensure the successful operation of the ECCS or CSS pumps in recirculation mode. Alternatively, coating chips could pass through the sump screen and become ingested into the ECCS or CSS suction line such that deleterious downstream effects (e.g., valve clogging, pump wear, heat exchanger & reactor fouling, etc.) could occur.

1.2 Objective

The objective of this work is to parametrically evaluate the transportability of coating chips of five different coating systems, under conditions of uniform flow. The effects of chip size, chip shape, chip density, chip thickness, and stream velocity on transportability are examined. The results of this work are intended to provide guidance for the evaluation of coating chip transport under plant-specific conditions. However, evaluators are cautioned to recognize the boundaries of this research when applying these observations to their specific plant conditions.

1.3 Testing Approach

Four salient transport properties in water at ambient temperature were studied: time-to-sink, terminal velocity, tumbling velocity and transport velocity. The tests were conducted as follows:

- The time-to-sink tests consisted of dropping five or ten pieces of coating chips from a height of 30.5 cm (12 in) onto a quiescent water surface and recording the time required for the chips to break the surface and begin to descend (sink). The number of chips sinking initially and the time required for 80 percent and 100 percent of the chips to sink was recorded.
- The terminal velocity tests consisted of placing five to ten coating chips below the surface of a quiescent pool and measuring the rate of chip descent.
- The tumbling velocity tests consisted of placing five coating chips on a flume floor, steadily increasing the stream velocity in the flume and recording the stream velocity required to initiate movement of the chips along the flume floor. The incipient tumbling velocity is the velocity at which the first chip begins to move and the bulk tumbling velocity is the velocity at which 80 percent of the chips have moved.
- The transport tests consisted of releasing a number of coating chips below the surface of a flowing stream at a preset velocity and recording the distance the chips traveled prior to coming to rest on the floor of the flume or the degree of settling as the chips reached the end of the flume.

2 COATING CHIP CHARACTERISTICS

2.1 Coatings Tested

Five coating systems of various film thicknesses, formulations and densities were selected for testing. These five systems represent the physical characteristics of much of the coating systems used in the containment buildings of PWR nuclear power plants. To replicate the original installed coating system to the greatest extent practical, each test sample was procured from one of the major suppliers of that system. The coating systems selected for testing and the rationale for their selection are described below.

- A non-DBA qualified alkyd coating (ALK), was selected as it represents the lower range of densities and film thicknesses found at nuclear power plants. Further, several equipment manufacturers used it as a standard coating on equipment installed inside containment.
- An inorganic zinc primer/epoxy system (ZE) was selected as it represents the upper range of coating densities and film thickness found at nuclear power plants. Also, ZE coating systems were frequently applied to steel structures at nuclear power plants.
- A two-layered epoxy system (E2) was selected as it represents a medium-density coating system frequently applied to steel structures at nuclear power plants.
- A six-layered epoxy, non-DBA-qualified (due to the number of coats) coating system, (E6) was selected as it represents a coating that may exist at some plants where coatings maintenance may have resulted in excessive layers of coatings being applied. This sample represents a thick, heavy coating system.
- A qualified multi-layered epoxy system for concrete (E3C) was selected for its rough surface structure and frequent use on concrete surfaces inside containment. The density is slightly greater than that of the E2 and E6 systems.

2.2 Coating Chip Size Selection

Coating chip tests were conducted using three distinct chip size ranges; 25 mm to 51 mm (1 in. to 2 in.), 3.2 mm to 6.4mm (1/8 in. to ¼ in.), 0.4 mm to 0.8 mm (1/64 in. to 1/32 in.) and one sample with a size distribution of 0.4 mm through 51 mm (1/64 in. through 2 in. These size ranges are considered to represent the bulk of the coating chips that would be generated during a LOCA. Larger coating chips than these size ranges would likely break up, due to their fragile nature, while smaller debris is treated as particulate in the sump analysis and, therefore, is assumed to transport.

2.3 Coating Film Preparation

Samples of five coating systems, as described in Paragraph 2.1 and Table 2-1, were prepared for use in the experiments described herein. The samples were prepared by the respective coating manufacturers, or their subcontractors, and were furnished to Naval Surface Warfare Center, Carderock Division, (NSWCCD) through Pacific Northwest National Laboratories. A detailed description of the sample preparation and quality assurance records are contained in Appendix H.

2.4 Sample Conditioning

The coating systems tested in this experiment are show in Table 2-1. Samples of each of these coatings were received in sheets at NSWCCD. The coatings density and thickness were verified and chips were prepared for quiescent settling and transport testing. The preparation consisted of creating chips in certain size ranges and shapes, "presoaking" samples for some tests, and thermal treatment of epoxy-based chips to evaluate the effect of curing on chip shape and density. The processes for generating chips sizes are described in Appendix A.

Table 2-1 Coatings Systems for Quiescent Settling and Transport Testing

Code	Supplier-Specified Nominal Density	Thickness	Description
ALK	1.15 g/cc (71.79 lb/ft^3)	1 coat – 2 mils	Low density alkyd topcoat, single layer. Unqualified nuclear containment coating. Ameron, Amercoat 5450
ZE	5.1 g/cc (318.3 lb/ft^3) (primer) 1.75 g/cc (109.24 lb/ft^3) (topcoat)	one coat primer–2.5 mils one topcoats – 5 mils	Inorganic Zinc primer, epoxy topcoat. Qualified nuclear containment coating. Ameron, Dimetcoat 6 primer, Amercoat 90 top coats
E2	1.75 g/cc (109.24 lb/ft^3)	2 coats - 5 mils per coat	All-epoxy two-layered system Qualified nuclear containment coating. Carboline, Carboguard 890N
E6	1.75 g/cc (109.24 lb/ft^3)	6 coats - 5 mils per coat	All-epoxy six-coat system Qualified nuclear containment coating-Unqualified thickness. Carboline, Carboguard 890N
E3C	1.1 g/cc (68.7 lb/ft^3) (sealer), 1.9 g/cc (118.6 lb/ft^3) (surfacer), 1.95 g/cc (121.7 lb/ft^3) (topcoat)	1 coat sealer- 1 mil 1 coat surfacer – 10 mils 2 topcoats – 4 mils per coat	All-epoxy three-component concrete system. Qualified nuclear containment coating. Keeler & Long, KL4129 epoxy sealer, KL6548S epoxy surfacer and KLD1 epoxy topcoat

2.4.1 Presoaking

To examine the effect of wetting (e. g., by post-LOCA containment spray) on chip settling properties, some time-to-sink tests were conducted using presoaked coatings chips. The chips were presoaked at 60°C (140°F) for 20 minutes. To ensure that the chips were not laden with excessive moisture, they were placed onto an absorbent sheet immediately before testing to remove surface moisture.

2.4.2 Sizing and Shaping

The as-manufactured coatings for testing were received in sheets for most of the coating systems. Therefore, it was necessary to create appropriately sized samples for testing by breaking up the sheets, both by hand and with a commercial blender, and classifying the chips into the required size ranges using standard sieves. The classified size ranges are as follows:

- 25.4 to 50.8 mm (1 to 2 inches) nominal width, flat and curled chips
- 3.2 to 6.4 mm (1/8 to 1/4 inches) nominal width
- 0.4 to 0.8 mm (1/64 to 1/32 inches) nominal width
- continuous size distribution defined as consisting of chips at least 10% (approximate, by weight) and no more than 25% (approximate, by weight) smaller than 6.4 mm (1/4 inches) in nominal width.

Testing of "continuous size distribution" samples is intended to qualitatively investigate possible interaction effects between different chip sizes. The brass sieves that were used conform to U.S. Bureau of Standards specifications. The sieves used had mesh openings of 50.8 mm (2 inches), 25.4 mm (1 inch), 6.4 mm (¼ inch), 0.4 mm (0.13 inch, number 6), 0.8 mm (0.03 inch, number 20), and 0.40 mm (0.016 inches, number 40). These sieve sizes were the closest match to the desired size ranges. The continuous size distributions were created by weighing out samples of segregated material to ensure that at least 10% (approximate, by weight) and no more than 25% (approximate, by weight) of the chips are smaller than 6.4 mm (1/4 inches) in nominal width.

After segregating the chip sizes in this manner, images of the samples were taken to ensure that the size distribution was accurate. Particle sizing software developed in Matlab was used to determine the major and minor axis dimensions. Cumulative distribution functions for a sample of 100 pieces of each coating and size are shown in Figure 2-1 through Figure 2-5 below for the major and minor axis dimensions. The figures show the percentage of chips that are less than the size indicated on the x-axis. From the figures it can be seen that 100% of the chips have an axis dimension less than the upper limit of the size range, and close to 100% of the chips have an axis dimension greater than the lower limit of the size range. The plot of the major axis length does not go to 100% because only one dimension needs to be less than the maximum size to fit through the sieve. Also, note that the continuous size distribution may have a bit more than 10% material that is less than 6.4 mm (1/4 inches) in nominal width because the distributions were created by weight, not count. Distributions are similar for other samples of the same size and coating.

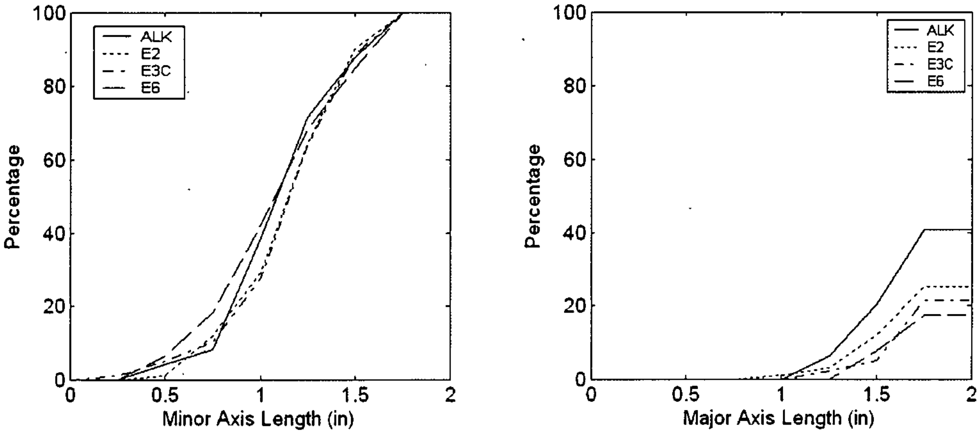


Figure 2-1 Cumulative Distribution for 25.4 to 50.8 mm (1 to 2 inches) Flat Chips

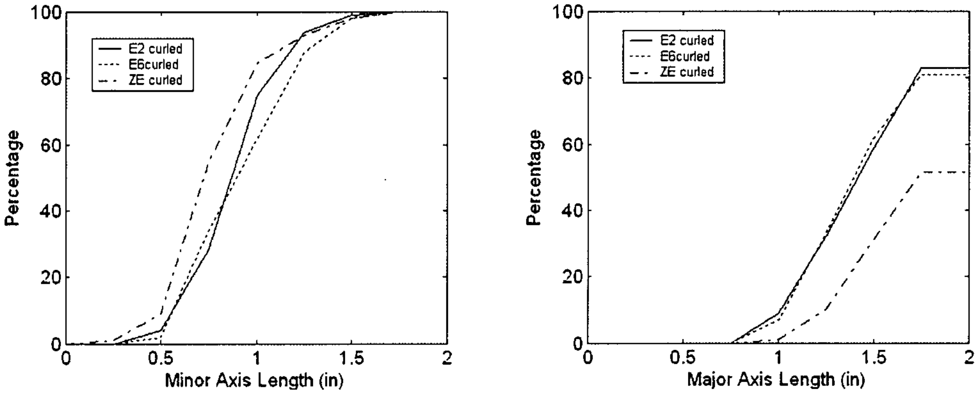


Figure 2-2 Cumulative Distribution for 25.4 to 50.8 mm (1 to 2 inches) Curled Chips

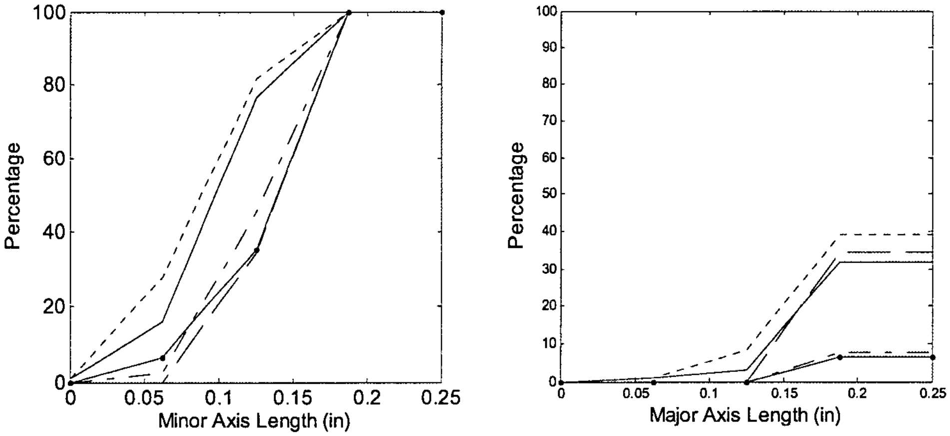


Figure 2-3 Cumulative Distribution for 3.175 to 6.35 mm (1/8 to 1/4 inches)

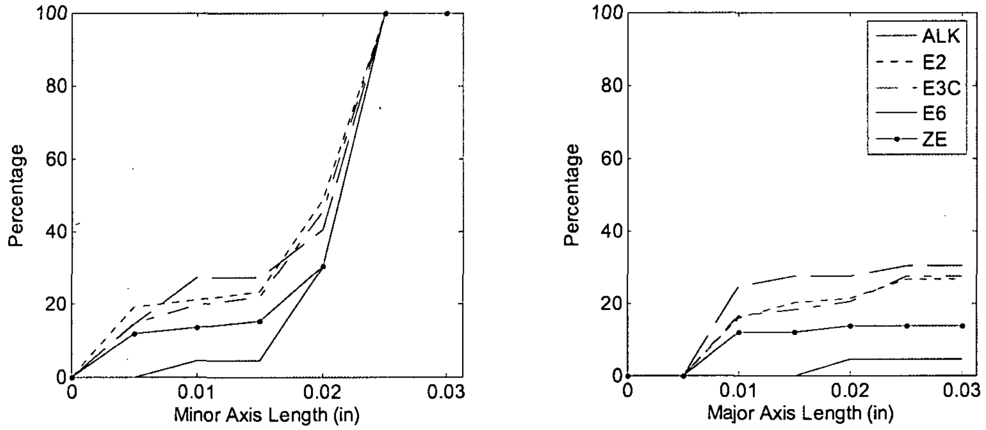


Figure 2-4 Cumulative Distribution for 0.40 to 0.79 mm (1/64 to 1/32 inches)

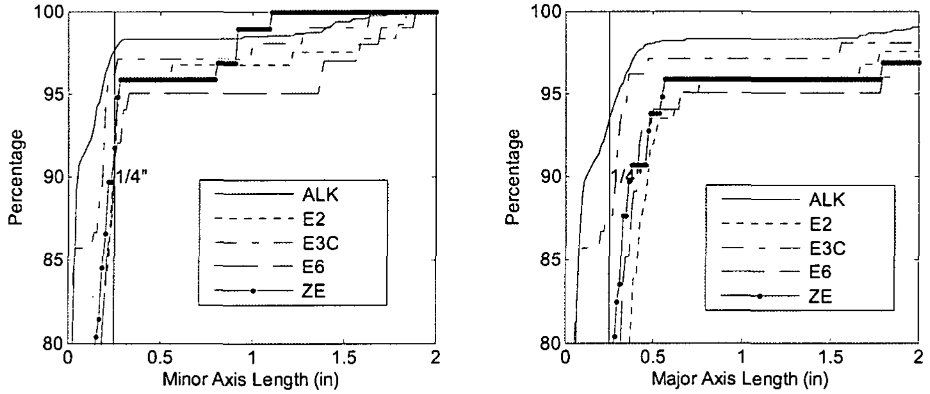


Figure 2-5 Cumulative Distribution for Continuous Size Distribution

Curling of chips was performed after the chips were appropriately sized. Curled chips were created by placing each chip near a heat lamp and then bending the hot chip by hand about one axis in a relatively random fashion and allowing the chip to cool. The procedure for creating the properly sized and shaped coating chips is contained in Appendix A.

Some anomalies, as described below, occurred during the creation of the chips.

- The ZE coating samples arrived in small pieces. Further, they were already curled and any attempt to flatten them failed because the chips would break. Therefore, tests with flat 25.4mm to 50.8 mm (1 in. to 2 in.) ZE chips were not performed.
- The 25.4mm to 50.8 mm (1 in. to 2 in.) E3C samples would not curl. Therefore, tests with as-received E3C curled chips were not performed. Thermally cured E3C samples did retain their curl and, therefore, were tested.
- The E2 and E6 samples lost their curl (relaxed) when presoaked in 60° C (140° F) water. The decision was made that it was more important to characterize the effect of shape on the transportability than to characterize the effect of presoaking at elevated temperature. Further, flat chips were already being tested. Therefore, the E2 and E6 chips were presoaked in room temperature 21° C (70° F) water.

2.4.3 Thermal Curing

During initial handling it was observed that heat caused some of the epoxy-based coatings to curl. A possible explanation was that the cross-linking of the epoxy polymer was accelerated by the elevated temperature. Therefore, thermal cure was performed on all epoxy-based samples (all samples with the exception of ALK) to determine if heating affected paint chip transport characteristics. Therefore, in addition to the "as-received" and curled sample conditions, the following cured samples were also evaluated:

- Flat, 25.4 to 50.8 mm (1 to 2 inches), heated to 49°C (120°F) for 48 hours
- Curled, 25.4 to 50.8 mm (1 to 2 inches), heated to 49°C (120°F) for 48 hours
- Flat, 25.4 to 50.8 mm (1 to 2 inches), heated to 60°C (150°F) for 14 days
- Curled, 25.4 to 50.8 mm (1 to 2 inches), heated to 65°C (150°F) for 14 days

The 25.4 to 50.8 mm (1 to 2 inches) was chosen as a representative sample because it was thought that any changes in characteristics and performance would most readily be seen at these sizes. Based on the observations of the behavior of the large chips, a decision would be made as to whether to treat the other chip sizes. The cured chips were prepared in a laboratory oven under a fume hood on the "as-received" sheets. The desired sizes and shapes were created after the curing. The results of size distribution analysis, density measurements, and quiescent settling tests were then used to determine if the thermal curing process had any significant effect on chip characteristics or performance. These results are discussed in the Quiescent Tests section below. An interesting artifact of thermal curing is that it was possible to curl the thermally treated E3C debris. Therefore, thermally treated curled E3C chips were included in the quiescent test matrix.

2.5 Coating Density Verification

Coating density was verified by measuring the weight of coating sample necessary to displace 1 mL of water. Multiple measurements (5 per sample) were made of each coating, and the average density and standard deviation are reported in Table 2-2. Also included in this table are the manufacturer's specified densities which generally compare well with the measured values. Generally, differences in density, due to accelerated curing, were relatively small (less than 4%) and appear to be within the measurement standard deviation. No clear trends were evident with continued curing, with the possible exception of the ZE system which became slightly less dense with curing. However, all changes were within the measurement standard deviation such that no significant curing effects on density were apparent.

Table 2-2 Sample Density

Coating	Average Measured Density	Standard Deviation	Manufacturer's Specified Density
	(g/mL, g/cc)	(g/mL, g/cc)	(g/mL, g/cc)
ALK (as received)	1.00	0.14	1.15
ZE (as received)	2.58	0.14	2.54
E2 (as received)	1.78	0.19	1.75
E6 (as received)	1.77	0.04	1.75
E3C (as received)	1.85	0.08	1.86
ZE (120°/2 days)	2.56	0.07	NA
E2 (120°/2 days)	1.72	0.08	NA
E6 (120°/2 days)	1.73	0.11	NA
E3C (120°/2 days)	1.88	0.07	NA
ZE (150°/14 days)	2.54	0.02	NA
E2 (150°/14 days)	1.74	0.04	NA
E6 (150°/14 days)	1.76	0.10	NA
E3C (150°/14 days)	1.84	0.09	NA

2.6 Coating Thickness Verification

For each coating system, the sample thickness was quantified using images of the edges of coating chips through a microscope. This was done to verify that the thickness of the chips was similar to the manufacturer's specified thickness. An example of the image for the as-received E3C sample is shown in Figure 2-6. Each image was calibrated using a slide with a 2000 μm circle. The thicknesses were then calculated using image processing software in Matlab. At least 4 samples were measured per coating type.

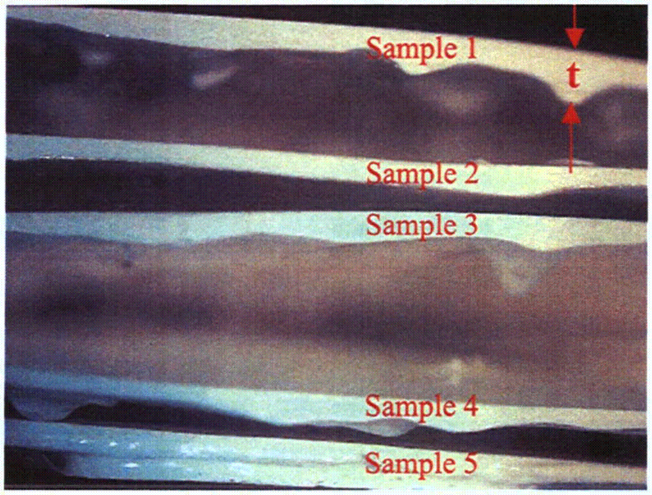


Figure 2-6 Microscope Image of E3C

Table 2-3 shows the average thickness for each coatings system. The E3C thickness was measured at the thickest part of the chips, and has the highest standard deviation due to the rippled shape of the chips (see Figure 2-6 above). The measured thicknesses are close to the manufacturer's specified thickness. Also, there is not a significant difference between the as-received coating chips thicknesses and the thermally cured thicknesses.

Table 2-3 Coating Thicknesses

Coating	Average Total Thickness from Microscope Camera Measurements	Standard Deviation	Manufacturer's Specified Total Thickness
	mm (mils)	mm (mils)	mm (mils)
ALK (as received)	0.056mm (2.2)	0.015 (0.6)	0.051 (2)
ZE (as received)	0.180 (7.1)	0.030 (1.2)	0.267 (10.5)
E2 (as received)	0.218 (8.6)	0.033 (1.3)	0.254 (10)
E6 (as received)	0.584 (23.0)	0.089 (3.5)	0.762 (30)
E3C (as received)	0.635 (25.0)	0.185 (7.3)	0.483 (19)
ZE (120°/2 days)	0.216 (8.5)	0.036 (1.4)	NA
E2 (120°/2 days)	0.211 (8.3)	0.036 (1.4)	NA
E6 (120°/2 days)	0.617 (24.3)	0.114 (4.5)	NA
E3C (120°/2 days)	0.594 (23.4)	0.089 (3.5)	NA
ZE (150°/14 days)	0.198 (7.8)	0.018 (0.7)	NA
E2 (150°/14 days)	0.206 (8.1)	0.041 (1.6)	NA
E6 (150°/14 days)	0.556 (21.9)	0.066 (2.6)	NA
E3C (150°/14 days)	0.597 (23.5)	0.104 (4.1)	NA

3 QUIESCENT TESTING

3.1 Test Description

The goals of the quiescent water tests were to determine (1) the time necessary for coating chips dropped onto the water surface to break the surface and begin sinking (time-to-sink tests), and (2) the rate of descent of submerged coating chips (terminal velocity tests). These tests were performed on all five coating systems--including the 25.4 to 50.8 mm (1 to 2 inches) thermally treated (cured) coatings systems.

3.1.1 Time-to-Sink Test

Time-to-sink tests were conducted by dropping each chip sample from a height of 0.3 m (1 ft). The onset of sinking is defined as the time at which a chip breaks the water surface and begins to descend. Three metrics for the time-to-sink tests were measured, including initial time-to-sink (time required for the first chip to begin sinking), bulk time-to-sink (time necessary for 80% of the chips to begin sinking), and final time-to-sink (time necessary for the last chip to begin sinking), where all times were measured using a stopwatch. The surface tension of the water in the quiescent water test facility was also measured during these tests. Tests were performed using approximately 100-200 chips for each sample lot. For the larger sizes (25.4 to 50.8 mm (1 to 2 inches)), the tests were conducted using 5-10 chips at a time to minimize the interaction between chips. This resulted in 10 to 20 tests per sample lot. As the chip size decreased, tests were conducted with larger amounts of chips. A detailed procedure for the time-to-sink tests can be found in Appendix B. Table 3-1 shows the matrix for the quiescent testing.

Table 3-1 Quiescent Test Matrix

Size/Shape	Thermal Treatment	Coating	Initial, Bulk, and Final Time to Sink	Terminal Velocity
25.4 to 50.8 mm (1 to 2 in) flat	None	ALK	dry & presoaked	presoaked
25.4 to 50.8 mm (1 to 2 in) flat	None 120°F/2 days 150°F/2 weeks	E2, E6, E3C	dry & presoaked	presoaked
25.4 to 50.8 mm (1 to 2 in) curled	None	ZE, E2, E6	dry & presoaked	presoaked
25.4 to 50.8 mm (1 to 2 in) curled	120°F/2 days 150°F/2 weeks	ZE, E2, E6, E3C	dry & presoaked	presoaked
3.2 to 6.4 mm (1/8 to 1/4 in)	None	ALK, ZE, E2, E6, E3C	dry & presoaked	presoaked
0.4 to 0.8 mm (1/64 to 1/32 in)	None	ALK, ZE, E2, E6, E3C	dry & presoaked	presoaked
Continuous Size Distribution	None	ALK, ZE, E2, E6, E3C	dry & presoaked	presoaked

3.1.2 Terminal Velocity Test

Terminal velocity tests were conducted by placing a presoaked chip sample under the water surface and measuring the maximum steady-state velocity of the chips as they fell to the bottom of the test tank. For the larger chips, 5-10 pieces of each sample were used for each test, while for the smaller chips about 1 gram was used. The sample was then presoaked in 140 degree Fahrenheit water for 20 minutes. The digital video camera began taking images, and the sample was placed under the surface of the water and released. Images were recorded until the sample reached the bottom of the tank. The images were saved to a folder identified with the sample number and recorded in a test log. This process was repeated until at least 100 particles were captured in the videos. A detailed procedure for the terminal velocity tests can be found in Appendix D.

3.2 Test Facility

The facility for the quiescent water tests of coating chips was set up in the Specialized Research and Advanced Development (SpecRAD) Laboratory in Building 4E, Room 109, at NSWCCD. This facility is comprised of a vertical Plexiglas tank with a camera for recording digital images from the side of the tank (Figure 3-1). The tank has a 0.3 m (1 ft) by 0.3 m (1 ft) cross-section, and is 1.2 m (4 ft) tall. The tank water is free of movement or flow, and was used for both terminal velocity and time-to-sink tests. The tensiometer was positioned alongside the tank (Figure 3-2). This tensiometer uses the Wilhemy plate method to measure surface tension. In this method, a thin plate is lowered to the surface of the liquid and the downward force directed to the plate is measured. Surface tension is the force divided by the perimeter of the plate (Holmberg, 2002).

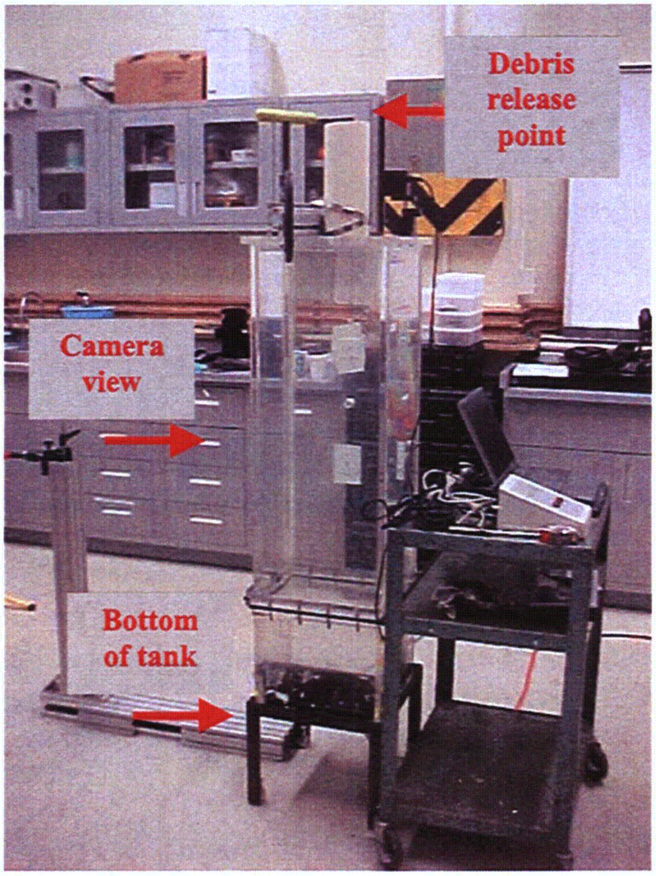


Figure 3-1 Quiescent Test Facility Vertical Tank

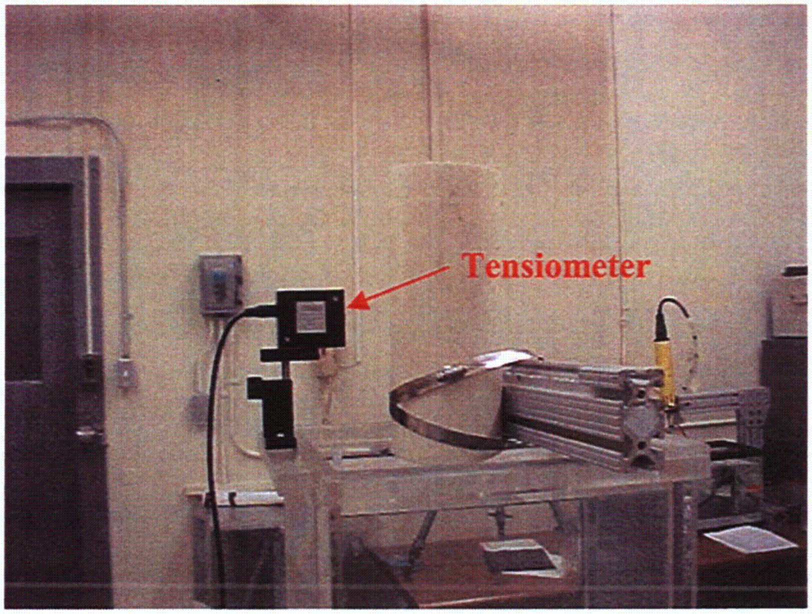


Figure 3-2 Tensiometer

3.3 Time-to-Sink Test Results

3.3.1 Large Chips

Appendix C contains bar charts which summarize the results of the time-to-sink test for 25.4 to 50.8 mm (1 to 2 inches) chips, both dry and pre-soaked. In each figure of Appendix C, the upper charts represent dry samples and the lower charts represent pre-soaked samples. In each figure, the left panels show the number of tests out of the total of generally 10 or 20 tests for which a certain percentage of chips sank immediately (initial time-to-sink tests). The middle panels show the number of tests for which the bulk (80%) of the chips sank in a particular time span. The right panels show the number of tests for which all (100%) of the chips sank in a particular time span. An entry of "Infinity" indicates the number of incidents in which the sink criterion was not met. Figure 3-3 and Figure 3-4 below summarize the results of the initial time-to-sink tests of the large chips. The complete time-to sink results for large chips are contained Appendix C.

Figure 3-3 shows the total percentage of flat 25.4 to 50.8 mm (1 to 2 in) chips that sank initially (within 1 second of being dropped onto the surface) for both dry and presoaked samples. No 25.4 to 50.8 mm (1 to 2 in.) ALK coating chips (dry or presoaked) sank initially in any of the time-to-sink tests. Further, the ALK chips remained on the surface indefinitely. Large percentages of the E2, E6, and E3C coating samples sank immediately. In general, more presoaked chips sank initially than did dry chips. However, the difference was not significant. Also, all flat 25.4 to 50.8 mm (1 to 2 inches) chips, regardless of coating type, either sank within 1 second of being dropped onto the surface, or remained on the surface indefinitely.

Figure 3-4 shows the percentage of curled 25.4 to 50.8 mm (1 to 2 in) chips that sank immediately, totaled over all tests, for both dry and presoaked samples. Almost all of the E6 chips sank immediately upon hitting the water surface. In contrast, E2 chips had the lowest percentage of chips sinking initially. Further, in all tests, some E2 chips remained on the surface indefinitely.

3.3.2 Small Chips

For the smaller sized chips (3.2 to 6.4 mm (1/8 to 1/4 inches) and 0.4 to 0.8 mm (1/64 to 1/32 inches)), the pieces either sank immediately, or remained on the surface indefinitely. As with the large ALK chips, none of the small ALK samples sank. Figure 3-5 illustrates that of the 3.2 to 6.4 mm (1/8 to 1/4 in) chips, E3C had the highest percentage of chips (approximately 90 percent) that sank initially, while ZE had approximately 50 percent of chips sink initially. Figure 3-6 illustrates that of the 0.4 to 0.8 mm (1/64 to 1/32 in) chips, E3C had the highest percentage of chips to sink initially, while E2 had 20 percent of chips sink initially. Generally, the smaller size chips exhibited a greater tendency to remain on the surface indefinitely.

Overall, the effect of presoaking on time-to-sink does not follow a clear trend. In some cases more presoaked chips sank immediately, in some cases fewer, and in some cases the same amount. Curling the chips does not have a clear effect either; for E6, a slightly larger amount of the curled chips sank immediately, but for E2, fewer of the curled chips sank than the flat chips. Over all sizes, the dry E6 and E3C chips have the greatest percentage of chips sinking immediately, suggesting that chip weight is a significant factor in determining sink rate.

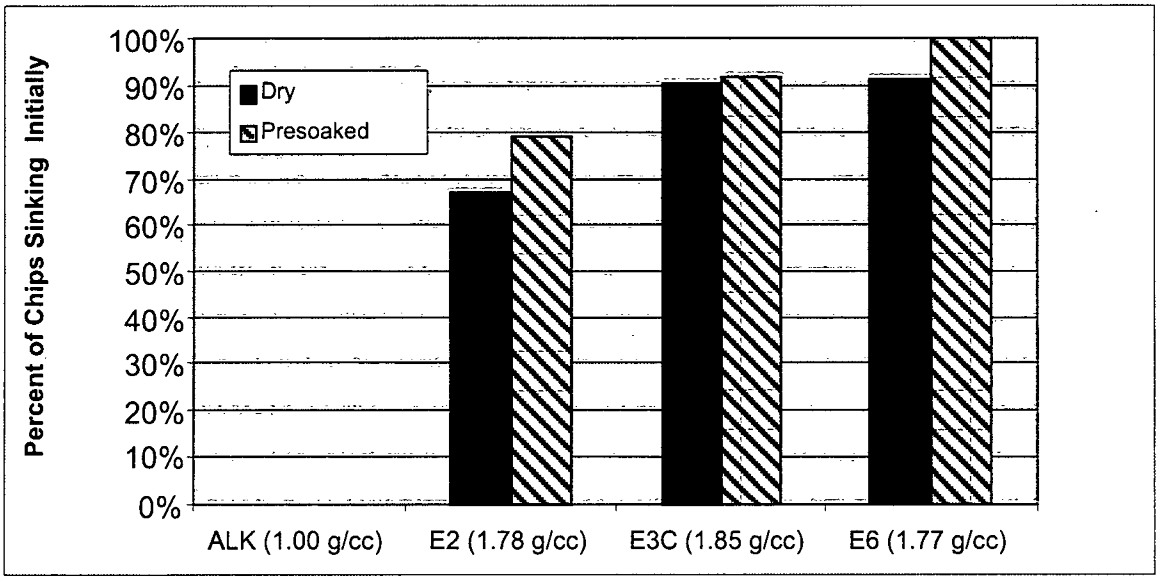


Figure 3-3 Percent of 25.4 to 50.8 mm (1 to 2 in) Flat Chips Sinking Initially

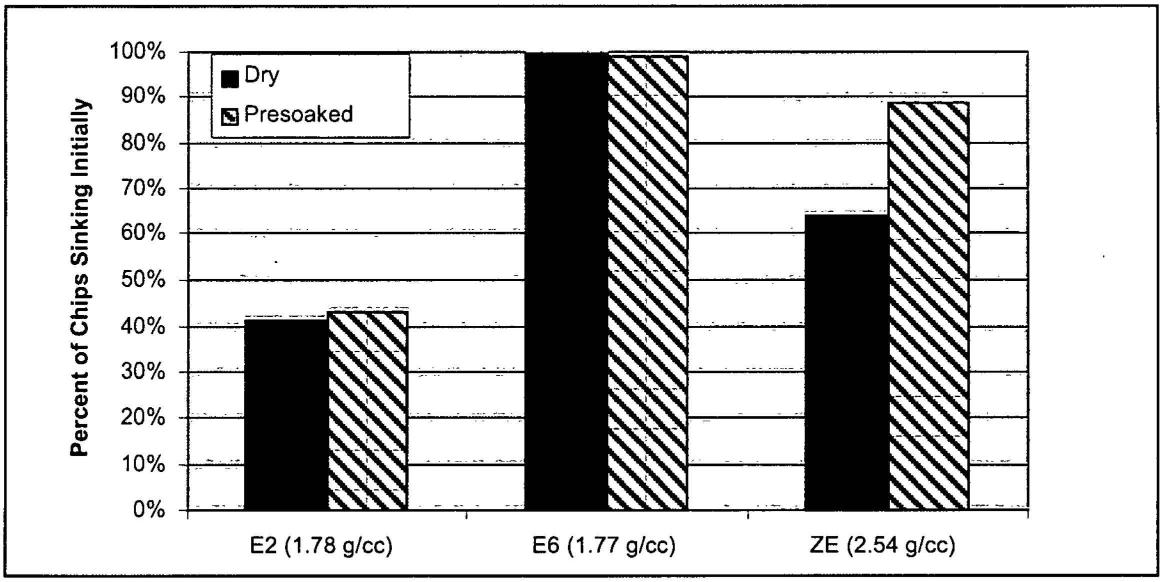


Figure 3-4 Percent of 25.4 to 50.8 mm (1 to 2 in) Curled Chips Sinking Initially

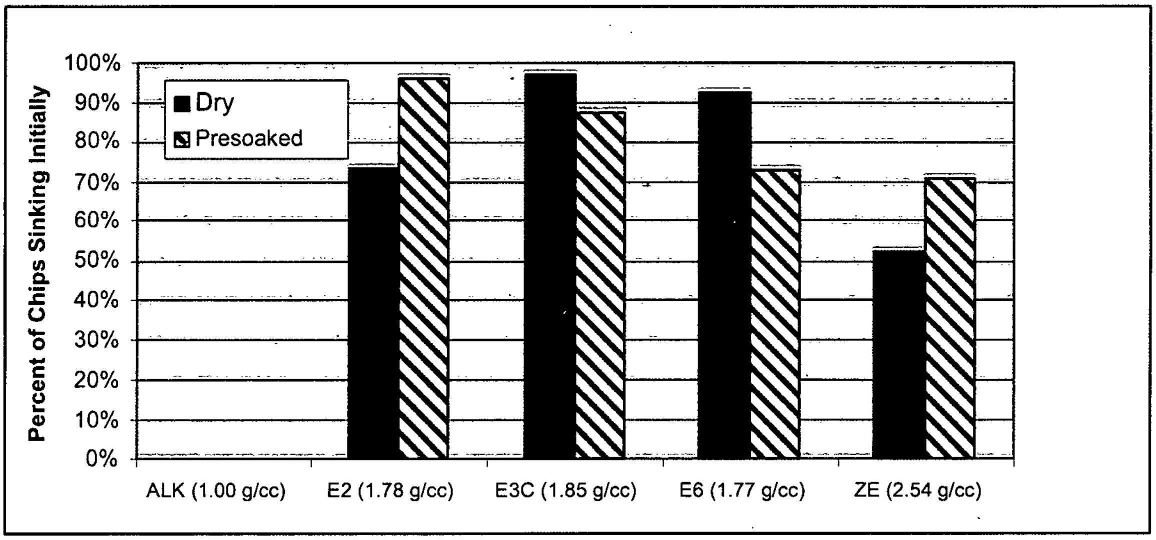


Figure 3-5 Percent of 3.2 to 6.35 mm (1/4 to 1/8 inches) Chips Sinking Initially

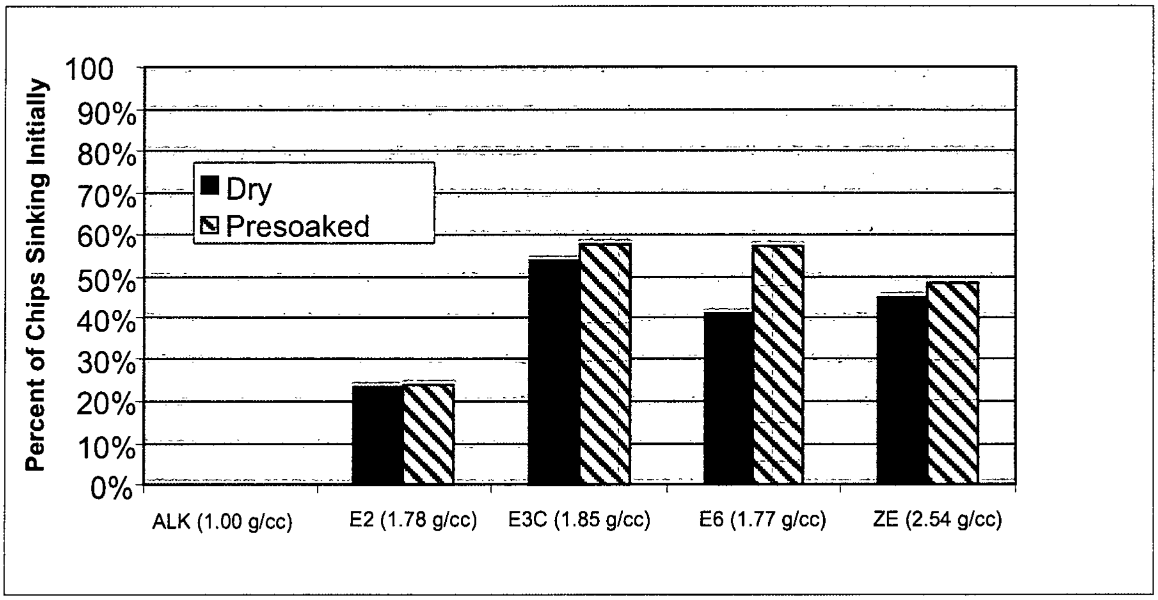


Figure 3-6 Percent of 0.4 to 0.8 mm (1/32 to 1/64 in) Chips Sinking Initially

3.4 Terminal Velocity Test Results

Table 3-2 shows the terminal velocity test results, where Vy is the vertical velocity (positive down). Figure 3-7 displays the terminal velocity data in graphical form for all of the "as-received" chips. This figure, illustrates that E3C and E6 have the largest values of terminal velocity over all sizes, while ZE is close behind and ALK is clearly lowest.

From Figure 3-7 it can be seen that the terminal velocity increased with size. However, it is more difficult to present an argument on the affect of shape (curl) on terminal velocity as there is insufficient data. From the available data for E2 and E6, it can be seen that curling had the effect of increasing terminal velocity. However, chip weight combined with chip shape may be a greater contributing factor as the curled E6 chips had a 44 % increase in terminal velocity over the flat E6 chips and the curled E2 chips had only a 14% increase over the E2 flat chips. The E6 chips have approximately three times the weight of the E2 chips. A plot of terminal velocity versus chip weight per unit area (Figure 3-9) indicates an upward trend with increasing chip size and weight per unit area. Further, chip size appears to be the dominant factor.

The effect of thermal treatment on terminal velocity is illustrated in Figure 3-8. The figure plots the terminal velocity test results for 25.4 to 50.8 mm (1 to 2 in) as-received and thermally treated chips. Generally, the change in terminal velocity, due to thermal treatment, is subtle and is within the standard deviation (see Table 3-2). The one exception may be E6 which exhibited a tendency to settle slower with increased thermal-treatment temperature. Because all of these coatings are epoxy based (E2 and E6 are Carboguard 890N) and there is no apparent change in density due to thermal treatment (see Table 2-2), all the epoxy based chips should exhibit similar behavior. Therefore, their terminal velocity versus thermal treatment temperature curves should be similar. One explanation for the reduction in terminal velocity for the thermally cured E6 is that the treated E6 may be more rigid and, therefore, returns to its original flat condition after being manually curled. This would explain why the terminal velocity of the thermally treated curled E6 approaches that of the thermally treated flat E6.

As stated in Paragraph 2.8, the extent to which thermally treated chips were tested was based on the observations of the 1" to 2" thermally treated and as-received chips. Because there was no observed statistically significant curing effects (as qualified above for E6) on chip density, chip thickness, time-to-sink, or terminal velocity, no further testing was performed with thermally cured chips.

Table 3-2 Terminal Velocity Results

Coating	Size	Shape	Thermal Treatment	Vy		Vy Std. Dev.	
				(ft/s)	(mm/s)	(ft/s)	(mm/s)
ALK	25.4 to 50.8 mm (1 to 2 in)	Flat	none	0.09	26.41	0.01	2.99
ALK	3.2 to 6.4 mm (1/8 to 1/4 in)	Flat	none	0.08	23.01	0.00	0.91
ALK	0.4 to 0.8 mm (1/64 to 1/32 in)	Flat	none	0.04	13.70	0.00	0.91
ZE	25.4 to 50.8 mm (1 to 2 in.)	Curled	none	0.30	91.84	0.07	20.56
ZE	25.4 to 50.8 mm (1 to 2 in.)	Curled	150°/2 weeks	0.23	70.77	0.05	16.37
ZE	25.4 to 50.8 mm (1 to 2 in.)	Curled	120°/2 days	0.30	91.81	0.09	28.18
ZE	3.2 to 6.4 mm (1/8 to 1/4 in)	Flat	none	0.21	64.96	0.02	5.78
ZE	0.4 to 0.8 mm (1/64 to 1/32 in)	Flat	none	0.26	78.38	0.06	16.98
E2	25.4 to 50.8 mm (1 to 2 in.)	Flat	none	0.22	68.02	0.03	9.26
E2	25.4 to 50.8 mm (1 to 2 in.)	Flat	150°/2 weeks	0.17	50.64	0.03	9.15
E2	25.4 to 50.8 mm (1 to 2 in.)	Flat	120°/2 days	0.18	56.27	0.03	8.75
E2	25.4 to 50.8 mm (1 to 2 in.)	Curled	none	0.25	77.45	0.02	6.04
E2	25.4 to 50.8 mm (1 to 2 in.)	Curled	150°/2 weeks	0.25	75.75	0.04	12.83
E2	25.4 to 50.8 mm (1 to 2 in.)	Curled	120°/2 days	0.23	68.73	0.02	6.00
E2	3.2 to 6.4 mm (1/8 to 1/4 in)	Flat	none	0.15	45.84	0.02	4.71
E2	0.4 to 0.8 mm (1/64 to 1/32 in)	Flat	none	0.13	39.29	0.02	4.68
E6	25.4 to 50.8 mm (1 to 2 in.)	Flat	none	0.32	97.76	0.07	20.40
E6	25.4 to 50.8 mm (1 to 2 in.)	Flat	150°/2 weeks	0.27	83.68	0.06	17.86
E6	25.4 to 50.8 mm (1 to 2 in.)	Flat	120°/2 days	0.28	84.25	0.10	31.64
E6	25.4 to 50.8 mm (1 to 2 in.)	Curled	none	0.46	140.80	0.08	23.23
E6	25.4 to 50.8 mm (1 to 2 in.)	Curled	150°/2 weeks	0.30	92.62	0.14	42.13
E6	25.4 to 50.8 mm (1 to 2 in.)	Curled	120°/2 days	0.35	105.33	0.08	22.96
E6	3.2 to 6.4 mm (1/8 to 1/4 in)	Flat	none	0.24	73.87	0.02	5.82
E6	0.4 to 0.8 mm (1/64 to 1/32 in)	Flat	none	0.16	47.42	0.03	8.71
E3C	25.4 to 50.8 mm (1 to 2 in.)	Flat	none	0.29	88.68	0.05	13.96
E3C	25.4 to 50.8 mm (1 to 2 in.)	Flat	150°/2 weeks	0.31	95.97	0.10	30.37
E3C	25.4 to 50.8 mm (1 to 2 in.)	Flat	120°/2 days	0.24	73.00	0.09	27.19
E3C	25.4 to 50.8 mm (1 to 2 in.)	Curled	150°/2 weeks	0.28	85.42	0.11	33.16
E3C	25.4 to 50.8 mm (1 to 2 in.)	Curled	120°/2 days	0.27	83.82	0.14	44.06
E3C	3.2 to 6.4 mm (1/8 to 1/4 in)	Flat	none	0.24	74.13	0.05	15.43
E3C	0.4 to 0.8 mm (1/64 to 1/32 in))	Flat	none	0.16	50.09	0.03	8.46

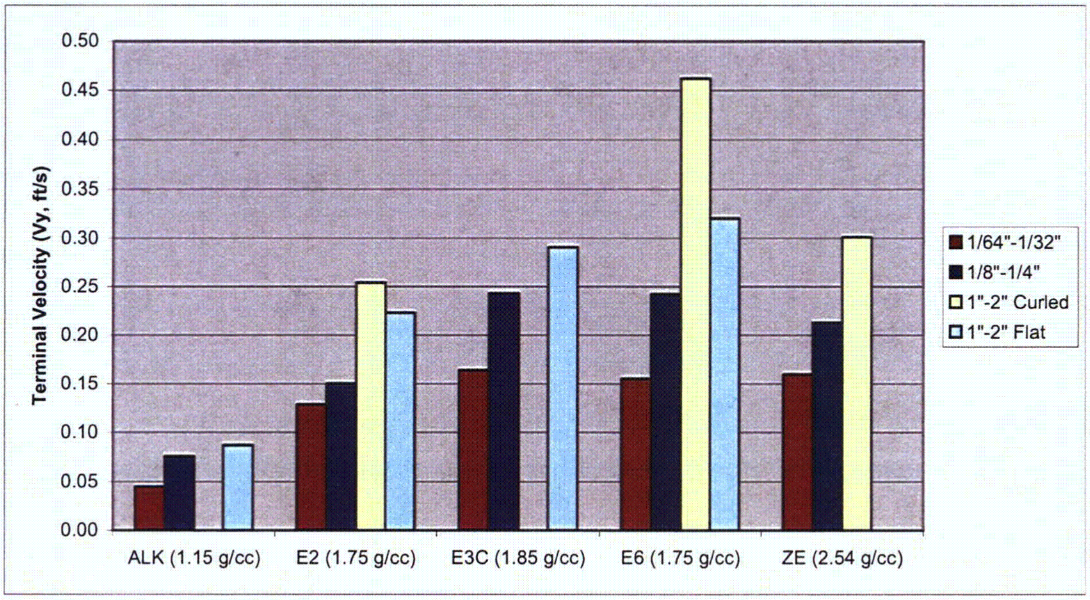


Figure 3-7 Terminal Velocity for "As-Received" Chips

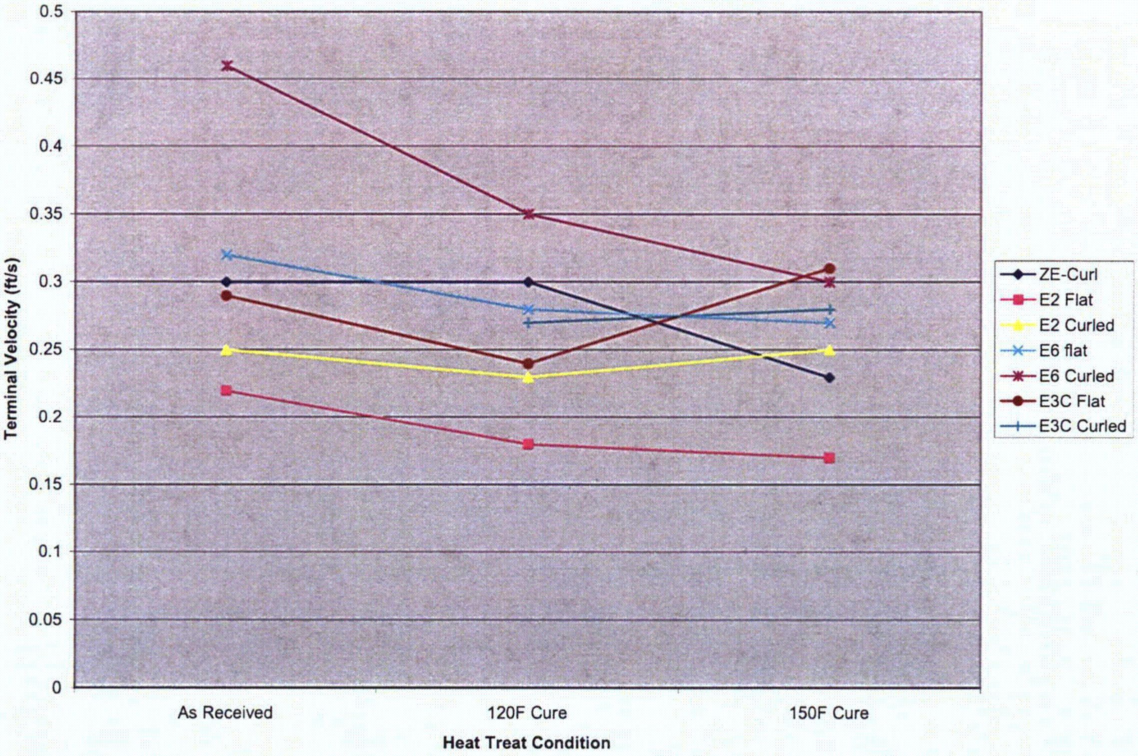


Figure 3-8 Terminal Heat-Treat Effects

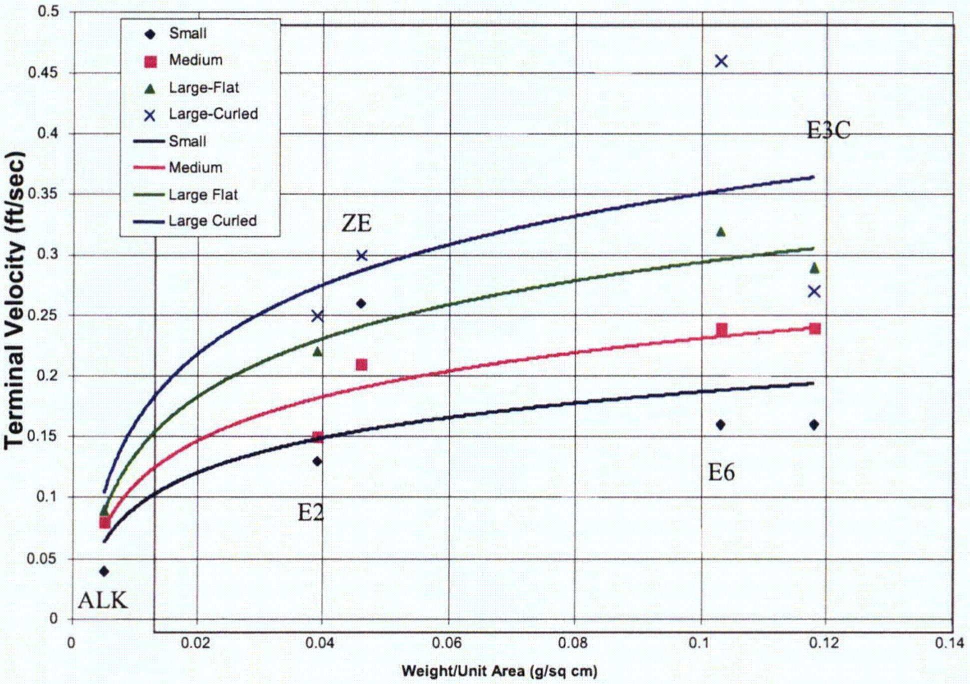


Figure 3-9 Terminal Velocity Trend With Chip Size and Weight per Unit Area

4 TRANSPORT TESTING

4.1 Transport Test Facility

The transport test facility was set up in the Circulating Water Channel (CWC) facility at NSWCCD (see Figure 4-1). The CWC is capable of developing steady velocities up to 4.6 m/s (15.2 ft/s). The transport test flume, a 9.1 m (30 ft) long tank with a 0.91 m (3 ft) by 0.91 m (3 ft) cross-section, was suspended in the CWC such that the depth of water in the flume was 0.76 m (30 in.), i.e. the bottom of the flume was 30 inches below the surface. (Figure 4-2, Figure 4-3). A schematic of the test flume, illustrating the "Front", "Middle," and "End" sections is shown in Figure 4-4. The "front section" represents the flume section within 0.3 meter (1 foot) of the chip release point, the "middle section" represents the flume section from 0.3 to 4 meters (1 to 13 feet) of the chip release point, and the "end section" represents the flume section from 4 to 6.7 meters (13 to 22 feet) of the chip release point. A filter, vertically partitioned into three sections (Figure 4-5) and located at the outlet end of the flume, collected and classified chips that reached the end of the flume. The chips reaching the filter have traveled the entire length of the flume and, therefore, are considered to have transported. At the filter, the "top" represents the upper 0.08 m (3 in) of the stream, the "middle" is the central 0.6 m (24 in) of the stream, and the "bottom" represents the bottom 0.08 m (3 in) of the stream.

The flume was constructed of acrylic to simulate the enamel or polymer coated concrete floors of containment buildings. To track chip movement, five underwater cameras were placed along the path of travel. The first two cameras were used to track the chip velocity in the tank near the release point—one positioned to view the chips from the side and one from above. The third and fourth cameras were spaced along the length of the flume to track chip movement further downstream, and the fifth camera was positioned to view the collection filter.

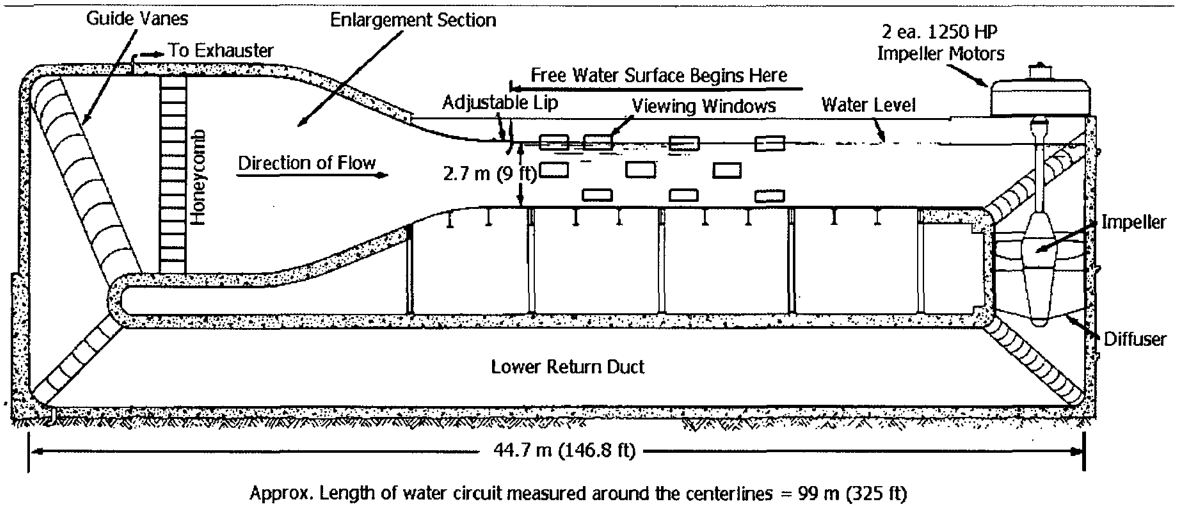


Figure 4-1 Circulating Water Channel Facility

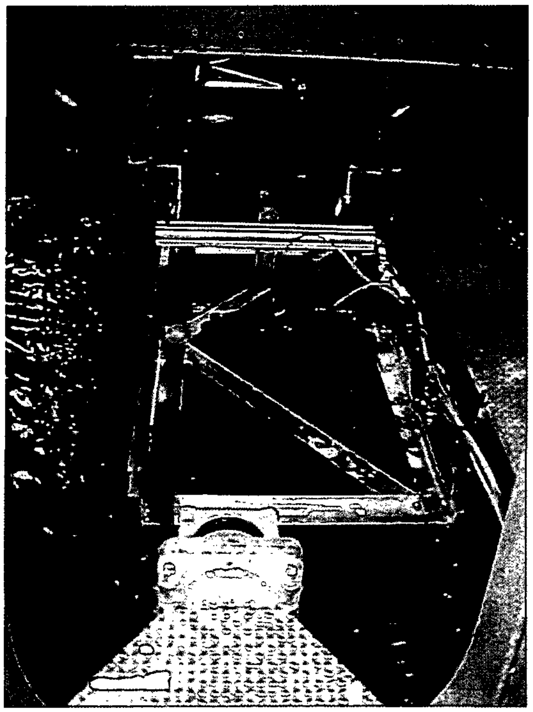


Figure 4-2 Transport Flume in Circulating Water Channel (overhead view)

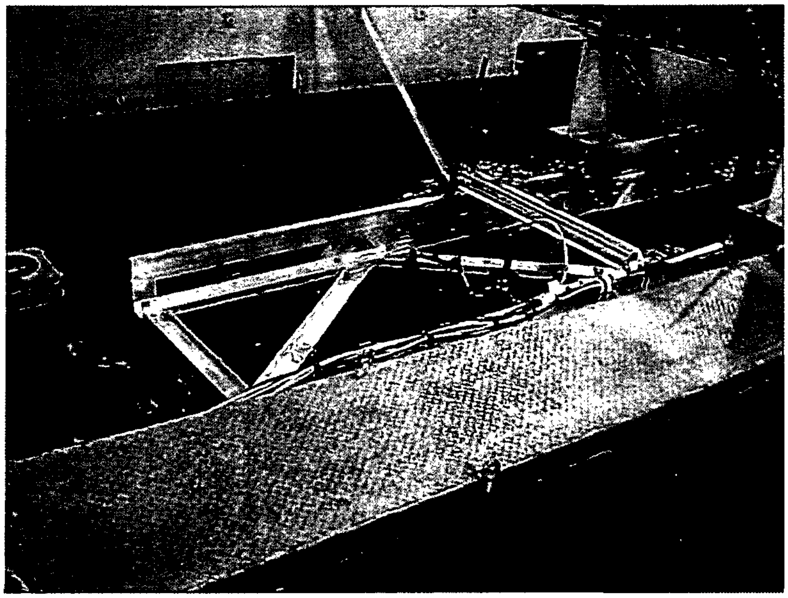


Figure 4-3 Transport Flume in Circulating Water Channel (side view)

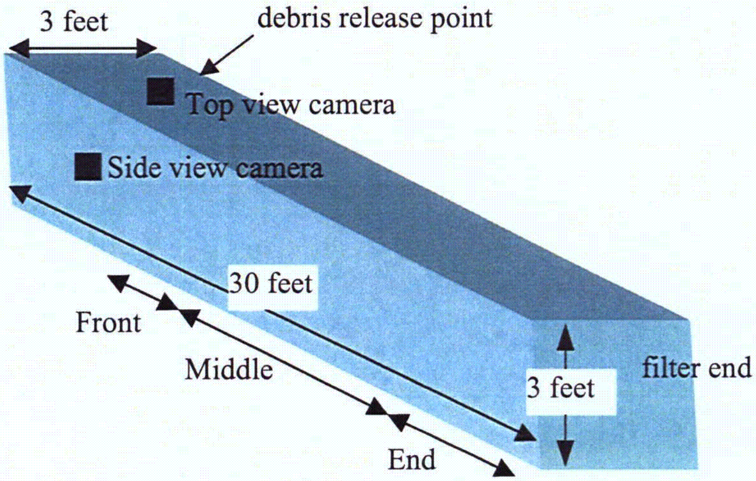


Figure 4-4 Schematic of Transport Flume

Figure 4-5 Filter for Transport Flume

4.2 Summary of Testing Procedure

The transport tests were performed to determine the transport behavior of coating chips in moving water. The transport tests consisted of tumbling velocity tests and steady-state velocity tests, with the test matrices shown in Table 4-1 and Table 4-2.

4.2.1 Tumbling Velocity

Tumbling velocity is defined as the minimum fluid velocity (averaged over the flume cross section) required to tumble (or slide) the chips on the flume floor. To determine this velocity, presoaked chip samples were placed on the bottom of the flume under zero-flow conditions. For large chips 5-10 chips were used per test, while for small pieces (1/64" to 1/32") 1 gram of chips were used per test. Samples were arranged such that no chips were touching or interfering with other chips, and so that the test sample was on the tank floor inside the marked area where the sample was viewable by the camera. Once the cameras and acoustic Doppler velocimeter (ADV) started recording, fluid velocity was slowly increased until both the incipient and bulk tumbling velocity could be determined. The incipient tumbling velocity is defined as the fluid velocity required for the first chips to begin tumbling or sliding. Bulk tumbling velocity is defined as the fluid velocity required for the bulk of the chips (80%) to begin tumbling or sliding. This process was repeated for at least 50 chips of each size, shape, and coating type. A detailed procedure for the tumbling velocity is included in Appendix E.

Table 4-1 Tumbling Velocity Test Matrix

Size/Shape	Coating	Tumbling Velocity
25.4 to 50.8 mm (1 to 2 in) Flat	ALK, E2, E6, E3C	incipient, bulk
25.4 to 50.8 mm (1 to 2 in) Curled	ZE, E2, E6	incipient, bulk
3.2 to 6.4 mm (1/8 to 1/4 in)	ALK, ZE, E2, E6, E3C	incipient, bulk
0.4 to 0.8 mm (1/64 to 1/32 in)	ALK, ZE, E2, E6, E3C	incipient, bulk
Distribution	ALK, ZE, E2, E6, E3C	incipient, bulk

4.2.2 Steady-State Velocity

In the steady state velocity tests, dry chip samples were released into a steady-flowing stream using a release chamber just below the water surface (about 0.08 m (3 in.)) and the chips' transport properties were observed. For large chips, 5-10 chips were used per test. For small chips (1/64" to 1/32"), 1 gram of chips was used per test. The steady-state transport tests were performed at two stream velocities—the bulk tumbling velocity and the pre-established threshold velocity of 0.06 m (0.2 feet per second). At the end of each steady state transport test, the following transport characteristics were recorded:

- Fraction of coating chips which transports by floating on the surface of the water (recovered from top of filter)
- Fraction of coating chips which transports by remaining suspended in the water
- (recovered from middle of filter)
- Fraction of coating chips which transports by tumbling or sliding along the bottom of the flume (recovered from bottom of filter)
- Fraction of coating chips which does not transport to end of flume (comes to rest before reaching the end of the flume)
- Distribution map of coating chips fragments that came to rest
- Velocity history of coating chips

This process was repeated for at least 50 chips of each size, shape, and coating type. A detailed procedure for the transport velocity test is included in Appendix F.

Table 4-2 Steady State Transport Test Matrix

Size/Shape	Coating	Transport Velocity
25.4 to 50.8 mm (1 to 2 in) Flat	ALK, E2, E6, E3C	0.06 m/s (0.2 ft/s), tumbling
25.4 to 50.8 mm (1 to 2 in) Curled	ZE, E2, E6	0.06 m/s (0.2 ft/s), tumbling
3.2 to 6.4 mm (1/8 to 1/4 in)	ALK, ZE, E2, E6, E3C	0.06 m/s (0.2 ft/s), tumbling
0.4 to 0.8 mm (1/64 to 1/32 in)	ALK, ZE, E2, E6, E3C	0.06 m/s (0.2 ft/s), tumbling
Distribution	ALK, ZE, E2, E6, E3C	0.06 m/s (0.2 ft/s), tumbling

4.3 Velocity Mapping

A SonTek ADV was used to measure the water velocity during the tumbling velocity testing. At the beginning of the experiment, for calibration purposes, measurements were made in 1-inch increments throughout the water column over various speeds to determine the average velocity over the cross section, as well as the velocity nearest the tank floor. Analysis of this data showed that the along-channel, free stream velocity varied by less than five percent throughout the water column.

4.4 Test Results

4.4.1 Tumbling Velocity Test

Table 4-3 shows the results for the tumbling velocity tests. The bulk tumbling velocity results in Table 4-3 are graphically depicted in Figure 4-6. The E6 coating had the highest tumbling velocity for the large, flat chips, while ALK chips of this size had the lowest tumbling velocity. For the remaining sizes, the ZE chips tend to have the highest tumbling velocities, with ALK having the lowest (except for the smallest sizes).

Table 4-3 Tumbling Velocity Test Results

Coating	Size/Shape	Incipient Velocity m/s (ft/s)	Bulk (80%) Velocity m/s (ft/s)
ALK	25.4 to 50.8 mm (1 to 2 in.)	0.049 (0.16)	0.140 (0.46)
E2	25.4 to 50.8 mm (1 to 2 in.)	0.110 (0.36)	0.259 (0.85)
E3C	25.4 to 50.8 mm (1 to 2 in.)	0.104 (0.34)	0.308 (1.01)
E6	25.4 to 50.8 mm (1 to 2 in.)	0.207 (0.68)	0.415 (1.36)
E2	25.4 to 50.8 mm (1 to 2 in.) curled	0.027 (0.09)	0.082 (0.27)
E6	25.4 to 50.8 mm (1 to 2 in.) curled	0.012 (0.04)	0.210 (0.69)
ZE	25.4 to 50.8 mm (1 to 2 in.) curled	0.079 (0.26)	0.131 (0.43)
ALK	3.2 to 6.4 mm (1/8 to1/4 in)	0.037 (0.12)	0.259 (0.85)
E2	3.2 to 6.4 mm (1/8 to 1/4 in)	0.174 (0.57)	0.363 (1.19)
E3C	3.2 to 6.4 mm (1/8 to 1/4 in)	0.207 (0.68)	0.390 (1.28)
E6	3.2 to 6.4 mm (1/8 to 1/4 in)	0.241 (0.79)	0.351 (1.15)
ZE	3.2 to 6.4 mm (1/8 to 1/4 in)	0.201 (0.66)	0.408 (1.34)
ALK	0.4 to 0.8 mm (1/64-1/32 in)	0.037 (0.12)	0.280 (0.92)
E2	0.4 to 0.8 mm (1/64-1/32 in)	0.201 (0.66)	0.308 (1.01)
E3C	0.4 to 0.8 mm (1/64-1/32 in)	0.149 (0.49)	0.299 (0.98)
E6	0.4 to 0.8 mm (1/64-1/32 in)	0.110 (0.36)	0.235 (0.77)
ZE	0.4 to 0.8 mm (1/64-1/32 in)	0.128 (0.42)	0.415 (1.36)
ALK	Distribution	0.018 (0.06)	0.274 (0.90)
E2	Distribution	0.107 (0.35)	0.366 (1.20)
E3C	Distribution	0.241 (0.79)	0.433 (1.42)
E6	Distribution	0.177 (0.58)	0.408 (1.34)
ZE	Distribution	0.040 (0.13)	0.442 (1.45)

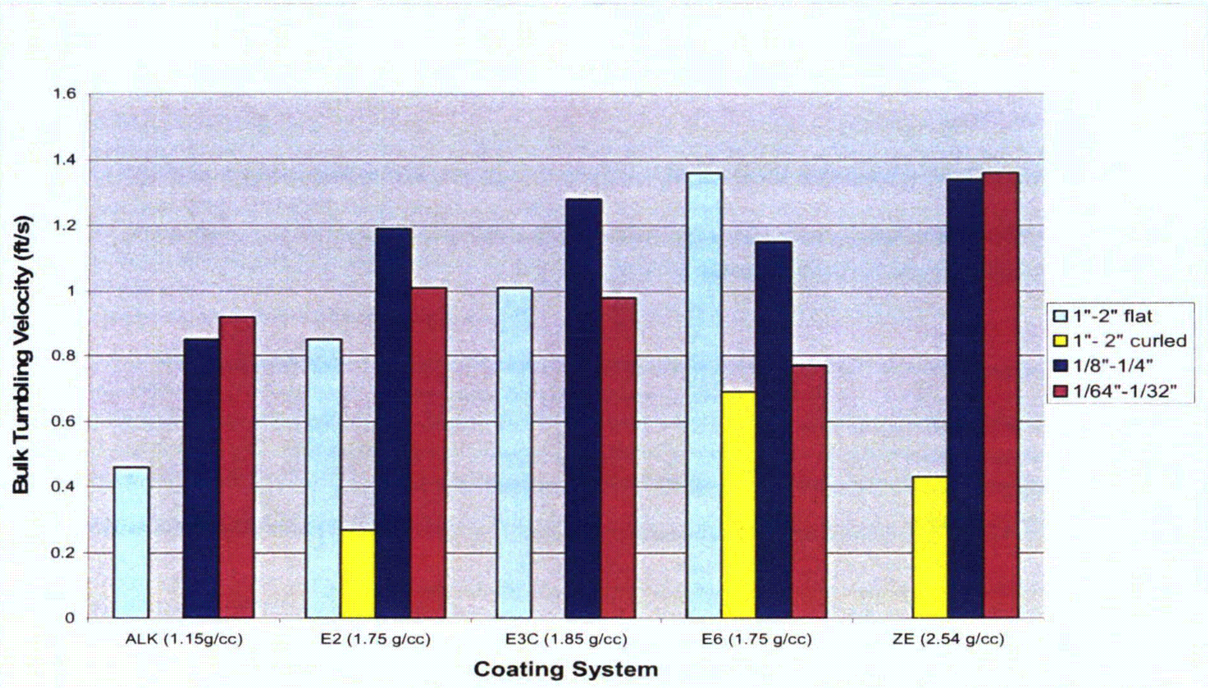


Figure 4-6 Bulk Tumbling Velocity Results

4.4.2 Steady-State Transport Test

Table 4-4 shows the chip transport velocities observed in the steady state transport tests, which were performed at the previously determined bulk velocity and the 0.06 m/s (0.2 ft/s) velocity. For each coating type and water velocity, the average and standard deviation of chip velocity, as well as the minimum and maximum chip velocity of all chips tested are listed. In general, the recorded average water velocities are slightly higher than the recorded average chip velocities, indicating a slip.

Appendix G contains plots summarizing the degree of transport of each of the coating systems and size ranges tested. The plots show the location in the flume where the chips came to rest or the section of the filter in which the chips were captured, as applicable. In these plots, the "front section" represents the flume section within 0.3 meter (1 foot) of the chip release point, the "middle section" represents the flume section from 0.3 to 4 meters (1 to 13 feet) of the chip release point, and the "end section" represents the flume section from 4 to 6.7 meters (13 to 22 feet) of the chip release point. (The end of the flume and the location of the collection filter are 7.7 meters (22 feet) from the release point). Any chips reaching the filter have traveled the entire length of the tank and, therefore, are considered to transport. At the filter, the "top" represents the upper 0.08 m (3 in) of the stream, the "middle" is the central 0.6 m (24 in) of the stream, and the "bottom" represents the bottom 0.08 m (3 in) of the stream. In the tests performed at 0.06 m/s (0.2 ft/s), only a small portion (two to four percent) of the ALK and E2 chips travel the length of the tank. All of the ZE, E6 and E3C coatings chips settled to the bottom of the flume and came to rest at or before the middle section of the tank. In tests performed at the coatings' bulk tumbling velocities, the degree of transport varied significantly. Chips with the higher bulk tumbling velocities transported the furthest. Large flat chips, large curled chips and mid-sized chips (except ALK) that transported were recovered in the bottom section of the filter. The bulk of the mid-sized ALK was recovered in the middle and top sections of the filter (71 percent and 21 percent, respectively). Small chips of ALK, E2 and ZE transported readily (over 60 percent) and were recovered, primarily, in the mid-section of the filter.

Table 4-4 Transport Test Results (Metric Units)

Coating	Size/Shape	Water Velocity (m/s)	Chip Velocity (m/s)			
			Average	St. Dev.	Min.	Max.
E2	25.4 to 50.8 mm	0.26*	0.192	0.012	0.180	0.207
	25.4 to 50.8 mm	0.06	0.043	0.015	0.015	0.070
	25.4 to 50.8 mm, curled	0.08*	0.058	0.012	0.040	0.079
	25.4 to 50.8 mm, curled	0.06	0.037	0.015	0.012	0.067
	3.2 to 6.4 mm	0.36*	0.241	0.012	0.223	0.259
	3.2 to 6.4 mm	0.06	0.040	0.012	0.018	0.067
	0.4 to 0.8 mm	0.31*	0.250	0.009	0.226	0.250
	0.4 to 0.8 mm	0.06	0.040	0.006	0.030	0.055
	Distribution	0.37*	0.326	0.009	0.317	0.335
	Distribution	0.06	0.040	0.012	0.018	0.061
E6	25.4 to 50.8 mm	0.41*	0.366	0.006	0.360	0.372
	25.4 to 50.8 mm	0.06	0.040	0.009	0.024	0.055
	25.4 to 50.8 mm, curled	0.21*	0.152	0.018	0.125	0.177
	25.4 to 50.8 mm, curled	0.06	0.049	0.021	0.021	0.085
	3.2 to 6.4 mm	0.35*	0.320	0.012	0.308	0.332
	3.2 to 6.4 mm	0.06	0.034	0.012	0.012	0.058
	0.4 to 0.8 mm	0.23*	0.201	0.000	0.189	0.213
	0.4 to 0.8 mm	0.06	0.046	0.006	0.034	0.058
	Distribution	0.41*	0.341	0.009	0.332	0.354
	Distribution	0.06	0.030	0.015	0.009	0.061
E3C	25.4 to 50.8 mm	0.31*	0.290	0.012	0.277	0.305
	25.4 to 50.8 mm	0.06	0.037	0.015	0.006	0.058
	3.2 to 6.4 mm	0.39*	0.268	0.012	0.253	0.287
	3.2 to 6.4 mm	0.06	0.034	0.012	0.015	0.058
	0.4 to 0.8 mm	0.30*	0.262	0.012	0.250	0.277
	0.4 to 0.8 mm	0.06	0.046	0.006	0.034	0.061
	Distribution	0.43*	0.305	0.009	0.293	0.314
	Distribution	0.20	0.027	0.009	0.012	0.046
ZE	25.4 to 50.8 mm, curled	0.13*	0.116	0.018	0.088	0.146
	25.4 to 50.8 mm, curled	0.06	0.049	0.021	0.012	0.088
	3.2 to 6.4 mm	0.41*	0.296	0.012	0.280	0.308
	3.2 to 6.4 mm	0.06	0.040	0.015	0.009	0.070
	0.4 to 0.8 mm	0.41*	0.351	0.006	0.347	0.357
	0.4 to 0.8 mm	0.06	0.043	0.009	0.030	0.055
	Distribution	0.44*	0.326	0.009	0.317	0.335
	Distribution	0.06	0.037	0.015	0.012	0.067
ALK	25.4 to 50.8 mm	0.14*	0.119	0.006	0.107	0.128
	25.4 to 50.8 mm	0.06	0.034	0.009	0.018	0.049
	3.2 to 6.4 mm	0.26*	0.256	0.009	0.244	0.265
	3.2 to 6.4 mm	0.06	0.052	0.009	0.040	0.064
	0.4 to 0.8 mm	0.28*	0.253	0.006	0.244	0.262
	0.4 to 0.8 mm	0.06	0.046	0.009	0.030	0.064
	Distribution	0.27*	0.259	0.006	0.250	0.271
	Distribution	0.06	0.034	0.009	0.021	0.049

*represents the bulk tumbling velocity

Table 4-5 Transport Test Results (English Units)

Coating	Size/Shape	Water Velocity (ft/s)	Chip Velocity (ft/s)			
			Average	St. Dev.	Min.	Max.
E2	1 to 2 in	0.85*	0.63	0.04	0.59	0.68
	1 to 2 in	0.20	0.14	0.05	0.05	0.23
	1 to 2 in, curled	0.27*	0.19	0.04	0.13	0.26
	1 to 2 in, curled	0.20	0.12	0.05	0.04	0.22
	1/8 to ¼ in	1.19*	0.79	0.04	0.73	0.85
	1/8 to ¼ in	0.20	0.13	0.04	0.06	0.22
	1/64 to 1/32 in	1.01*	0.82	0.03	0.74	0.82
	1/64 to 1/32 in	0.20	0.13	0.02	0.10	0.18
	Distribution	1.20*	1.07	0.03	1.04	1.10
	Distribution	0.20	0.13	0.04	0.06	0.20
E6	1 to 2 in	1.36*	1.20	0.02	1.18	1.22
	1 to 2 in	0.20	0.13	0.03	0.08	0.18
	1 to 2 in, curled	0.69*	0.50	0.06	0.41	0.58
	1 to 2 in, curled	0.20	0.16	0.07	0.07	0.28
	1/8 to ¼ in	1.15*	1.05	0.04	1.01	1.09
	1/8 to ¼ in	0.20	0.11	0.04	0.04	0.19
	1/64 to 1/32 in	0.77*	0.66	0.00	0.62	0.70
	1/64 to 1/32 in	0.20	0.15	0.02	0.11	0.19
	Distribution	1.34*	1.12	0.03	1.09	1.16
	Distribution	0.20	0.10	0.05	0.03	0.20
E3C	1 to 2 in	1.01*	0.95	0.04	0.91	1.00
	1 to 2 in	0.20	0.12	0.05	0.02	0.19
	1/8 to ¼ in	1.28*	0.88	0.04	0.83	0.94
	1/8 to ¼ in	0.20	0.11	0.04	0.05	0.19
	1/64 to 1/32 in	0.98*	0.86	0.04	0.82	0.91
	1/64 to 1/32 in	0.20	0.15	0.02	0.11	0.20
	Distribution	1.42*	1.00	0.03	0.96	1.03
	Distribution	0.20	0.09	0.03	0.04	0.15
ZE	1 to 2 in, curled	0.43*	0.38	0.06	0.29	0.48
	1 to 2 in, curled	0.20	0.16	0.07	0.04	0.29
	1/8 to ¼ in	1.34*	0.97	0.04	0.92	1.01
	1/8 to ¼ in	0.20	0.13	0.05	0.03	0.23
	1/64 to 1/32 in	1.36*	1.15	0.02	1.14	1.17
	1/64 to 1/32 in	0.20	0.14	0.03	0.10	0.18
	Distribution	1.45*	1.07	0.03	1.04	1.10
	Distribution	0.20	0.12	0.05	0.04	0.22
ALK	1 to 2 in	0.46*	0.39	0.02	0.35	0.42
	1 to 2 in	0.20	0.11	0.03	0.06	0.16
	1/8 to ¼ in	0.85*	0.84	0.03	0.80	0.87
	1/8 to ¼ in	0.20	0.17	0.03	0.13	0.21
	1/64 to 1/32 in	0.92*	0.83	0.02	0.80	0.86
	1/64 to 1/32 in	0.20	0.15	0.03	0.10	0.21
	Distribution	0.90*	0.85	0.02	0.82	0.89
	Distribution	0.20	0.11	0.03	0.07	0.16

*represents the bulk tumbling velocity

5 CONCLUSIONS

The quiescent tests demonstrated that (1) light-weight coating chips, specifically alkyd chips, dropped onto the water surface tended to remain on the surface indefinitely, (2) a large percent of the heavy coating chips (six-coat epoxy and epoxy system for concrete) sank immediately, and (3) a lower percent of the medium-weight coating chips (two-coat epoxies, zinc/epoxy systems) sank initially. These results imply that a large percentage of low density coating chips and a small percentage of higher density coating chips that ended up on the pool surface could transport with the current generated by the ECCS/CSS recirculation pumps.

The tumbling velocity tests demonstrated that the highest bulk tumbling velocity was associated with the heaviest flat coating chips, approximately 0.43 m/s (1.4 ft/s). The curled and light chips had the lowest tumbling velocities with the bulk of the chips tumbling at 0.08 m/s (0.27 ft/s) and 0.14 m/s (0.46 ft/s) for curled two-coat epoxy and one-coat alkyd coating systems, respectively. In the steady-state velocity test, at a uniform water velocity of 0.06 m/s (0.2 ft/s), all but the lightest chips came to rest at the bottom of the flume within a short distance of the release point. Only a small percent of the medium-sized alkyd chips transported to the end of the test flume by floating on the surface. These results imply that coating chips possessing physical characteristics similar to the coatings tested herein will likely not transport significant distances at uniform stream velocities of 0.06 m/s (0.2 ft/s) or less.

6 REFERENCES

Holmberg, Krister. Handbook of Applied Surface and Colloid Chemistry, Volumes 1-2 , 2002 John Wiley & Sons.

APPENDIX A: PROCEDURE FOR SIZING COATING CHIPS

E2, E3C, E6, and ZE Sample

Method for size 1" – 2" flat

1) Place sheet(s) of material in bag
2) Break up by hand into small pieces (approximately 1 to 2 inches)
3) Use 1" and 2" sieve to filter out chips larger than 2" and smaller than 1"
4) Add sieved material to sample container.
5) Repeat steps 1 to 4 to obtain sufficient sample population (~200-400 pieces)
6) Weigh sample and record in table.
7) Place sample in container for storage until test
8) Label container with sample number from chart

Note: ZE samples arrived in a curled shape, and could not be flattened, so no flat ZE chips were created.

Method for size 1" – 2" curled

1) Place sheet(s) of material in bag
2) Break up by hand into small pieces (approximately 1 to 2 inches)
3) Use 1" and 2" sieve to filter out chips larger than 2" and smaller than 1"
4) Repeat steps 1 to 4 to obtain sufficient sample population (~200-400 pieces)
5) Curl each piece by holding next to the heat lamp and bending piece by hand in a relatively random fashion.
6) Add sieved material to sample container.
7) Weigh sample and record weight in table.
8) Place sample in container for storage until test.
9) Label container with sample number from chart.

Note: As-received E3C did not hold curl; therefore, no curled as-received E3C chips were created.

Method for size 1/8" – 1/4"

1) Place sheet(s) of material in bag
2) Break up by hand into small pieces (approximately 1 to 2 inches).
3) Crumble pieces in bag by hand to smallest size possible.
4) Use entire set of sieves to filter chips into size ranges.
5) Add sieved material to sample containers.
6) Repeat steps 1 to 5 to obtain desired amount of sample.
7) Weigh sample(s) and record in table.
8) Place sample in container for storage until test
9) Label container with sample number from chart.

Method for size range 1/64" – 1/32"

1) Place sheet in bag
2) Break up by hand into large pieces
3) Place large pieces in blender
4) Place in blender and blend for 15 seconds
5) Use entire set of sieves to filter chips into size ranges.
6) Add sieved material to sample containers.
7) Weigh sample(s) and record in table.
8) Place sample in container for storage until test
9) Label container with sample number from chart.

ALK Sample

Method for size 1" – 2" flat

1) Cut a large piece of paint from the sample sheets.
2) Peel large piece from the plastic sheet.
3) Break peeled sheet by hand into small pieces (approximately 1 to 2 inches)
4) Use 1" and 2" sieve to filter out chips larger than 2" and smaller than 1"
5) Add sieved material to sample container.
6) Repeat steps 1 to 5 to obtain sufficient sample population (~200 pieces)
7) Weigh sample and record in table.
8) Place sample in container for storage until test
9) Label container with sample number from chart

Method for size 1" – 2" curled

Curled chips could not be manufactured with the provided sample. Material was not sufficiently rigid to hold curl.

Method for size 1/8" – 1/4"

1) Cut a large piece of paint from the sample sheets.
2) Peel large piece from the plastic sheet.
3) Break peeled sheet by hand into small pieces (approximately 1 to 2 inches)
4) Place pieces in blender and blend for approximately 0.5 seconds.
5) Use entire set of sieves to filter particles into size ranges.
6) Add sieved material to sample containers.
7) Repeat steps 1 to 6 to obtain desired amount of sample.
8) Weigh sample(s) and record in table.
9) Place sample in container for storage until test
10) Label container with sample number from chart.

Method for size range 1/64" – 1/32"

1) Cut a large piece of paint from the sample sheets.
2) Peel large piece from the plastic sheet.
3) Break peeled sheet by hand into small pieces (approximately 1 to 2 inches)
4) Place pieces in blender and blend for approximately 3 seconds.
5) Use entire set of sieves to filter chips into size ranges.
6) Add sieved material to sample containers.
7) Repeat steps 1 to 6 to obtain desired amount of sample.
8) Weigh sample(s) and record in table.
9) Place sample in container for storage until test
10) Label container with sample number from chart.

APPENDIX B: PROCEDURE FOR TIME-TO-SINK TESTS

Test Procedure: Time-to-Sink test, dry chips

1) Count 20 pieces from sample and weigh for large pieces. For small pieces (1/64" to 1/32") weigh out 1 gram of particles.
2) Take digital picture of sample spread on light or dark background, depending on paint chip color in order to perform size characterization. Record picture number and test number in test log.
3) Place test sample in release mechanism.
4) Record water surface tension.
5) Release sample and start timer.
6) Record Initial Time-to-Sink (first pieces sinking) in test log.
7) Record Bulk (80%) Time-to-Sink (average time for bulk of chips) in test log.
8) Record Final Time to Sink in test log.
9) Repeat 10 times for each paint sample.

Test Procedure: Time-to-Sink test: Presoaked Paint Chips

1) Count 10-20 pieces from sample and weigh for large pieces. For small pieces (1/64" to 1/32") weigh out 1 gram of particles.
2) Take digital picture of sample spread on light or dark background, depending on paint chip color in order to perform size characterization. Record picture number and test number in test log.
3) Presoak chips in 140 degree Fahrenheit water for 20 minutes.
4) Remove excess water from presoaked sample by separating chips and placing on an absorbent sheet.
5) Place test sample in release mechanism.
6) Record water surface tension.
7) Release sample and start timer.
8) Record Initial Time-to-Sink (first pieces sinking) in test log.
9) Record Bulk (80%) Time-to-Sink in test log.
10) Record Final Time-to-Sink in test log.
11) Repeat 10 times for each paint sample.

APPENDIX C: RESULTS FOR TIME-TO-SINK TEST

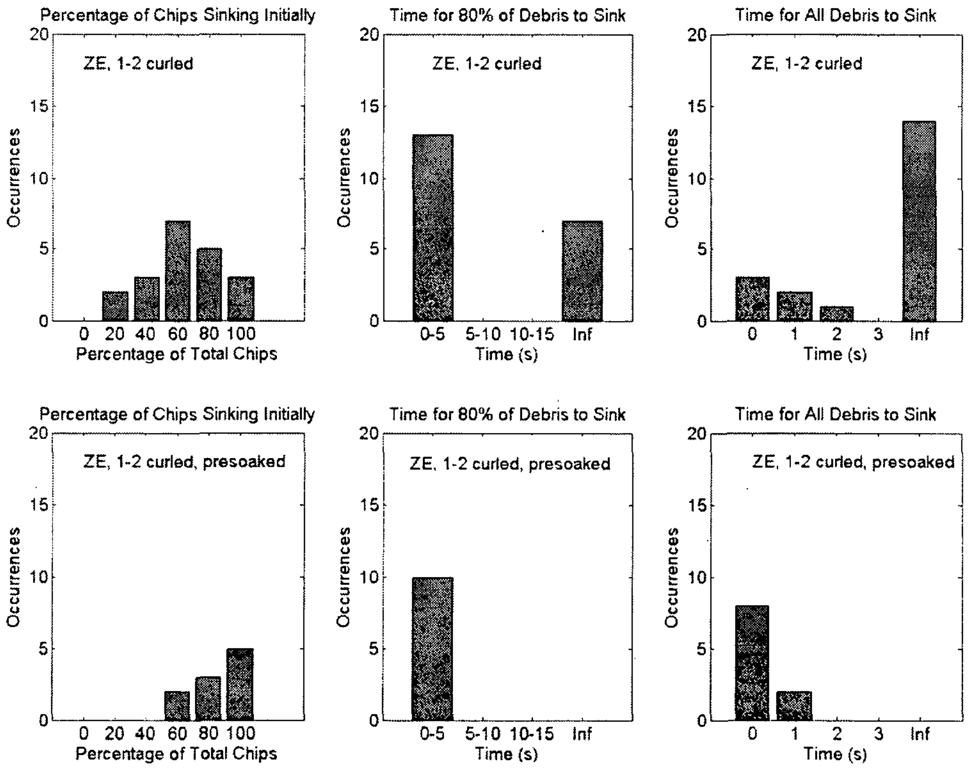


Figure C-1 ZE, 1"-2", Curled, as Received, Time-To-Sink Test Results

Note: Each row of each figure in Appendix C provides results for a set of "time-to-sink" tests for the sample listed on the graph. For example, in the "Percentage of Chips Sinking Initially Test" (upper left panel of Figure C-1) , out of 20 tests for ZE, 1"-2", curled, as-received, dry chips, 20% of the chips sank initially in 2 of the tests, 40% sank initially in 3 of the tests, 60% sank in 7 of the tests, 80% sank in 5 of the tests, and 100% sank in 3 of the tests.

In the graph that describes the bulk time for the chips to sink (entitled "Time for 80% of Chips to Sink"), the number of occurrences is on the y-axis, while the time for the chips to sink (in seconds) is on the x-axis. The top middle panel shows that in 13 of the tests, 80% of the chips sank between 0-5 seconds. In 7 tests, most of the chips remained on the surface, never having 80% of the total sink. The graph entitled "Time for All Chips to Sink" shows the same information for 100% of the chips.

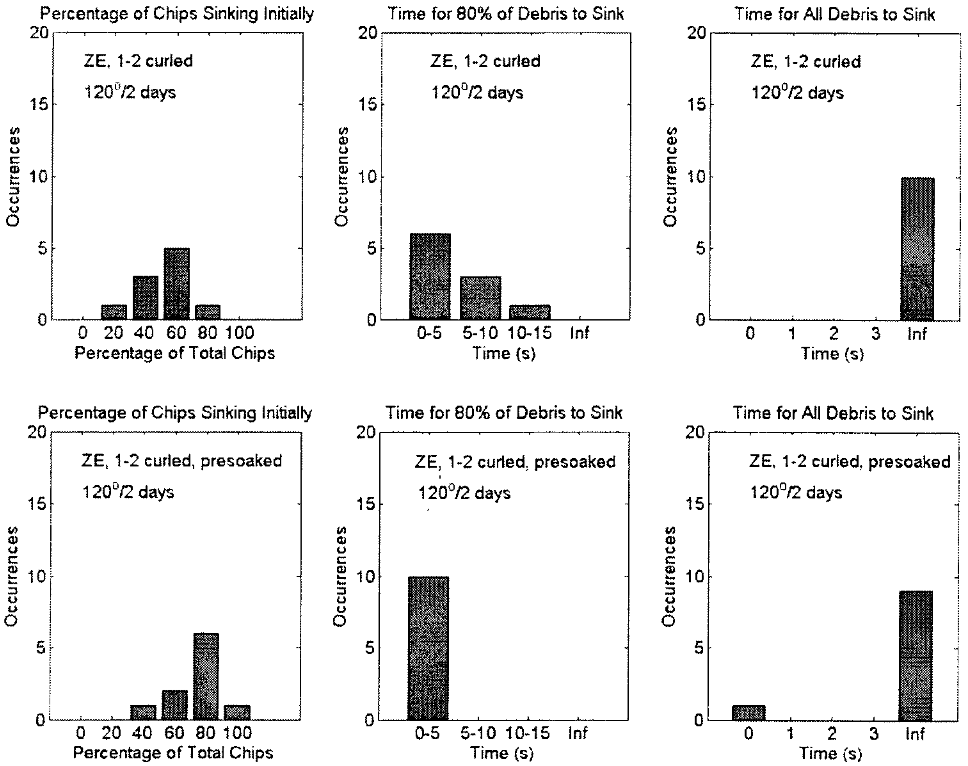


Figure C-2 ZE, 1"-2", Curled, Thermal Cured at 120°F for 2 Days, Time-To-Sink Test Results

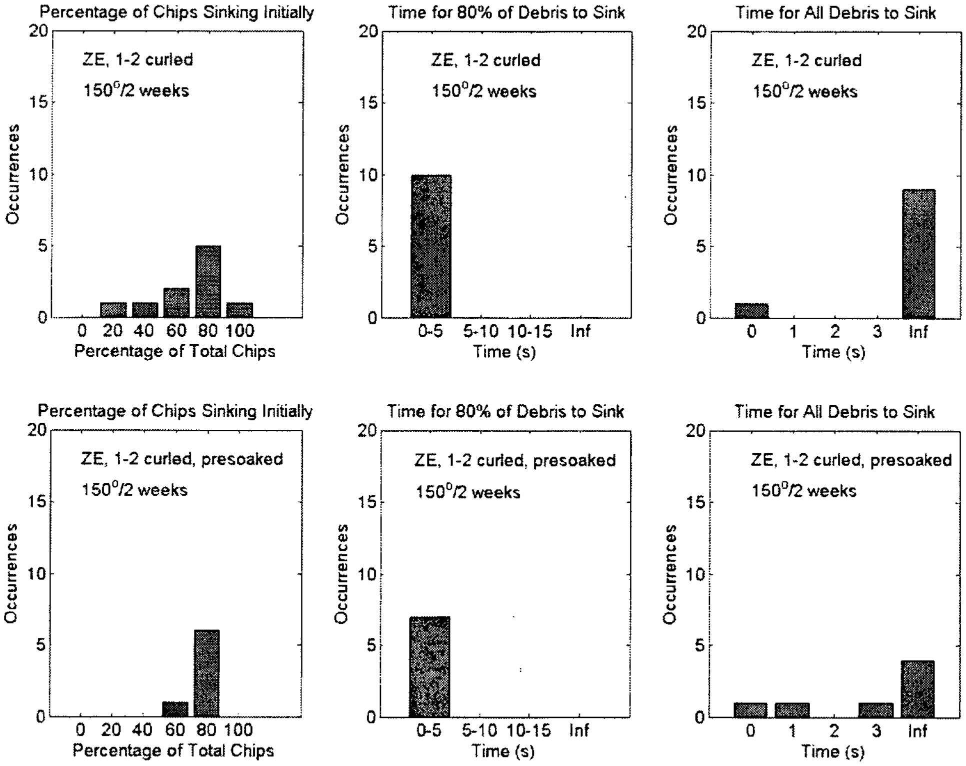


Figure C-3 ZE, 1"-2", Curled, Thermal Cured at 150°F for 2 Weeks, Time-To-Sink Test Results

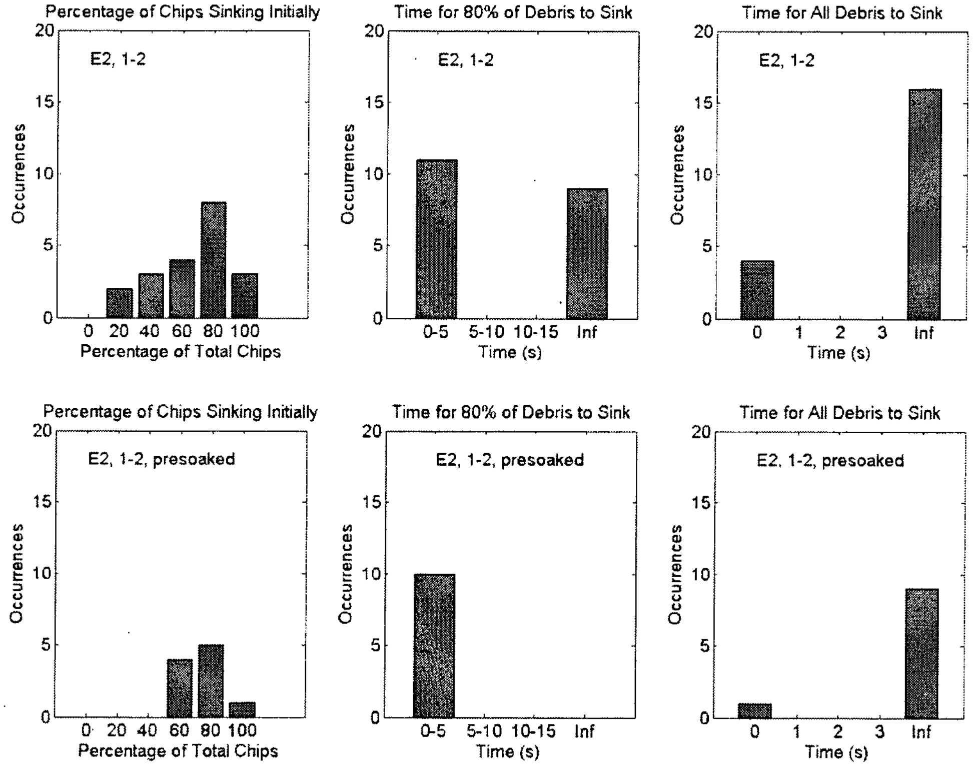

Percentage of Chips Sinking Initially
Time for 80% of Debris to Sink
Time for All Debris to Sink
Percentage of Chips Sinking Initially
Time for 80% of Debris to Sink
Time for All Debris to Sink

Figure C-4 E2, 1"-2", Flat, as Received, Time-To-Sink Test Results

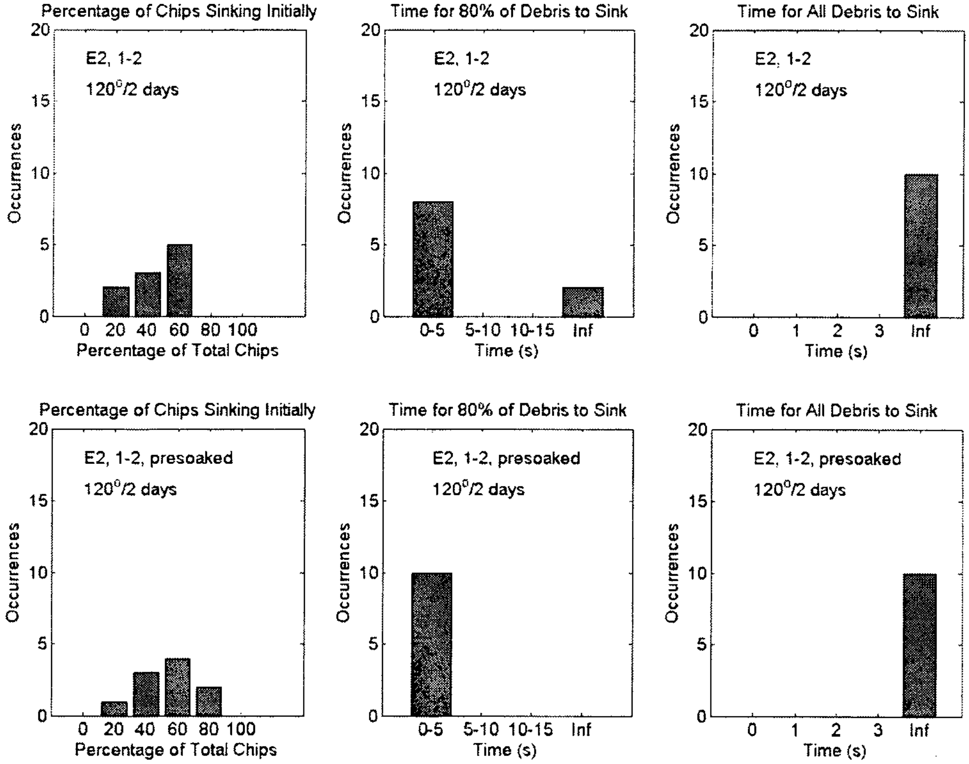


Figure C-5 E2, 1"-2", Flat, Thermally Cured at 120° F for 2 Days, Time-To-Sink Test Results

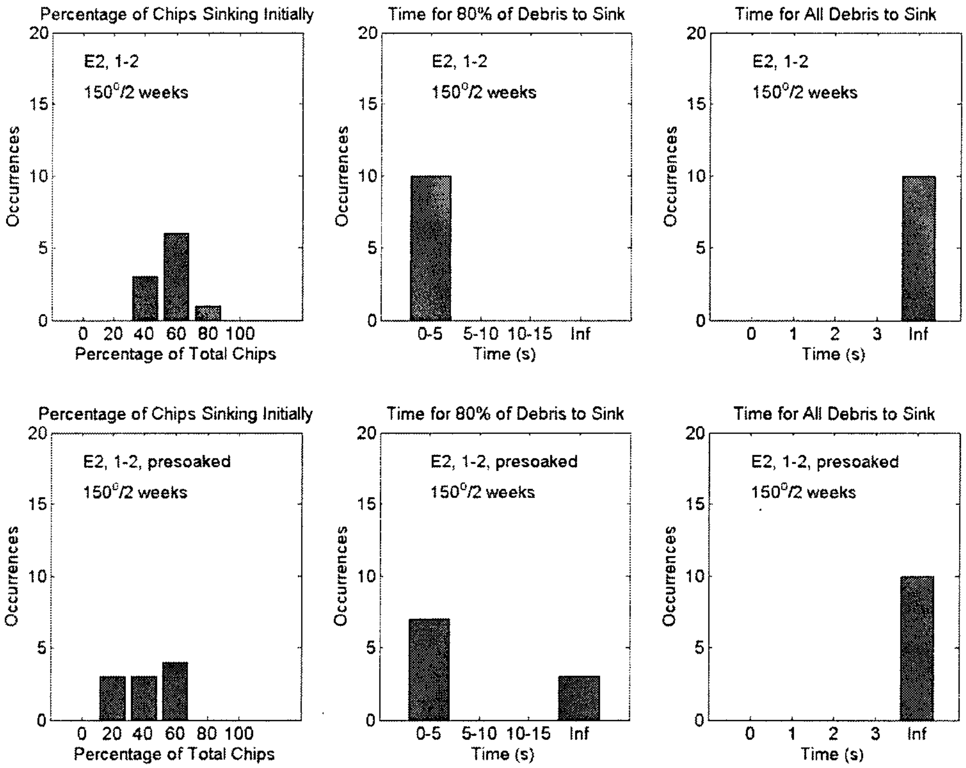


Figure C-6 E2, 1"-2", Flat, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

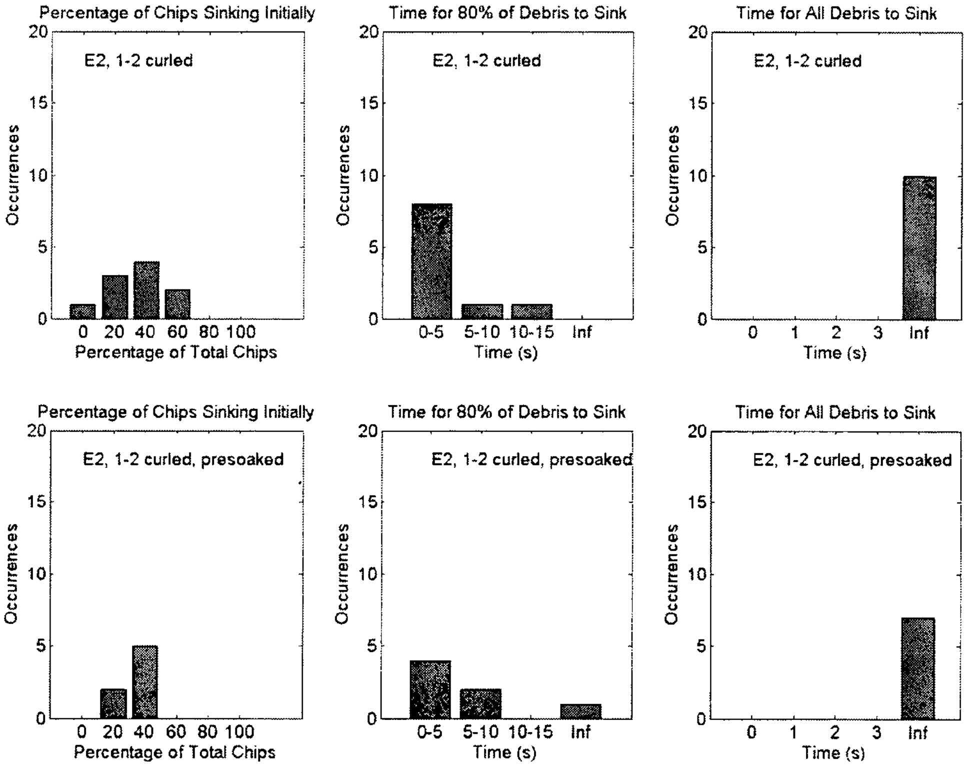


Figure C-7 E2, 1"-2", Curled, as Received, Time-To-Sink Test Results

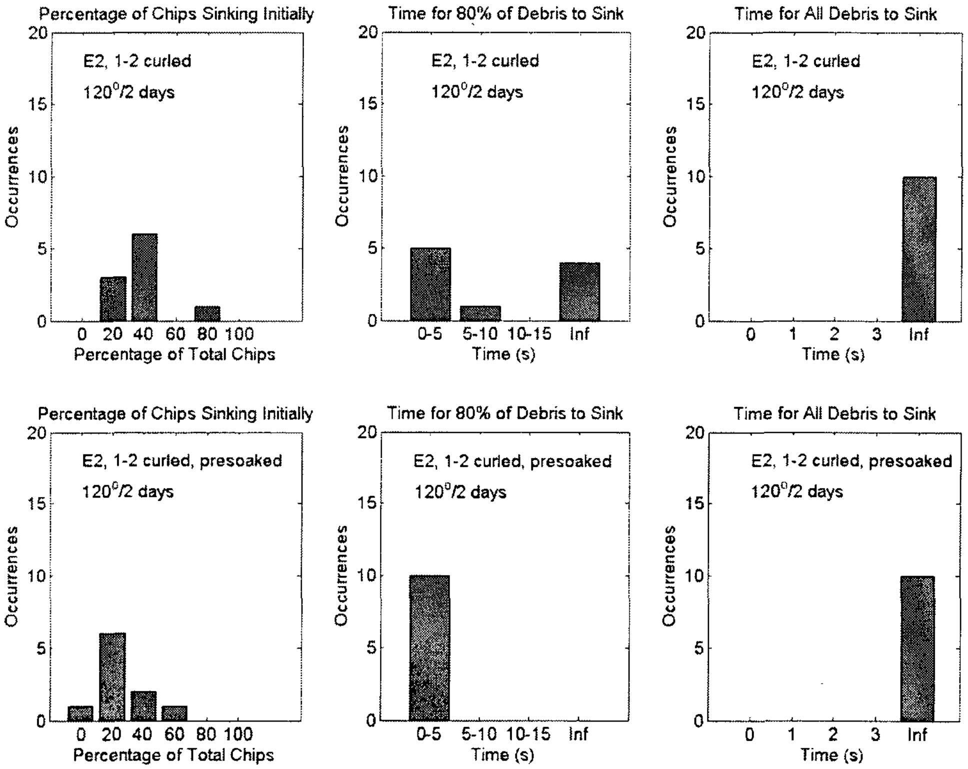


Figure C-8 E2, 1"-2", Curled, Thermally Cured at 120° F for 2 Days, Time-To-Sink Test Results

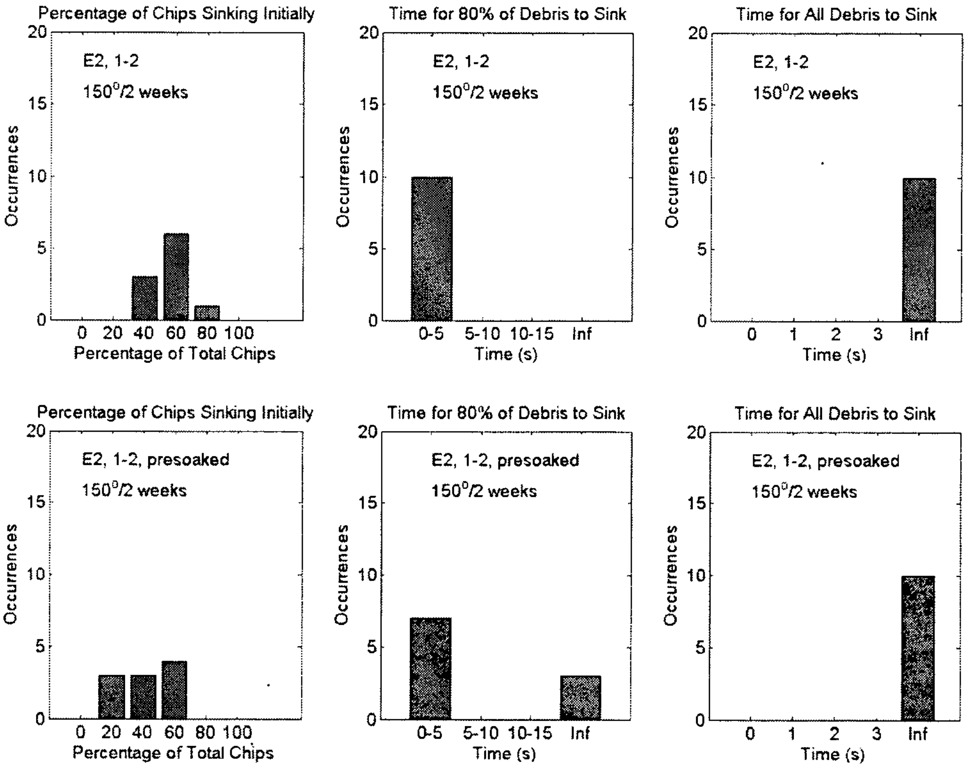


Figure C-9 E2, 1"-2", Curled, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

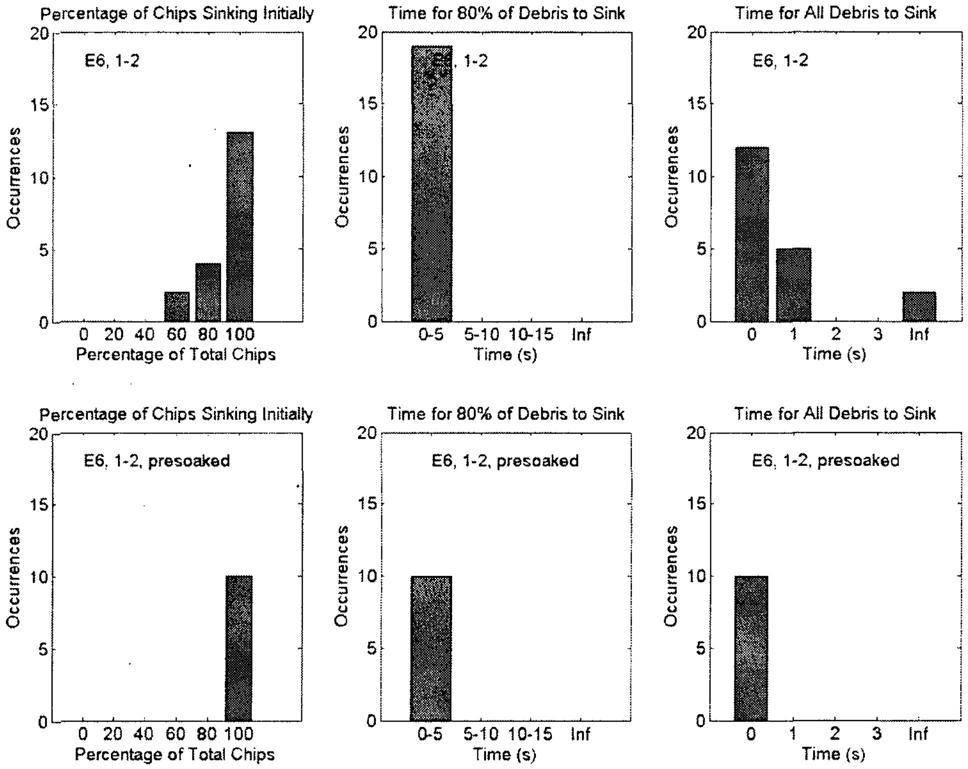


Figure C-10 E6, 1"-2", Flat, as Received, Time-To-Sink Test Results

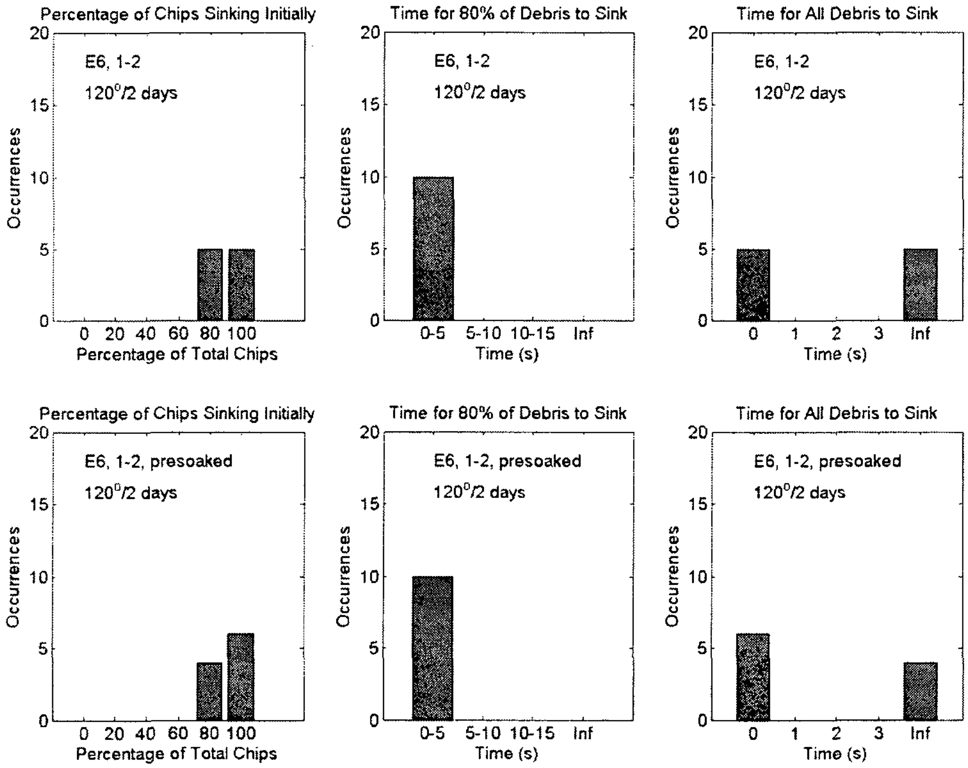


Figure C-11 E6, 1"-2", Flat, Thermally Cured at 120° F for 2 Days, Time-To-Sink Test Results

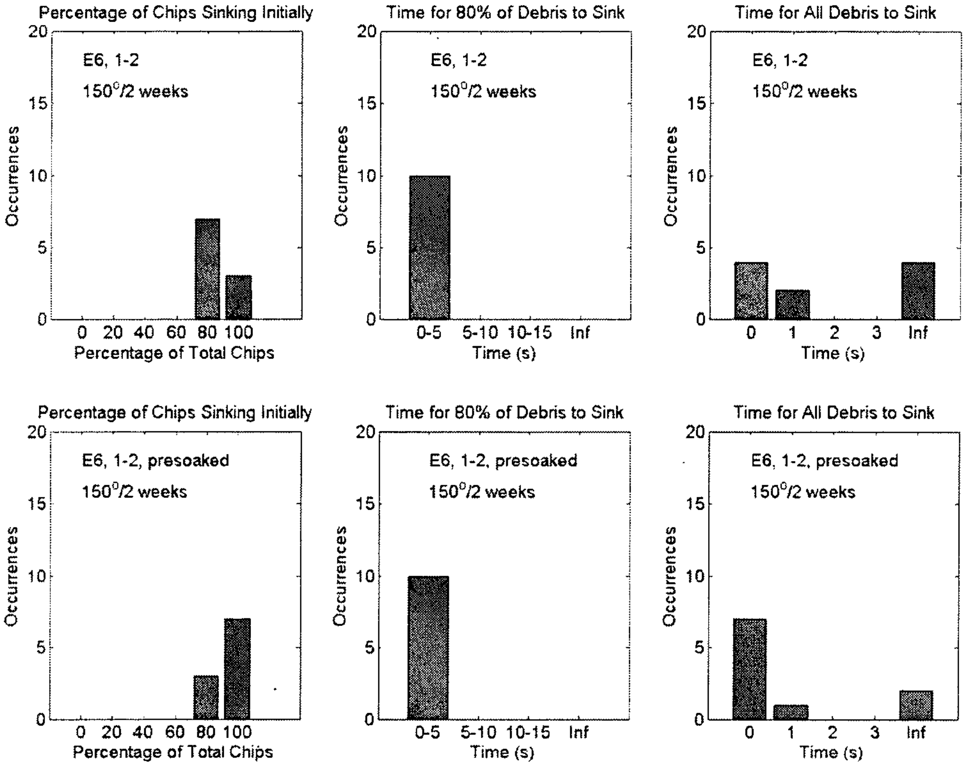


Figure C-12 E6, 1"-2", Flat, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

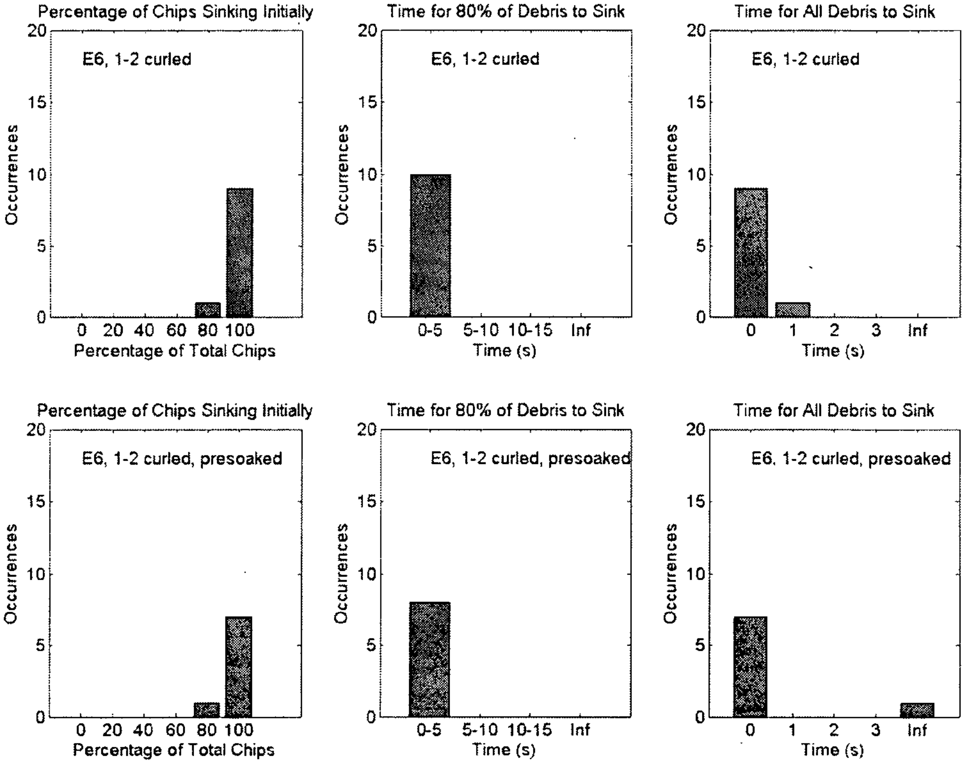


Figure C-13 E6, 1"-2", Curled, as Received, Time-To-Sink Test Results

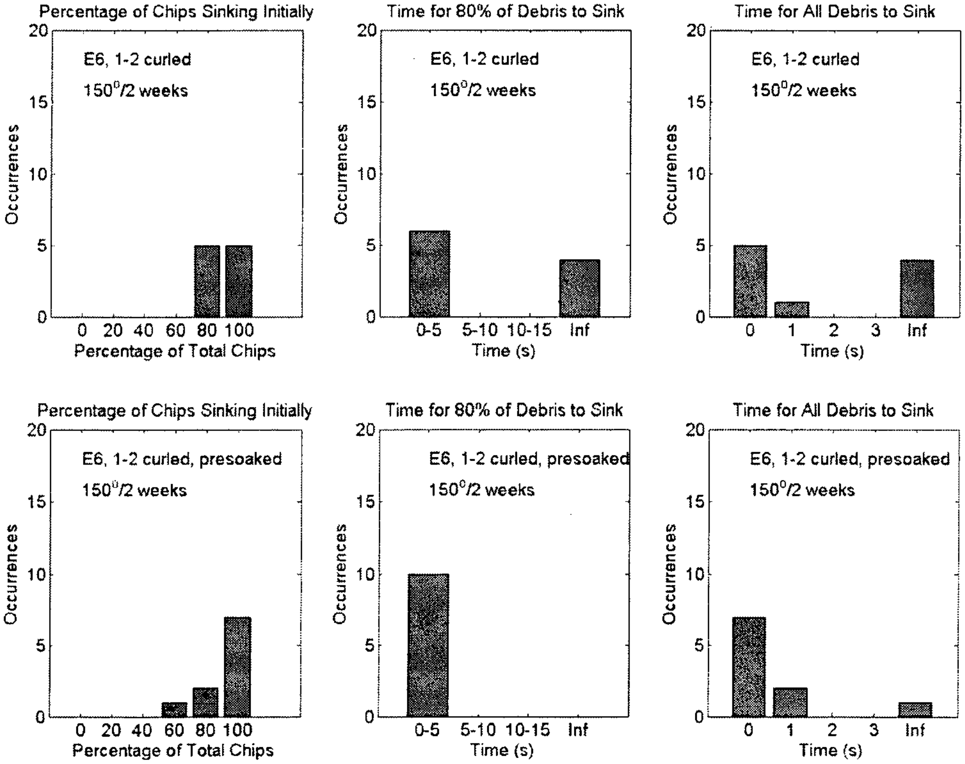


Figure C-14 E6, 1"-2", Curled, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

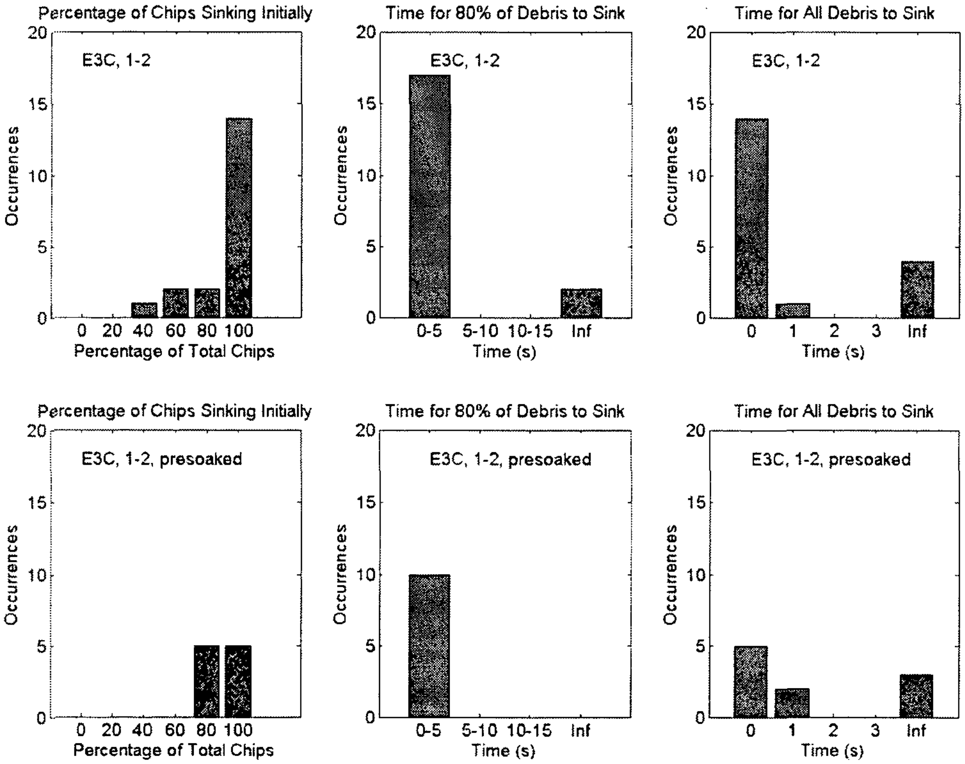


Figure C-15 E3C, 1"-2", Flat, as Received, Time-To-Sink Test Results

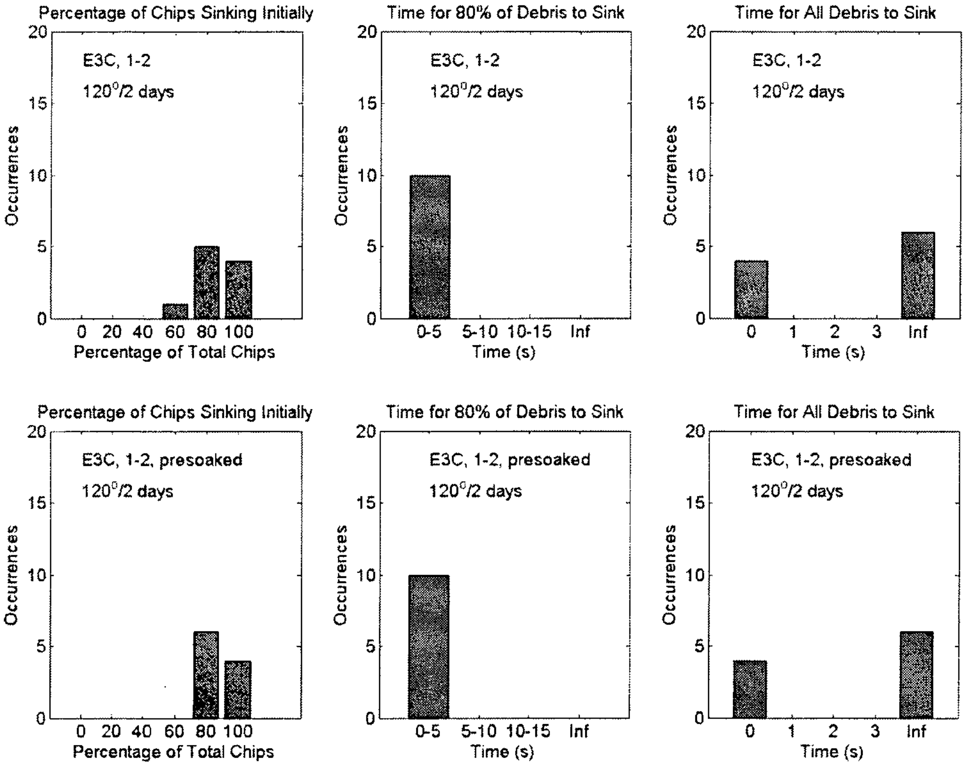


Figure C-16 E3C, 1"-2", Flat, Thermally Cured at 120° F for 2 Days, Time-To-Sink Test Results

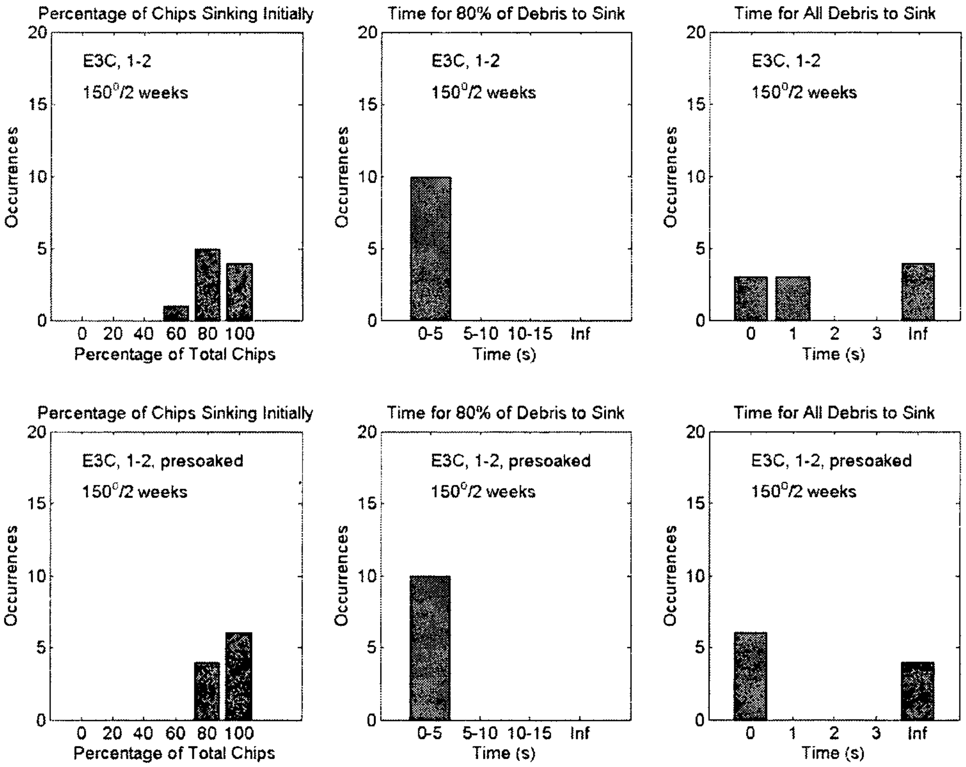


Figure C-17 E3C, 1"-2", Flat, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

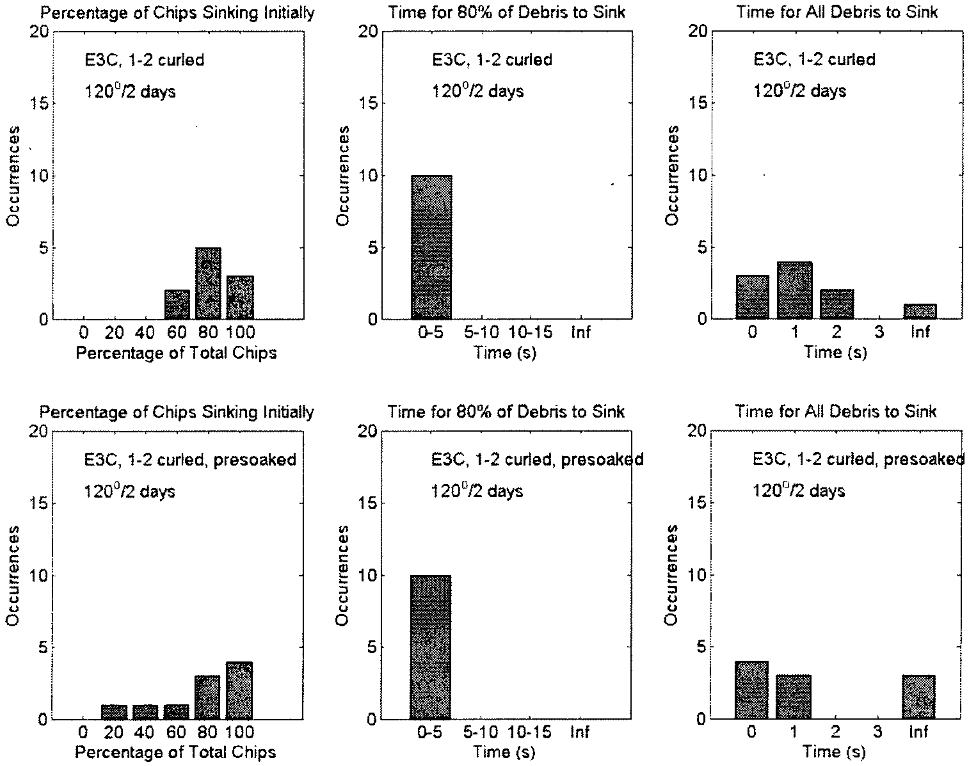


Figure C-18 E3C, 1"-2", Curled, Thermally Cured at 120° F for 2 Days, Time-To-Sink Test Results

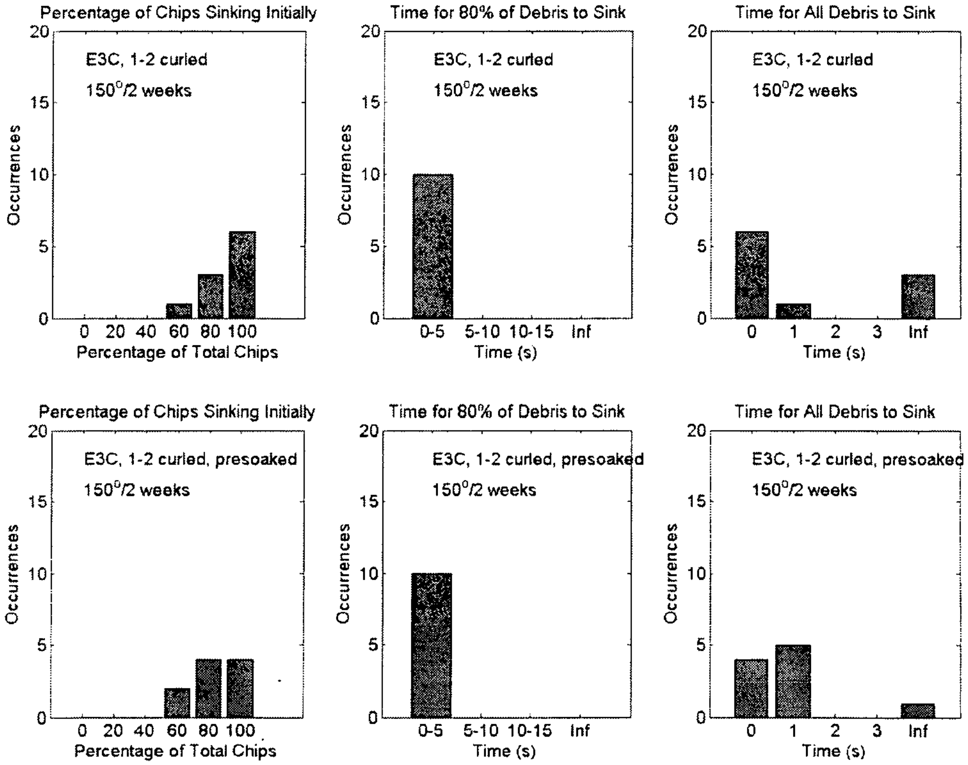


Figure C-19 E3C, 1"-2", Curled, Thermally Cured at 150° F for 2 Weeks, Time-To-Sink Test Results

APPENDIX D: PROCEDURE FOR TERMINAL VELOCITY TESTS

1) Count 5-10 pieces from sample for larger pieces. Weigh sample. For small pieces (1/64" to 1/32") weigh out 1 gram of chips.
2) Take digital picture of sample spread on light or dark background, depending on paint chip color in order to perform size characterization. Record picture number and test number on test sheet.
3) Presoak particles in 140 degree Fahrenheit water for 20 minutes.
4) Record water surface tension.
5) Place test sample under the surface of the water.
6) Release sample.
7) Record video images of sinking paint chips.
8) Save images to folder identifying sample number and record in test log.
9) Repeat until at least 100 chips are shown in videos.

APPENDIX E: PROCEDURE FOR TUMBLING VELOCITY TESTS

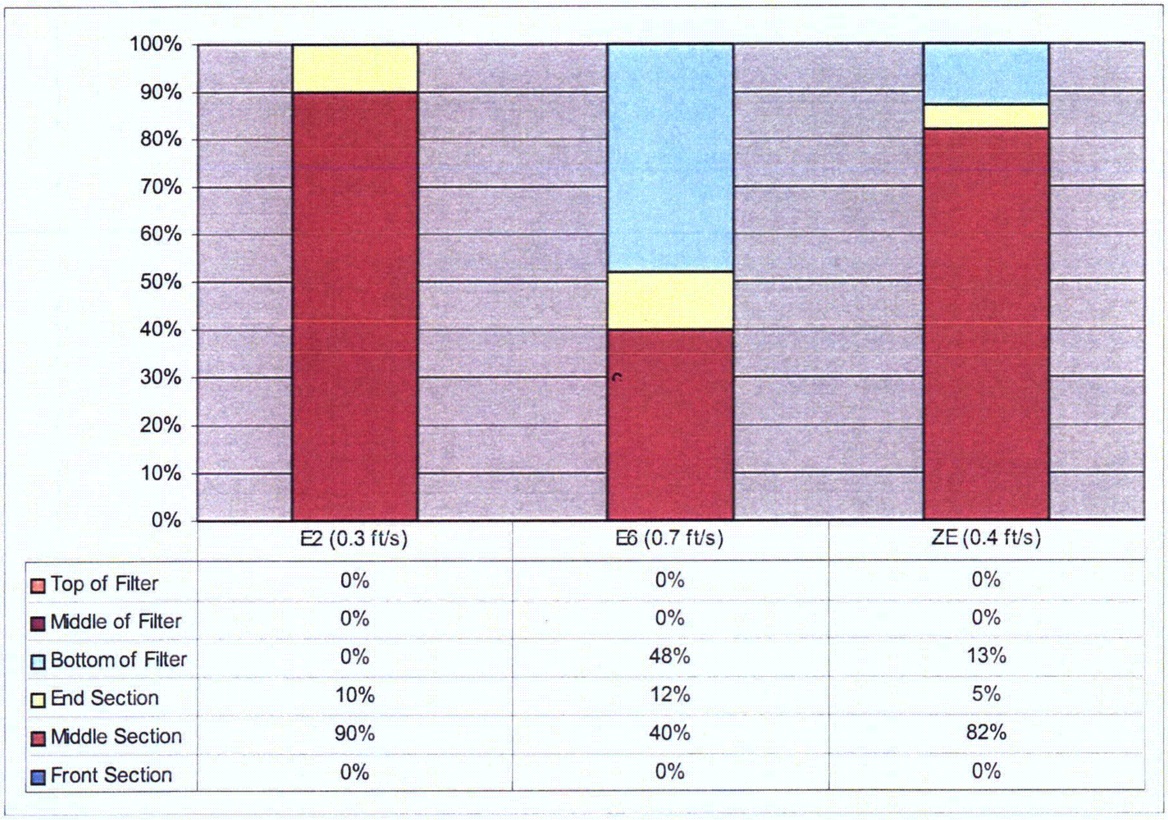
1) Count 5-10 pieces from sample for larger chips. Weigh sample. For small pieces (1/64" to 1/32") weigh out 1 gram of particles.
2) Take digital picture of sample spread on light or dark background, depending on paint chip color in order to perform size characterization. Record picture number and test number on test sheet.
3) Presoak particles in 140 degree Fahrenheit water for 20 minutes.
4) Place test sample on the tank floor inside marked area where the sample is viewable by the camera.
5) Start recording video and acoustic Dopler velocimeter (ADV) velocity.
6) Slowly increase flume velocity until all chip have been brought into suspension.
7) Save images to folder identifying sample number and record in test log.
8) Repeat this process for at least 50 particles.

APPENDIX F: PROCEDURE FOR TRANSPORT TEST

1) Count 5-10 pieces from sample for larger pieces. Weigh sample. For small pieces (1/64" to 1/32") weigh out 1 gram of chips.
2) Take digital picture of sample spread on light or dark background, depending on paint chip color in order to perform size characterization. Record picture number and test number on test sheet.
3) Set flume velocity to desired test velocity.
4) Place chips into release chamber and close door.
5) Insert release chamber into tank.
6) Start recording video and acoustic Doppler velocimeter (ADV) velocity.
7) Release chips into tank.
8) Continue recording images and data until all chips stops moving.
9) Record the number of chips pieces in each section of the tank and filter.
10) Save images to folder identifying sample number and record in test log.
11) Repeat this process for at least 50 chips.

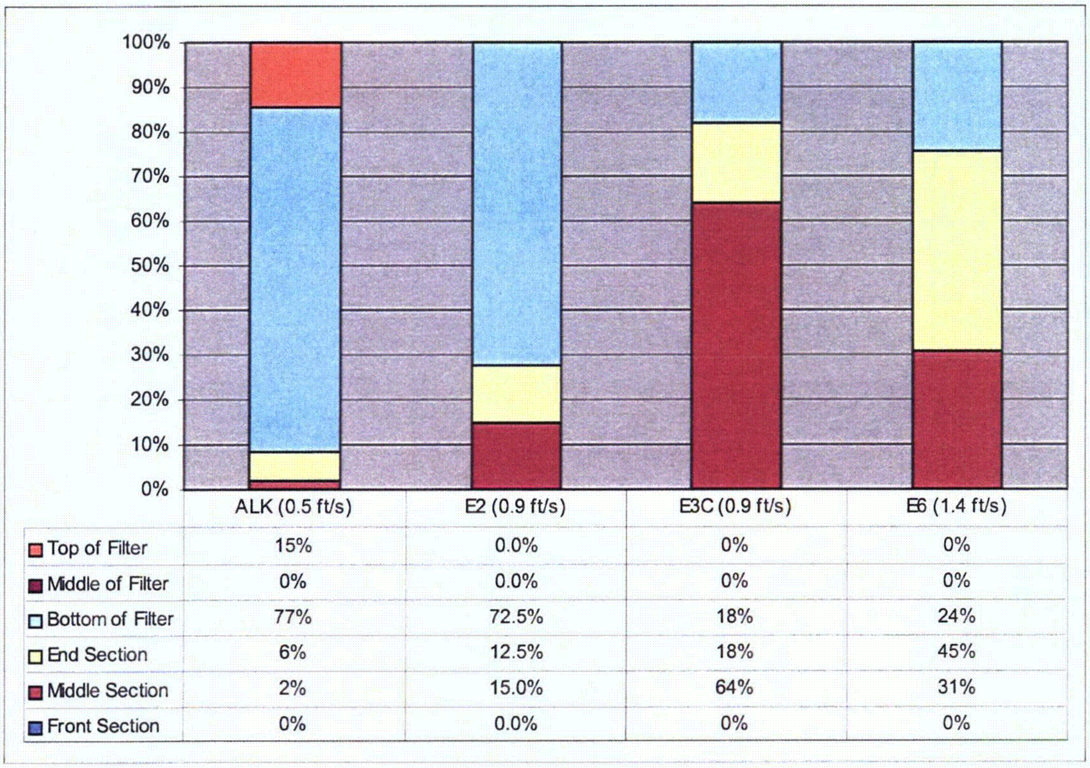
APPENDIX G: RESULTS FOR STEADY-STATE TRANSPORT TEST

Appendix G contains plots summarizing the degree of transport of each of the coating systems and size ranges tested. The plots show the location in the flume where the chips came to rest or the section of the filter on which the chips were captured, as applicable. In these plots, the "front section" represents the flume section within 0.3 meter (1 foot) of the chip release point, the "middle section" represents the flume section from 0.3 to 4 meters (1 to 13 feet) of the chip release point, and the "end section" represents the flume section from 4 to 6.7 meters (13 to 22 feet) of the chip release point. (The end of the flume and the location of the collection filter are 7.7 meters (22 feet from the release point)). Any chip reaching the filter has traveled the entire length of the tank and, therefore, are considered to transport. At the filter, the "top" represents the upper 0.08 m (3 in) of the stream, the "middle" is the central 0.6 m (24 in) of the stream, and the "bottom" represents the bottom 0.08 m (3 in) of the stream.



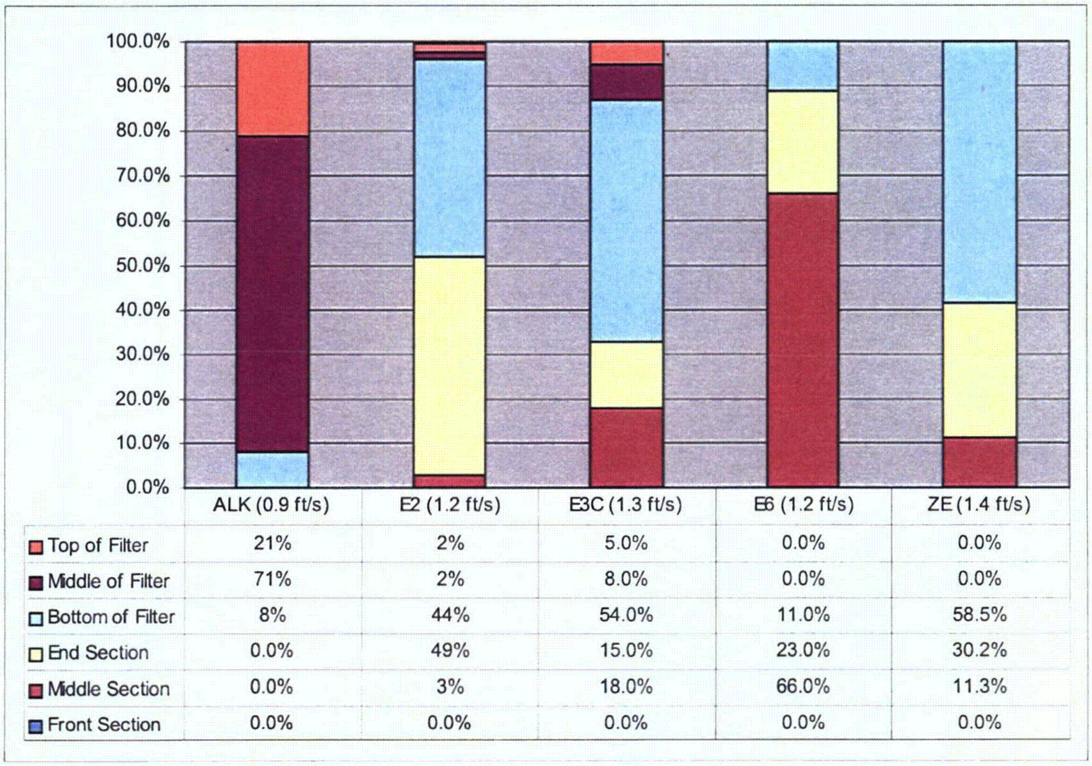
	E2 (0.3 ft/s)	E6 (0.7 ft/s)	ZE (0.4 ft/s)
Top of Filter	0%	0%	0%
Middle of Filter	0%	0%	0%
Bottom of Filter	0%	48%	13%
End Section	10%	12%	5%
Middle Section	90%	40%	82%
Front Section	0%	0%	0%

Figure G-1 Transport Test Results for Curled, 1"-2" Chips, at the Bulk Tumbling Velocity



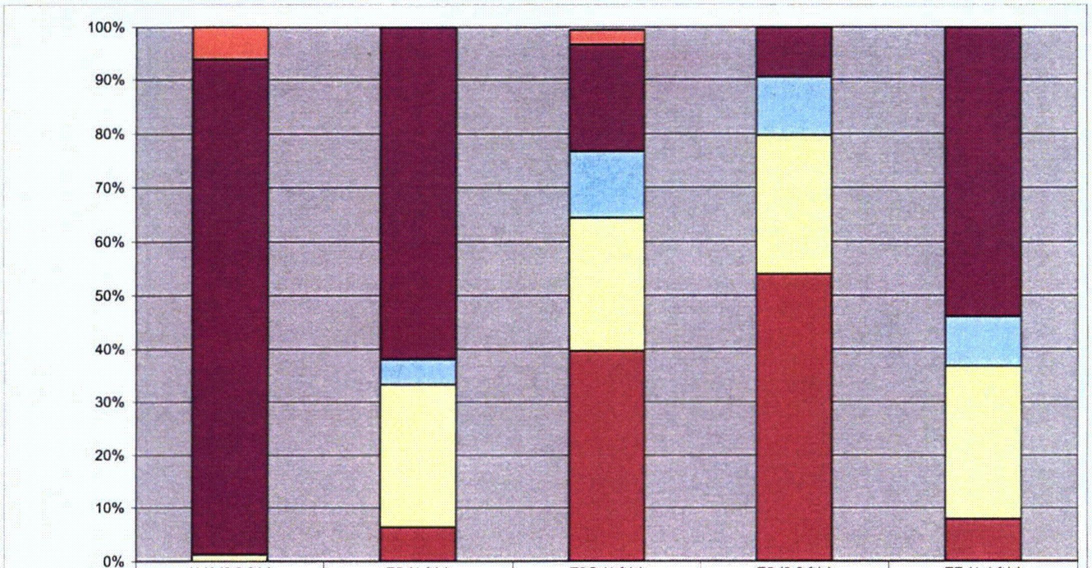
	ALK (0.5 ft/s)	E2 (0.9 ft/s)	E3C (0.9 ft/s)	E6 (1.4 ft/s)
🟥 Top of Filter	15%	0.0%	0%	0%
🟥 Middle of Filter	0%	0.0%	0%	0%
🟦 Bottom of Filter	77%	72.5%	18%	24%
🟨 End Section	6%	12.5%	18%	45%
🟥 Middle Section	2%	15.0%	64%	31%
🟦 Front Section	0%	0.0%	0%	0%

Figure G-2 Transport Test Results for Flat, 1"-2" Chips, at the Bulk Tumbling Velocity



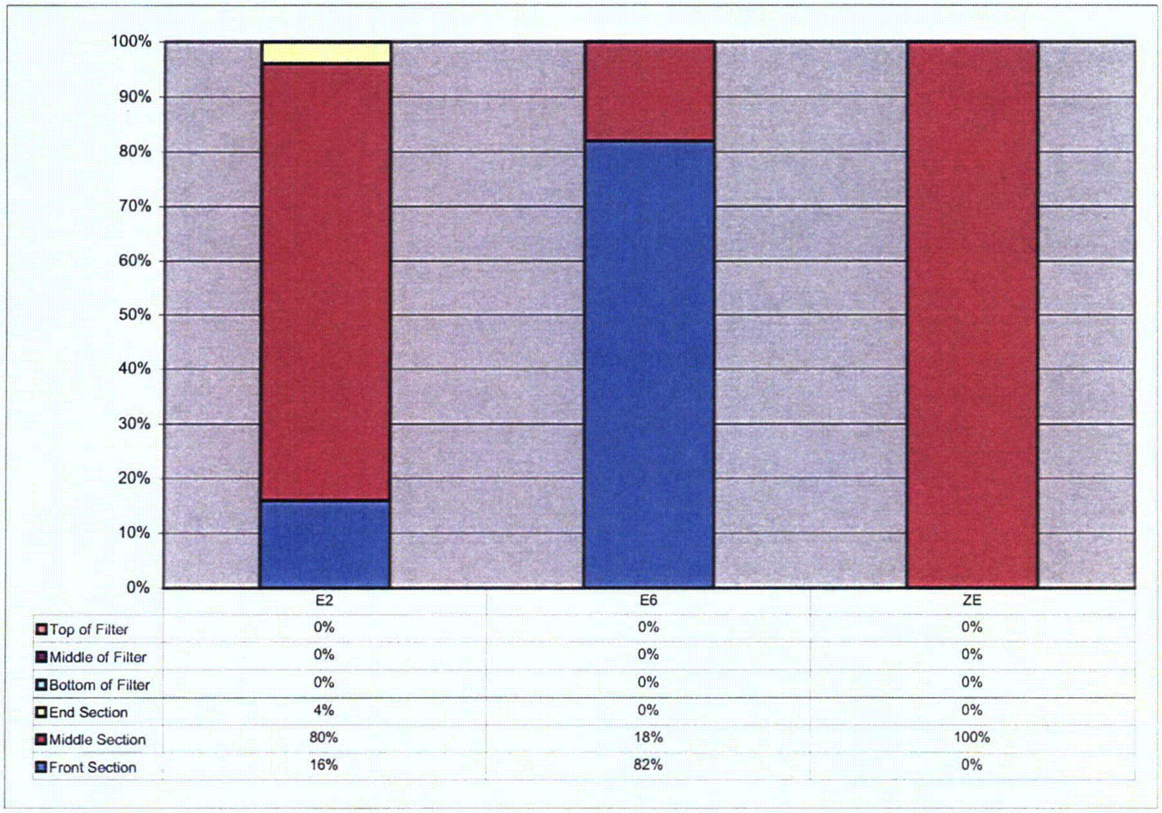
	ALK (0.9 ft/s)	E2 (1.2 ft/s)	E3C (1.3 ft/s)	E6 (1.2 ft/s)	ZE (1.4 ft/s)
🟥 Top of Filter	21%	2%	5.0%	0.0%	0.0%
🟫 Middle of Filter	71%	2%	8.0%	0.0%	0.0%
🟦 Bottom of Filter	8%	44%	54.0%	11.0%	58.5%
🟨 End Section	0.0%	49%	15.0%	23.0%	30.2%
🟥 Middle Section	0.0%	3%	18.0%	66.0%	11.3%
🟦 Front Section	0.0%	0.0%	0.0%	0.0%	0.0%

Figure G-3 Transport Test Results for 1/8”-1/4” Chips, at the Bulk Tumbling Velocity



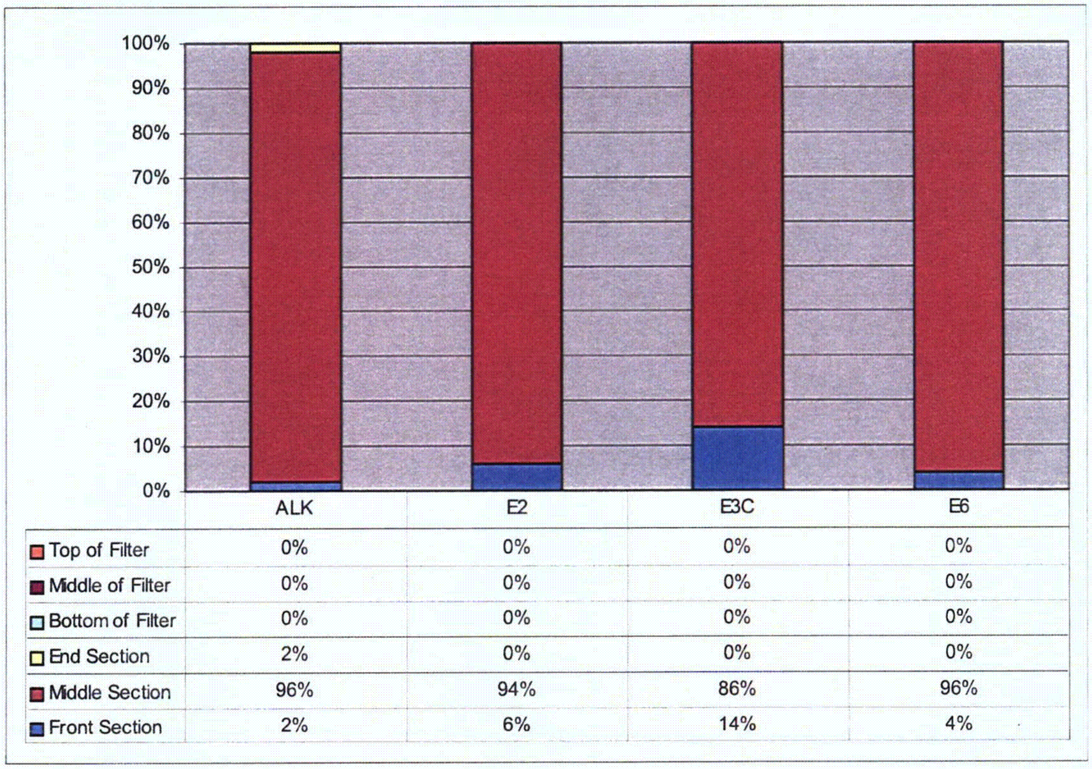
	ALK (0.9 ft/s)	E2 (1 ft/s)	E3C (1 ft/s)	E6 (0.8 ft/s)	ZE (1.4 ft/s)
🟧 Top of Filter	6%	0%	3%	0%	0%
🟫 Middle of Filter	93%	62%	20%	9%	54%
🟦 Bottom of Filter	0%	5%	12%	11%	9%
🟨 End Section	1%	27%	25%	26%	29%
🟥 Middle Section	0%	6%	40%	54%	8%
🟦 Front Section	0%	0%	0%	0%	0%

Figure G-4 Transport Test Results for 1/64”-1/32” Chips, at the Bulk Tumbling Velocity



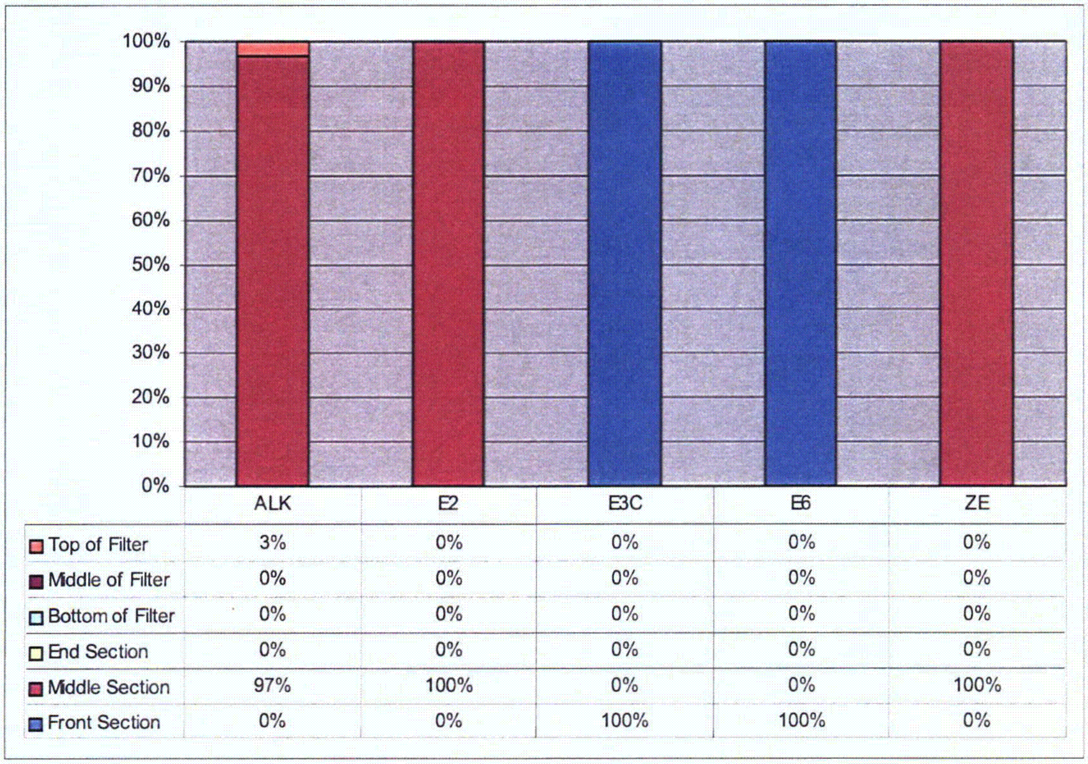
	E2	E6	ZE
🟥 Top of Filter	0%	0%	0%
🟪 Middle of Filter	0%	0%	0%
⬜ Bottom of Filter	0%	0%	0%
🟨 End Section	4%	0%	0%
🟥 Middle Section	80%	18%	100%
🟦 Front Section	16%	82%	0%

Figure G-5 Transport Test Results for Curled, 1"-2" Chips, at 0.2 ft/s



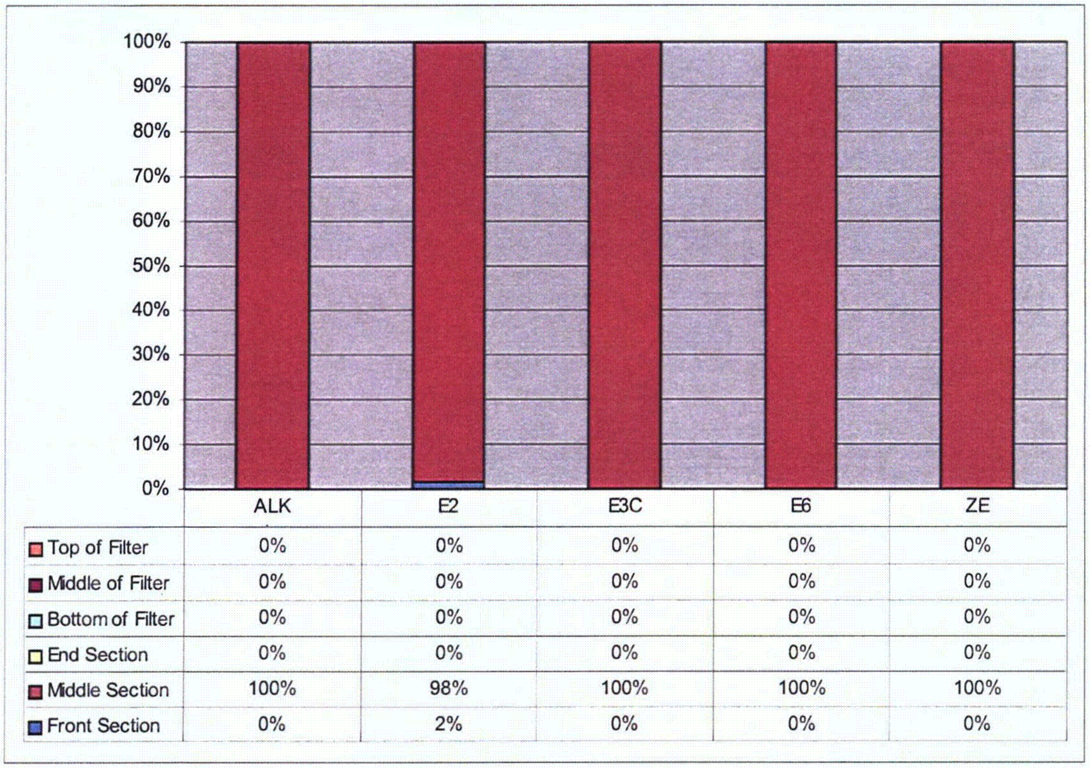
	ALK	E2	E3C	E6
🟥 Top of Filter	0%	0%	0%	0%
🟪 Middle of Filter	0%	0%	0%	0%
⬜ Bottom of Filter	0%	0%	0%	0%
🟨 End Section	2%	0%	0%	0%
🟥 Middle Section	96%	94%	86%	96%
🟦 Front Section	2%	6%	14%	4%

Figure G-6 Transport Test Results for Flat, 1"-2" Chips, at 0.2 ft/s



	ALK	E2	E3C	E6	ZE
🟧 Top of Filter	3%	0%	0%	0%	0%
🟪 Middle of Filter	0%	0%	0%	0%	0%
☐ Bottom of Filter	0%	0%	0%	0%	0%
🟨 End Section	0%	0%	0%	0%	0%
🟥 Middle Section	97%	100%	0%	0%	100%
🟦 Front Section	0%	0%	100%	100%	0%

Figure G-7 Transport Test Results for 1/8"-1/4" Chips, at 0.2 ft/s



	ALK	E2	E3C	E6	ZE
🟥 Top of Filter	0%	0%	0%	0%	0%
🟥 Middle of Filter	0%	0%	0%	0%	0%
□ Bottom of Filter	0%	0%	0%	0%	0%
□ End Section	0%	0%	0%	0%	0%
🟥 Middle Section	100%	98%	100%	100%	100%
🟦 Front Section	0%	2%	0%	0%	0%

Figure G-8 Transport Test Results for 1/64”-1/32” Chips, at 0.2 ft/s

APPENDIX H: COATING SYSTEMS SAMPLE PREPARATION

Samples of five containment coatings systems were prepared for transport testing. Nuclear Regulatory Commission (NRC) staff initiated contact with coatings manufactures and down-selected to the five systems from three manufactures as shown in Table H-1. These included a single coat alkyd, four epoxy systems, and a inorganic zinc/epoxy system. Three of these were Nuclear Service Level I coatings qualified for in-containment use. The coating systems are listed in Table H-1.

Table H-1. Coatings Systems for Manufacture – Transport Tests

System Code	**Nuclear Service Level 1**		
ALK	no	Manufacturer	Ameron
		Coating type	Alkyd topcoat
		Components	Amercoat 5450 (one coat)
ZE	yes	Manufacturer	Ameron
		Coating type	Inorganic zinc primer/epoxy topcoat
		Components	Dimetcote 6 (one coat) followed by Amercoat 90 (two coats)
E2	yes	Manufacturer	Carboline
		Coating type	Two-layered all epoxy system
		Components	Carboguard 890N (two coats)
E6	no	Manufacturer	Carboline
		Coating type	Six-layered all epoxy system
		Components	Carboguard 890N (six coats)
E3C	yes	Manufacturer	Keeler & Long
		Coating type	Multi-layered epoxy system for concrete
		Components	KL4129 epoxy sealer (one coat) followed by KL6548S epoxy surfacer (one coat) followed by KLD1 epoxy topcoat (two coats)

Three original requirements were set for the samples:

- Quantity required for each coating system was 125 ft^2
- Size distribution requirement for each coatings system was that >25% of chips must be > 1-inch average width.
- Preparation of the samples should be as close as possible to that used for the original application.

Transport testing required coatings samples that were free from the underlying substrate. In typical applications, this substrate would be either concrete or steel. Since the coating is not easily removed from these materials, the approach recommended by all three manufacturers was to apply the coating onto plastic sheets. After drying/curing, the coating layer could be removed from the plastic sheets for further sample preparation. This recommended practice was followed by all three manufacturers. The samples were shipped to the test facility adhered to the plastic sheets, rolled, folded up, or cut into smaller sheets to fit in a box for shipping. Removal of the coatings from the sheeting was accomplished by the testing laboratory.

Other than the difference in substrate and a modified procedure for one sample that is described below, application procedures followed the recommended guidelines for each coating or coatings system. Quality assurance documentation provided with each sample is described below.

For Nuclear Service Level 1 Coating System Samples (sample codes ZE, E2 and E3C):

1) Certification that the coating system was applied according to application procedures for the Nuclear Service Level 1 coating system, plus a copy of that procedure and sample preparation sheets completed during the application.
2) Material certifications for components in the coating system.

For non-Nuclear Service Level 1 Coating System Samples (sample codes ALK and E6):

1) Application should follow good industrial practice for the coating system. Provide application procedure used and sample preparation sheets completed during the application.
2) Coatings Shelf-Life Certification.

A modified process was used with Ameron's zinc primer/epoxy topcoat sample (system code ZE). For this sample, it was found that the inorganic zinc primer would become brittle and crack if dried for the recommended time. Subsequent application of the epoxy coat could not be made without spalling off much of the cracked primer. To produce a uniformly layered sample, the normal procedure was modified to allow a shortened drying time for the primer. Also, rather than applying two coats of epoxy (Amercoat 90) a thicker single coat was applied. This also helped eliminate the cracking and spalling experienced when applying a second epoxy coat. The dry film thickness (DFT) of the thicker single coat was 5 mils (0.005 inch) as compared with the 8 mil recommended thickness of the two epoxy layers. Ameron has successfully tested this coating system in design basis accident (DBA) tests when the epoxy DFT is 5 mils.

The Ameron and Keeler & Long samples were prepared in the respective manufacturers' facilities. The Carboline samples were prepared by a subcontractor, Corrosion Control Consultants & Labs CCC&L, in accordance with Carboline application procedures and Carboline furnished coating material.

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10. SUPPLEMENTARY NOTES

E. L. Geiger, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Generic Safety Issue (GSI)-191 "Assessment of Debris Accumulation on PWR Sump Performance" raised the concern of debris transport to pressurized-water-reactor (PWR) sump screens following a loss-of-coolant accident (LOCA) and subsequent impact to emergency core cooling systems (ECCS) and containment spray systems (CSS) during ECCS sump recirculation. Failed coatings are a potential source for debris transported to the ECCS sump screens. This NUREG/CR describes a limited number of tests conducted to study the transportability of coatings debris (chips) in ambient temperature water, at specific conditions of uniform flow. Five coating systems, typical of coatings applied to surfaces of equipment and structures located in the containment buildings of PWR plants, were tested. The effect of chip size, chip shape, chip density, chip thickness, and stream velocity were examined through two types of tests--Quiescent settling test and uniform flow transport test. A statistically meaningful number of data test were conducted for each coating type, chip size and shape in each test category in order to more accurately quantify observations. It is intended that the transport parameters observed in these tests be applied, as appropriate, in the evaluation of coating chip transport under plant-specific conditions.

The quiescent tests demonstrated that coating chips, having a specific gravity of 1.0 to 1.1, dropped onto the water surface tended to remain on the water surface indefinitely and heavier chips tended to sink almost immediately. However, even with heavier chips, a small percentage of chips did not sink initially and remained on the surface indefinitely. The transport tests demonstrated that the transport of submerged coating chips of all densities tested is insignificant at stream velocities less than 0.2 feet per second.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Coatings debris
Debris transport
Emergency Core Coolong System
Blockage
Clogging
Flow testing
Quiescent testing

13. AVAILABILITY STATEMENT

unlimited

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