US Army Corps of Engineers®
Cold Regions Research & Engineering Laboratory

Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Progress in Evaluating Surface Coatings for Icing Control at Corps Hydraulic Structures

Removal of accreted ice during the winter at Corps hydropower and navigation projects is time-consuming, costly, and sometimes hazardous. Annual maintenance costs incurred at Corps of Engineers projects as a result of ice problems were estimated by Haynes et al. (1993) to be $33 million in 1992 (Fig. 1). A previous issue of *Ice Engineering* (Haehnel 2002) described an ongoing icing research program at the Cold Regions Research and Engineering Laboratory (CRREL), part of the Corps' Engineer Research and Development Center (ERDC). Program tasks included an assessment of thermoplastics and spray-on coatings for reducing the cost of icing control at Corps projects. The goal of the research effort is to determine whether commercially available surface coatings and thermoplastic cladding materials can make icing control more economical. In this issue, we will discuss further progress made in this program in the form of laboratory and field tests.

Figure 1. Ice buildup on miter gate at a Mississippi River navigation lock.

Numerous materials, coatings, and paints having low friction properties are commercially available. Many are even marketed as "icephobic," the name implying that ice accretion is reduced or eliminated. Our research has shown that these materials will not prevent ice buildup. In fact, ice often builds on these materials at the same rate as on any other material. Instead, they typically reduce the force or energy required to remove it (i.e., the bond strength of the ice to the icephobic material is lower). For this reason, icephobics are sometimes used in conjunction with other ice removal techniques, such as heating, electro- or pneumatic expulsion, or—more often than not—baseball bats and pike poles.

How do we decide which materials or coatings to use? The choice involves an examination of at least four factors. These are 1) whether ice adhesion strength is significantly reduced, 2) the material's durability or longevity, 3) its cost, and 4) its ease of application. Our research provides the user with actual laboratory and field data on the first two of these factors. This information, combined with information available from the manufacturer on Factors 3 and 4, allows a project engineer to estimate the new material's potential benefit. It should be noted that a surface material having before-exposure ice adhesion qualities that are similar to another coating's after-exposure qualities might be considered equivalently suitable for field use at a Corps hydro facility, when lifetime benefit/costs are considered.

Laboratory testing

We have measured in the laboratory the adhesion strength of ice to common paints used by the Corps of Engineers for protecting steel hydraulic structures as well as that for several candidate icephobic coatings. The test apparatus is a cone configuration, typically used to evaluate the performance of adhesive joints (Anderson et al. 1977). In this configuration, an adhesive is used to bond concentric cones of variable angle to which an axial load is applied, so that the cones are pulled or pushed apart. By varying the cone angle, the relative amounts of shear and tension being applied to the adhesive joint can be controlled. We test using a cone angle of 0° (see concentric cylinders labeled as pile and mold shown in Figure 2), which predominantly loads the adhesive in shear. In our test, ice is the adhesive, and the inner cylinder (or pile) is either made entirely of the material to be evaluated, or it is a steel or aluminum pile coated with a candidate icephobic material. Several examples of test piles are shown in Figure 3.

Approximately 36 hours after the sample freezes and reaches a temperature of –10°C, it is loaded at a constant rate of 0.06 mm/min until the ice–pile bond fails. The measured load at the time the bond fails is used to compute the shear strength of the bond (the maximum load divided by pile–ice contact area). This is our indicator of the adhesive strength of the ice bonded to the material of interest. The adhesion value that we report for each material is typically an average value obtained from six replicates. This test procedure is fully described in Haehnel and Mulherin (1998).

Because the paints used by the Corps have been developed over many years for their high durability, a selected low-adhesion coating would be applied over the Corps paints rather than replacing them. Our laboratory test was designed to simulate this condition, and the coatings were layered over samples that already had the Corps paints applied. Since an alternate means of protection might be to clad an area with a low-adhesion material, several candidate thermoplastic materials were evaluated as well. Table 1 lists the paints, low-adhesion coatings, and thermoplastics tested in the laboratory.

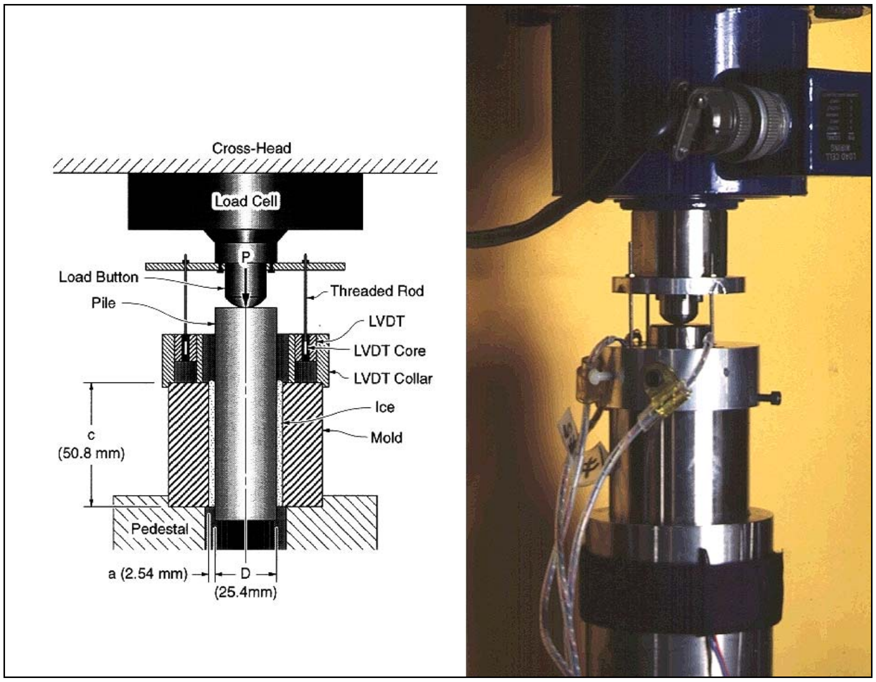


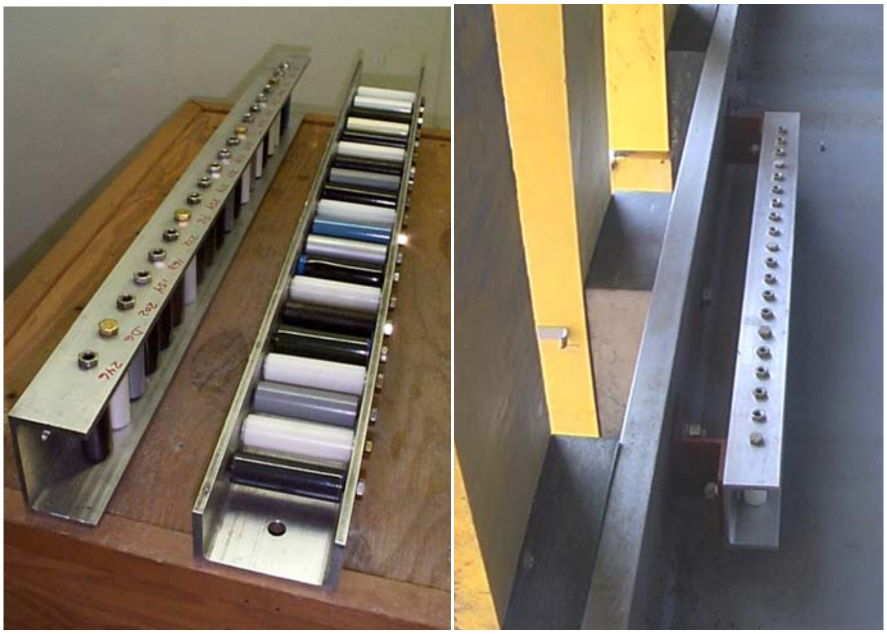
Figure 2. Zero-degree cone test configuration (left) and instrumented sample pile and mold in testing machine (right).

Figure 3. Several thermoplastic (front) and coated-steel sample piles (rear).

Table 1. Materials and coatings evaluated at CRREL using a 0° cone test to measure the adhesive shear strength of ice.

Construction Materials	
Material	**Composition**
Teflon	Polytetrafluoroethylene (PTFE) thermoplastic
UHMW Polyethylene	Ultra-high molecular weight polyethylene thermoplastic
Acetal	Acetal copolymer thermoplastic
Dupont Delrin	Polyoxymethylene homopolymer thermoplastic
Bare Carbon Steel	Cold rolled 1018
Bare Stainless Steel	Type 410
Bare Aluminum	Type 7075
Corps Paints	
Material	**Composition**
C-200a	Coal tar epoxy
V-102e	Vinyl resin, type 3 (18.2), aluminum powder (8.3) diisodecyl phthalate (3.1) methyl isobutyl ketone (33.8), toluene (36.6% by weight)
V-103c	Vinyl resin, type 3 (20), carbon black (1.5), diisodecyl phthalate (3.4), methyl isobutyl ketone (36.0), toluene (39.1% by weight)
V-766e	Vinyl resin, type 3 (5.6) and type 4 (11.6), titanium dioxide and carbon black (13.0), diisodecyl phthalate (2.9), methyl isobutyl ketone (32.0), toluene (34.7) ortho phosphoric acid (0.2% by weight)
MIL-P-24441C Type III	VOC-compliant polyamide epoxy
Commercial Low-Friction Coatings	
Material	**Composition**
BMS 10-60	BMS (Boeing Material Spec) 10-60 polyurethane over BMS 10-11 epoxy primer
Envelon	Resin-based ethylene acrylic acid copolymer
Inerta 160	Trimethyl hexamethylenediamine epoxy
Interlux Brightside	A one-part polyurethane finish coat with Teflon additive
Kiss-Cote	Kiss-Cote 1083 (polydimethyl siloxane) clear liquid wiped onto aluminum samples and Kiss-Cote MegaGuard (polydimethyl siloxane) clear liquid wiped onto steel samples
PSX-700	Siloxane and polyurethane epoxy
SA-RIP-4004	Saturated polyester resins modified with fluorotelomer intermediates activated with a biuret of HDI
Slip Plate #1	Natural graphite coating in mineral spirits
Troyguard	Fluoropolymer suspension in mineral spirits mixed with clear acrylic urethane
Troyguard/BMS 10-60	Fluoropolymer suspension in mineral spirits mixed with BMS 10-60 polyurethane
WC-1-ICE	Saturated polyester resins in fluoropolyol with PTFE and organofunctional silicone fluid additives, modified with a fluorotelomer intermediate, and activated with a trimer of HDI
Wearlon	Water-based, methyl silicone copolymer epoxy

a. Miter gate with yellow, ice-covered rub rails, similar to gate where test piles were fielded.



b. (Left) Two sample racks, each with 20 piles randomly ordered for field testing. (Right) Sample rack in place behind gate rub rails.

Figure 4. Exposure test configuration.

Field testing

After laboratory testing at CRREL, the sample piles were mounted in random order in six test racks of 20 samples each and installed below the full-pool elevation at Mississippi River Lock and Dam 25 (near St. Louis) in mid-January 2002. Here, the samples were subject to periodic draining and flooding associated with normal locking operations. (Figure 4 shows the exposure test configuration.) After six and a half months (mid-January to August 2002) of exposure to cyclical drying and wetting, and abrasion from ice, suspended sediment, and debris, the samples were returned to CRREL. After washing with a mild detergent, they were retested for ice adhesion. The samples were then re-racked, returned to Lock and Dam 25, and reinstalled below waterline in November 2002. Plans call for them to be retested at CRREL after another year of field exposure.

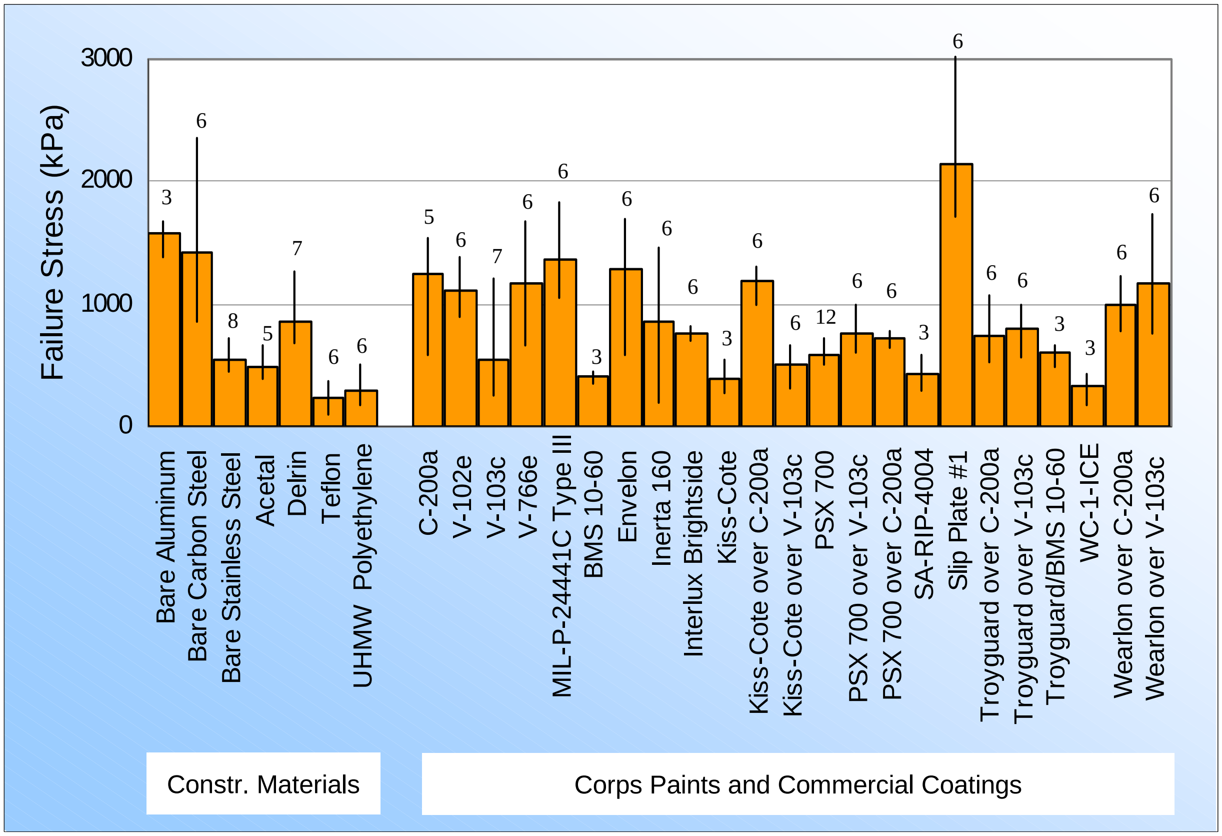


Figure 5. Results of laboratory ice adhesion shear testing of some construction materials, USACE paints, and commercial icephobic coatings. Error bars indicate the range in test values, numbers represent the number of that sample type tested, and the height of each column is the measured mean value.

Results

Figure 5 shows the results of our laboratory adhesion tests for the various coatings and materials in their new condition. The height of each bar indicates the average failure stress measured for each material; the error bars indicate the range in values measured for the entire coating or material group. The number at the top of each error bar shows the sample size.

Teflon and polyethylene had the lowest average adhesion strengths, as do the commercial coatings WC-1-ICE and Kiss-Cote, which were each applied to aluminum piles. On carbon steel piles, we found that the V-103c vinyl paint performed as well as PSX-700. In fact, all the icephobics except Kiss-Cote *increased* the mean adhesion strength for V-103c, though not significantly. Although the V-103c vinyl paint by itself appears to significantly lower ice adhesion, this is not generally true for the other paints typically used by the Corps. The V-766e and V-102e had average adhesion strengths that were only 20–25% less than bare carbon steel, and epoxies C-200a and MIL-P-24441C Type III have adhesion strengths about the same as bare carbon steel. Furthermore, using the Wilcoxon Ranked Sum test, we found that there was no statistical difference, at the 95% confidence interval, between the performance of the V-103c and any of the coatings applied to it. However, there was a statistical difference between C-200a alone and C-200a with TroyGuard applied over it. Furthermore, we found that all the icephobic coatings except Kiss-Cote reduced the mean adhesion strength for the C-200a coal tar epoxy, with both PSX-700 and TroyGuard reducing the adhesion strength by about 40 percent.

Table 2 and Figure 6 show the results of laboratory adhesion test comparisons before and after field exposure of the sample piles. The table lists their standard deviations, whereas the figure shows the data ranges with the use of error bars. These results show that, in most cases, there was no statistically significant difference in the before-and-after adhesion strengths (the orange data, Figure 6). These materials all seemed to hold up well in this six-month field trial, both in qualitative appearance of their general condition, and as measured by relatively little difference in ice adhesion.

Table 2. Before- and after-exposure ice adhesion stress values, in kPa, for materials and coatings. Percentage changes in boldface type were statistically significant at the 95% confidence interval.

Material	Pre-Exposure Shear Stress (kPa)		Post-Exposure Shear Stress (kPa)		Change in Mean Value (%)
	Mean	Standard Deviation	Mean	Standard Deviation	
Thermoplastics					
Acetal	544.6	147.5	355.7	94.8	**–35**
Delrin	864.3	213.4	508.5	334.9	**–41**
Teflon	237.8	103.0	230.2	343.5	–3
UHMWPE	294.8	120.7	179.9	65.4	–39
Off-the-Shelf-Coatings					
PSX-700	659.3	48.0	977.7	52.8	**48**
Inerta	851.8	500.3	563.2	191.3	–56
Envelon	1279.0	403.0	983.8	72.5	–23
Standard USACE Lock Coatings					
MIL-P-24441	1361.8	260.7	1408.3	327.4	3
V-102e	1119.7	180.7	1373.7	290.2	23
V-766e	1164.5	348.9	957.3	163.9	–18
V-103c	536.0	237.9	725.1	233.2	35
C-200a	1250.6	396.8	1317.3	414.6	5
Standard Lock + Off-the-Shelf Coatings					
V-103c + PSX-700	765.8	139.5	959.7	46.2	**25**
V-103c + TroyGuard	795.9	168.5	643.3	170.4	–19
V-103c + Wearlon	1162.7	418.3	1219.2	155.9	5
V-103c + Kiss-Cote	497.9	143.7	657.6	69.7	**32**
C-200a + Kiss-Cote	1196.3	110.5	1503.7	200.3	**26**
C-200a + Wearlon	984.7	145.7	1124.1	152.6	14
C-200a + PSX-700	729.6	60.8	729.2	139.2	0
C-200a + TroyGuard	732.6	188.3	670.4	125.9	–8

Notably, two of the thermoplastics, Acetal and Delrin, even had significantly lower after-exposure ice adhesion values. Four of the coating combinations, however, had statistically significantly higher after-exposure values. Both the C-200a and V-103c Corps paints having Kiss-Cote applied over them yielded higher average adhesion values, indicating that the clear, liquid (invisible, after it dries) Kiss-Cote material had eroded away during the six-month exposure period. This conclusion is consistent with the measured adhesion strengths for both of these samples after they were weathered; each sample had adhesion values in the same range as the comparable uncoated and weathered Corps paint samples. This indicates that even though Kiss-Cote is effective at reducing the adhesion strength of ice when newly applied, it may require annual, or more frequent reapplication.

The PSX-700 epoxy coating both by itself and over the V-103c Corps paint yielded higher after-exposure adhesion values. However, the PSX-700 coating did not bond well to the underlying V-103c. One of these six replicates was damaged when portions of the coating peeled during the before-exposure adhesion testing, and most of the "PSX-700 over V-103c" samples returned from the field with flaking in the outer coating, revealing the Corps paint beneath. This particular system's durability, both in the laboratory and field testing, was limited as a result of poor bonding between the outer PSX-700 and the V-103c undercoat. The PSX-700 by itself appeared to withstand the field trial very well (its general condition was excellent) even though its ice adhesion values increased.

Conclusions

Icephobic materials do not prevent ice formation on exposed structures. Instead, they lower the adhesion strength of ice and therefore may be considered as enhancements to other ice removal methods, such as mechanical, steam, electro-thermal, or electro-mechanical. Laboratory and field-exposure results provide information that can assist in evaluating the relative performance of materials and coating systems. "Performance" of the coating systems was measured in terms of durability and the strength with which ice adheres to each system before and after field exposure.

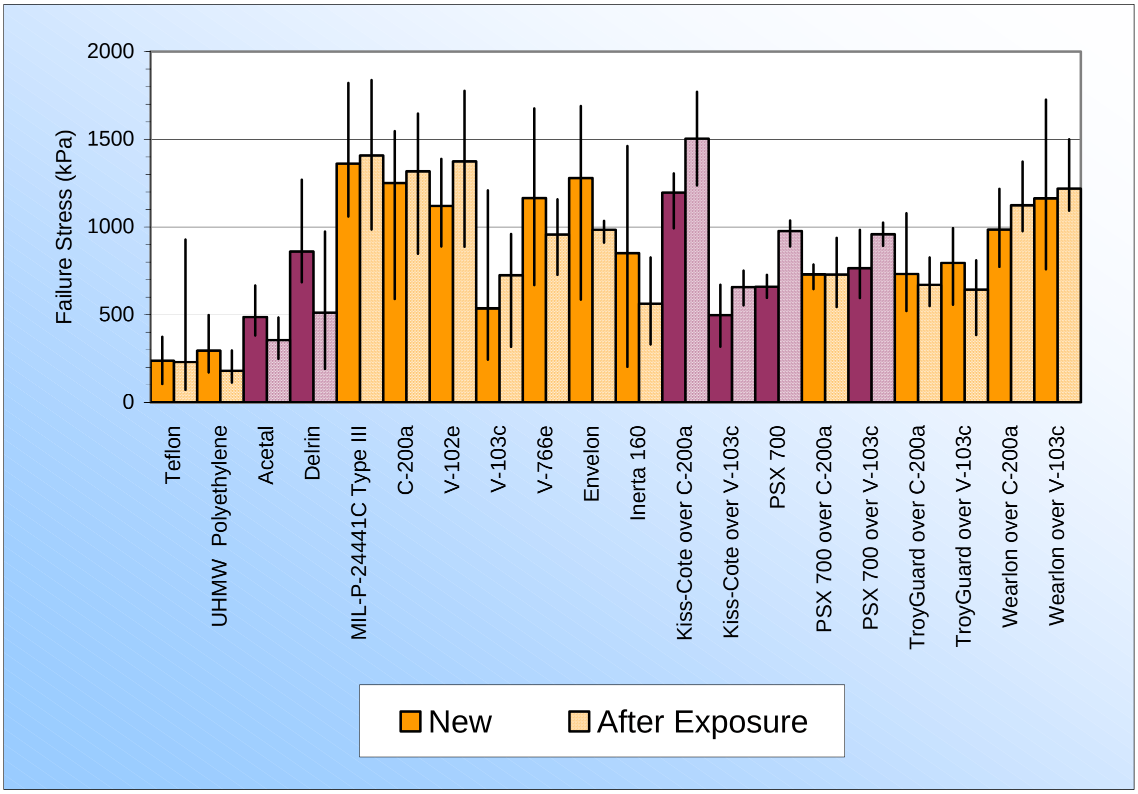


Figure 6. Comparison of laboratory shear testing before and after field exposure. Error bars indicate the range of six replicate samples, and the height of each column is the measured mean value. Orange data represent materials that exhibited no statistically significant difference between the average before- and after-exposure values. Purple data were significantly different after exposure at the 95% confidence interval.

Of the standard Corps paints we tested, only the V-103c system has a substantially low affinity for ice adhesion, i.e., in the same range as the icephobic materials that we tested. Also, our average adhesion test value for V-103c increased only slightly after the six-month-long field exposure. The test results indicate that using a commercial icephobic topcoat on other Corps paints could be of benefit by reducing the effort required to remove ice. Some of the icephobics that we tested have one-half to one-third the ice adhesion strength of bare metal. Teflon and UHMW polyethylene as cladding materials are even better in this regard. Although other methods of removal will still be required, icephobics may reduce the energy, man-hours, and cost required to deice Corps structures. It was evident from the after-exposure condition survey and the ice adhesion testing results that most of the coatings held up well during the six-month field trial, and that longer exposure is warranted to obtain further performance delineation between these systems.

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Acknowledgments

This work was supported by funding from the U.S. Army Corps of Engineers (USACE) Civil Works Research-and-Development-funded Cold Regions Engineering Program work units *Characterization of Ice Impacts on Winter O&M* #39862, *Control of Icing at Corps Projects* #39864, and *Winter Operations and Maintenance at Corps Structures* #33283. Special thanks are extended to Dr. Kathleen White, Research Hydraulic Engineer at CRREL, for manuscript review; Al Beitelman of ERDC's Construction Engineering Research Laboratory in Champaign, Illinois, for expert sample preparation and coating; and Jerry Stroud, Lockmaster at USACE Lock and Dam 25, for providing a site for and personnel who assisted with field trials. Technical and experimental assistance at CRREL was provided by Christopher Donnelly, Dennis Lambert, and John Gagnon.

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