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Determination of Acreage Thermal Protection Foam Loss From Ice and Foam Impacts

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Contents

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Abstract

A parametric study was conducted to establish Thermal Protection System (TPS) loss from foam and ice impact conditions similar to what might occur on the Space Launch System. This study was based upon the large amount of testing and analysis that was conducted with both ice and foam debris impacts on TPS acreage foam for the Space Shuttle Project External Tank. Test verified material models and modeling techniques that resulted from Space Shuttle related testing were utilized for this parametric study. Parameters varied include projectile mass, impact velocity and impact angle (5° and 10° impacts). The amount of TPS acreage foam loss as a result of the various impact conditions is presented.

1.0 Introduction

Several elements of the Space Launch System (SLS) launch vehicle were derived from similar systems that were a part of the Space Shuttle Program (SSP). These include an aluminum (Al) Core Vehicle covered with thermal insulating foam; a configuration similar to the foam covered External Tank of the Space Shuttle. During the Return to Flight effort after the Columbia accident, the External Tank was assessed for the SSP specific debris environment, using a combination of testing and analysis. As a result, the tools necessary for a full assessment of potential impacts to a similar configuration, such as SLS, were available. Using these models from the Space Shuttle program, damage to thermal insulating foam resulting from a range of impact masses and velocities can be predicted. These predictions can give insight and relevant technical data to the SLS program debris assessment.

During the Return-to-Flight effort all of the materials which were identified as either potential debris sources were tested to determine their mechanical properties. These materials included several varieties of low-density thermally insulating foam, ablators, and ice. The tests were conducted at a variety of locations including NASA's Marshall Spaceflight Center, Langley Research Center, and Glenn Research Center. Material models of the most threatening debris sources were created using the mechanical properties obtained from these tests and were certified by the SSP (Refs. 1 and 2). Because of their potential for causing significant damage, ice and the densest of the foams, PDL-1034 (Product Development Laboratory) were selected for assessment as projectiles in this study. A material model had also been created for the foam which covers the general surface of the tank or the SLS core vehicle, referred to as acreage foam. The acreage foam was a sprayed-on-foam, NCFI 24-124 (North Carolina Foam Industries). This acreage foam was used as the target in the current study.

Multiple series of impact tests were conducted by the Glenn Research Center Impact Dynamics Group in conjunction with Lockheed Martin Space Systems Company, Michoud Assembly Facility (MAF) (Refs. 3 and 4) in support of SSP. These tests included multiple debris materials, with varying angle impacts, onto acreage foam covered tank panels and foam covered protuberances. They were conducted to both assess the damage tolerance and to verify analytical models. For this study, selected tests from both the series of ice impacts onto acreage NCFI foam panels, and the series of PDL foam impacts onto acreage NCFI foam panels, were used as model verification tests. These selected tests were re-analyzed using current software and material model versions, and current finite element meshes, demonstrating prediction capability.

As a part of the effort to demonstrate damage tolerance of the Space Shuttle External Tank, Lockheed Martin MAF performed a series of analyses assessing the rise in thermal stresses due to the loss of insulating foam (Ref. 3). A general set of impact cases was not assessed, but only specific debris transport cases were evaluated. The only resulting parameters from the impact analysis, which are inputs to the damage assessment, are descriptions of the foam loss. As a result, any impact condition which results in a similar foam loss can be compared to the baseline thermal stress assessment. For this study, the margin assessment of the LH_2 barrel panel due to damage in the insulating acreage foam was used as a baseline. The margin of safety in the LH_2 barrel panel was reduced to +0.01 because of the worst case foam loss. Therefore, the damage assessment in this study was conducted by comparing the resulting foam loss from a general set of input cases to the worst case foam assessed by Lockheed Martin MAF.

Components of the External Tank other than the LH_2 barrel panel will have a margin greater than +0.01 for the same area of foam loss. In addition, if the Core Vehicle is designed with larger margins for nominal flight conditions than the External Tank, then greater foam loss can be tolerated. As a result, the results from these analyses are presented both in terms of LH_2 barrel panel margin and area of foam loss. Using the results presented in terms of LH_2 barrel panel margin can give a quick margin assessment, and for a more complete assessment the provided area of foam loss charts can be used.

2.0 Material Models and Certification

Previous to Return-to-Flight, numerical analyses involving ice were rarely performed for many reasons, including the absence of sufficient computer power, software that could handle both the extreme deformations of the ice and accurately model the structural response of the vehicle, and most important; the availability of an accurate model for ice. The Columbia Space Shuttle tragedy motivated a large scale safety review of the Space Shuttle, and included in that review was a requirement for certifying the ability of the leading edge of the wing to safely sustain impacts of various types of debris including ice. Ice, however, is not a commercial structural material, and aside from high velocity impact situations of interest to the aerospace industry, is rarely subjected to high strain rate impact conditions. Although ice had been studied extensively, only a very few efforts had been made to model it numerically at the high strain rates expected for shuttle, and for the present SLS vehicle. To overcome the lack of an appropriate ice model for Return-to-Flight, a new ice model was developed and is described in detail in Reference 2. This ice model is used for the present SLS ice impact study.

Then, as now, the primary analytical tool was LS-DYNA, which is commercial finite element software (Ref. 5). The constitutive relationships of the ice model were implemented into LS-DYNA as MAT PLASTICITY COMPRESSION TENSION EOS. The material model inputs used in this study are given in Table 1. This model also allows the inclusion of ice's strain rate sensitivity, which is given in Table 2. An Equation of State is also used with this constitutive model, in this case to prevent high frequency stress oscillations from triggering unrealistic, premature ice failure. This Equation of State was determined heuristically and is shown in Table 3.

The density of the ice used in this assessment, and reflected in Table 1, is that of clear, solid ice. Where bare metal is exposed to air, and is in contact with cryogenic temperature fluids, ice will form. This ice is sometimes lower-density frost, but depending on conditions, clear, solid ice also forms. This higher density, clear, solid ice creates more damage as an impactor than frost. However, the differences in damage that occurs due to the smaller variations in clear, solid ice density and strength are not significant, especially when impacting a soft, weak material such as thermal insulating foam. The ice density and strength values shown in Table 1 are the same as those used for all SSP certification analysis, and reflect the highest density ice. This value is appropriately conservative because ice that forms in remelting, such as in an icicle, is often single crystal ice, and this is the type of ice formation that occurred on the External Tank, and can be expected to occur on the SLS.

The material models for the foam utilized constitutive relationships already available within LS-DYNA. The PDL-1034 was modeled using MAT SIMPLIFIED RUBBER/FOAM, as PDL is an elastic foam, which will recover its original shape after compressive loading is removed, up to very large strains. The constant material model inputs used in this study are given in Table 4. The behavior of this material model is primarily dependent on input stress-strain curves, with a different curve for each defined strain rate. These strain rate dependent curves are shown in Figure 1.

TABLE 1.—ICE MATERIAL MODEL PROPERTIES

Mass density	8.4×10^{-5} lb sec^2/in.^{4} (0.032 lb/in.^{3})
Young's modulus	1.35×10^6 lb/in.^{2}
Initial compressive flow stress	2100 lb/in.^{2}
Initial tensile flow stress	210 lb/in.^{2}
Plastic tangent modulus	100 lb/in.^{2}
Poisson's ratio	0.33
Pressure cut-off in compression	715 lb/in.^{2}
Pressure cut-off in tension	62.8 lb/in.^{2}

TABLE 2.—STRAIN RATE SENSITIVITY OF ICE

Strain rate, sec^{-1}	Stress scale factor
1.0	1.00000
10.0	1.25660
100.0	1.51320
200.0	1.59044
300.0	1.63562
400.0	1.66768
500.0	1.69255
600.0	1.71287
700.0	1.73005
800.0	1.74493
900.0	1.75805
1000.0	1.76979
1100.0	1.78042
1500.0	1.81498
10000.0	2.02639

TABLE 3.—EQUATION OF STATE LOADING

ln volumetric strain	Pressure, lb/in.^{2}	Bulk modulus, lb/in.^{2}
0.0	0	1.3×10^6
-7.693×10^{-3}	1×10^4	1.3×10^6
-3.125×10^{-2}	1×10^4	3.2×10^5
-10	1×10^4	1.0×10^3

TABLE 4.—PDL-1034 FOAM MATERIAL MODEL PROPERTIES

Mass density	4.992×10^{-6} lb sec^2/in.^{4} (0.001927 lb/in.^{3})
Linear bulk modulus	1540. lb/in.^{2}
Damping coefficient	0.05
Poisson's ratio	0.011
Failure strain (tension)	0.0677

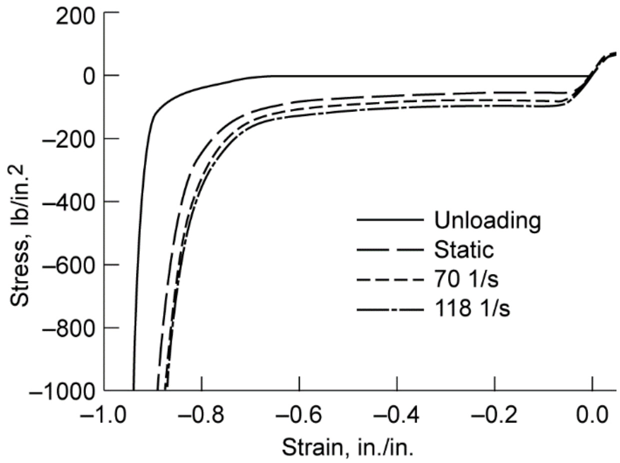


Figure 1.—PDL-1034 foam model stress-strain curves.

TABLE 5.—NCFI FOAM MATERIAL MODEL PROPERTIES

Mass density	3.597×10^{-6} lb sec^2/in.^{4} (0.001388 lb/in.^{3})
Elastic modulus (normal)	800 lb/in.^{2}
Elastic modulus (transverse)	200 lb/in.^{2}
Elastic shear modulus (out of plane)	400 lb/in.^{2}
Elastic shear modulus (transverse)	100 lb/in.^{2}
Shear modulus	402.01 lb/in.^{2}
Bulk modulus	269.36 lb/in.^{2}
Damping coefficient	0.05
Minimum principle failure strain	100% = –0.9; 75% = –0.675
Maximum principle failure strain	100% = 0.094; 75% =0.0705

The NCFI was modeled using MAT TRANSVERSELY ANISOTROPIC CRUSHABLE FOAM, as it does not recover its original shape after compression. The constant material model inputs used in this study are given in Table 5. The reason for the differing strain to failure values, 100 and 75 percent, will be discussed in the next section. The behavior of this material model is also primarily dependent on input stress-strain curves. Since the foam is anisotropic, direction specific stress-strain curves are required and are shown in Figure 2. The strain rate sensitivity used in this model is included by the scaling of the yield stress, as shown in Figure 3.

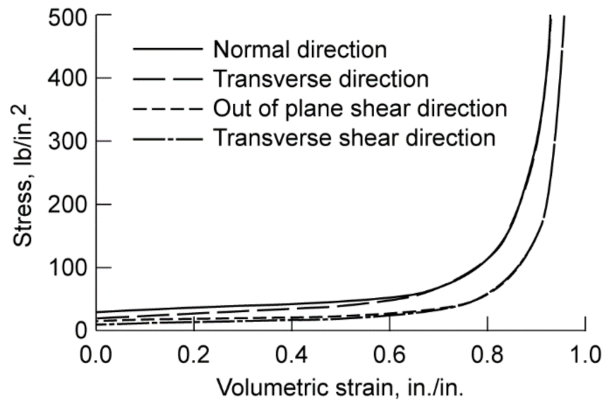


Figure 2.—NCFI foam model stress-strain curves.

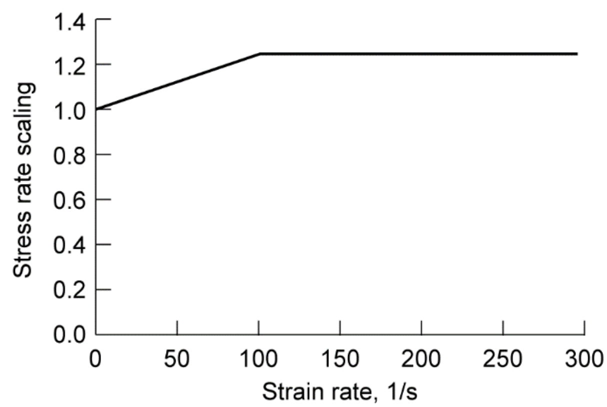


Figure 3.—NCFI strain rate scaling on yield stress.

TABLE 6.—ALUMINUM MATERIAL MODEL PROPERTIES

Mass density	2.5389×10^{-4} lb sec^2/in.^{4} (0.098 lb/in.^{3})
Young's modulus	1.02×10^{7} lb/in.^{2}
Poisson's ratio	0.330

Both the material models for ice and PDL-1034 were certified by the Space Shuttle Program System Integration Control Board and the Orbiter Configuration Control Board by the Space Shuttle Program. The NCFI 24-124 material model was not board certified. However, it was created using the same analytical methods and internal reviews as the PDL and ice models. The input to all of the constitutive material models is primarily based upon mechanical property test data.

The Al of the tank skin simulation was modeled as a simple elastic material, as no plastic deformation was expected or noted from any ice or foam impacts. The input parameters for this material model are given in Table 6.

3.0 Impact Model Verification

Modeling of ice and foam impacts, and subsequent damage to structure-insulating foam, requires complex, and not routinely used analysis. Before this analysis can be used for prediction, verification must be performed to insure that the modeling methodology is sound, and appropriate for use for the SLS application. Fortunately, as presented in Section 2.0, reliable ice and foam materials model were developed, and subsequently used, during the Space Shuttle Program Return-to-Flight. Other analytical parameters and techniques such as mesh sizes and contact algorithms must also be included in an overall analytical verification. For the Space Shuttle Program, impacts to the external tank and the orbiter were a major concern, and extensive work was performed to develop reliable impact analytical models, insuring that these impacts would not jeopardize the vehicle integrity. The materials models, parameters, and other analytical techniques developed during the Space Shuttle Program were used in the verification performed for this study.

The verification consisted of comparing impact tests that were performed during the Space Shuttle Program Return-to-Flight (Refs. 3 and 4) with analysis modeling these specific tests. This current verification is a repetition of the Return-to-Flight verification; only using a current version of LS-DYNA, final certified material models, and newly created meshes. (The meshes used in Return-to-Flight were no longer available.) Specific tests, out of the many which were conducted, were selected based upon projectile masses, velocities, and impact angles being most relevant to SLS. Both ice (described in Section 3.1) and PDL foam (described in Section 3.2) impact tests onto the acreage foam test panels were modeled.

The LO_2 and LH_2 acreage test panels were fabricated from NCFI 24-124 sprayed per STP 1535. Final foam thickness was 1.00 ±0.25 in. and were left in the net-sprayed condition. Foam was sprayed onto 2219T-87 2- by 2-ft by 0.375-in. nominal thick Al substrates as shown in Figure 4. A finite element model of the acreage test panel was created and is shown in Figure 5. The element size used in this model was the same as that found by Lockheed Martin MAF to produce the most accurate analysis. Additional details of the test fixture are provided in the Reference 4.

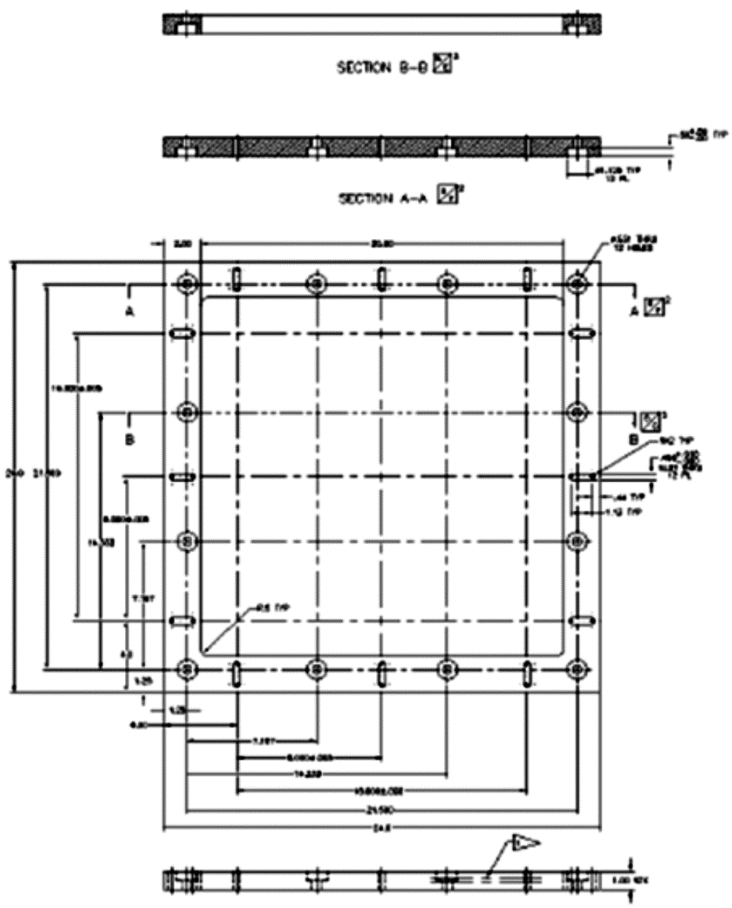


Figure 4.—Acreage foam on Al plate test specimen drawing.

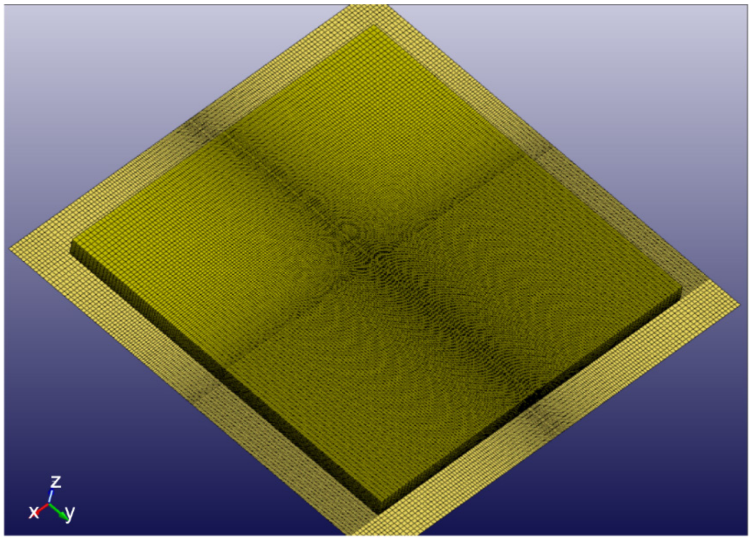


Figure 5.—Finite element model of acreage test panel

In many of the test articles, including those that were used for the verification, the foam regularly failed at the Al and foam interface layer. It was also observed that the character of the NCFI foam in this region was slightly different than in the remainder of the panel, with the foam cell size being slightly smaller and less elongated. The correlation analysis for both the PDL foam and ice impacts did not originally duplicate the propensity that the NCFI foam showed for failing at this interface layer. As a result, a thin layer of foam elements was included between the foam and Al plate to model the adhesion between the foam and plate. A limited set of iterations was performed, and the failure strain in this layer of NCFI foam elements was reduced 75 percent from that of the acreage foam, as given in Table 5. No other physical properties were modified in this layer. The 75 percent reduction in failure strain is only an approximation of the reduced adhesion strain and/or strength, but it does appear to adequately model the interface behavior, as described in Section 3.1 and 3.2.

3.1 Ice Verification Results

The ice model is developed using the Arbitrary Lagrangian Eulerian (ALE) capabilities of the commercial analysis code, LS-DYNA. Details of this approach are provided elsewhere (Ref. 5); however for the present application, the acreage foam and the Al substrate are modeled as Lagrangian parts, and the ice is modeled as Eulerian. A void is created, and travels along with the ice impactor, and provides for a space for the ice to expand as the ice breaks up during the impact event (Figure 6).

Table 7 shows the ice impact tests performed under the Return-to-Flight program (Ref. 3, Table 10), and the resulting area of foam effected. For the purpose of validating the present model, the final two cases (FF172 and FF174) were modeled, and the results of the model were compared to the test data. FF172 and FF174 were selected since they both were performed with shallow impact angles (15°), which is closer to the shallow impact angles expected for SLS. Just as important, these two tests used the smallest size projectiles, with weights closest to those expected for SLS. These two cases also represent two distinctly different sizes of ice projectiles.

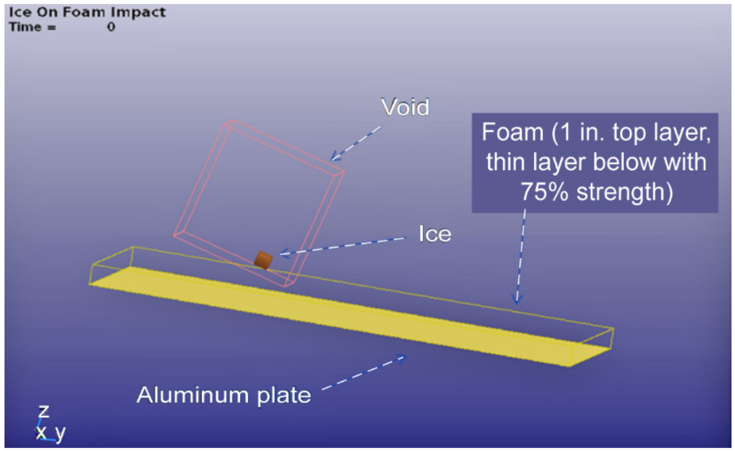


Figure 6.—LS-DYNA ice on foam impact model.

TABLE 7.—ICE IMPACT TEST MATRIX AND AREA AFFECTED FROM REFERENCE 3 (TABLE 10)

		Test Article				Projectile Test Article											
Part	Back-ing plate, in.	Test No.	TPS Config.	Shape	Substrate Thick-ness, in.	Impac-tor	Shape	Length (approx.) in.	Diam., in.	Sabot + ice, grams	Sabot, grams	Ice, grams	Ice, lb	Angle, deg.	Velocity, fps	Panel ID	Area affected, in.^{2}
LO_2/LH_2 Acreage	1	FF157	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	141.39	100.55	40.84	0.090	45	868	JR1903 #4-2	166.5
LO_2/LH_2 Acreage	1	FF158	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	140.41	99.93	40.48	0.089	45	846	JR1903 #4-11	169.75
LO_2/LH_2 Acreage	1	FF160	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	140.4	99.89	40.51	0.089	30	973	JR1903 #2-4	188.25
LO_2/LH_2 Acreage	1	FF161	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	139.89	99.58	40.31	0.089	30	972	JR1903 #4-10	172.25
LO_2/LH_2 Acreage	1	FF162	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	139.98	99.57	40.41	0.089	15	995	JR1903 #3-3	95
LO_2/LH_2 Acreage	1	FF163	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	1.25	140.2	99.78	40.42	0.089	15	966	JR1903 #2-13	142.75
LO_2/LH_2 Acreage	1	FF165	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	114.95	100.62	14.33	0.032	15	865	JR1903 #3-11	73
LO_2/LH_2 Acreage	1	FF166	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	113.98	100.21	13.77	0.030	15	878	JR1903 #4-9	90.75
LO_2/LH_2 Acreage	1	FF167	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	114.82	100.56	14.26	0.031	30	813	JR1903 #4-12	85
LO_2/LH_2 Acreage	1	FF168	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	114.56	100.14	14.42	0.032	30	791	JR1903 #1-8	79.5
LO_2/LH_2 Acreage	1	FF169	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	114.25	100.19	14.06	0.031	45	793	JR1903 #2-2	86.25
LO_2/LH_2 Acreage	1	FF170	NCFI24-124	Flat panel	0.375	Ice	Cylinder	2.25	0.75	113.71	99.79	13.92	0.031	45	782	JR1903 #5-9	101.25
LO_2/LH_2 Acreage	1	FF172	NCFI24-124	Flat panel	0.375	Ice	Cylinder	1.125	0.75	106.65	99.93	6.72	0.015	15	865	JR1903 #1-1	86.9375
LO_2/LH_2 Acreage	1	FF174	NCFI24-124	Flat panel	0.375	Ice	Cylinder	0.72	0.75	103.64	99.82	3.82	0.008	15	872	JR1903 #1-4	35.815

Figure 7 shows the damaged foam and exposed Al for test FF174. For this test, the ice enters from the right side of the image and travels to the left. Near the center of the test plate, the ice fully penetrates the foam, hits the Al plate, and then rebounds off the plate. During impact with the plate, the ice breaks into multiple pieces, and during rebound the expanded volume of ice damages a broader area of foam.

Figure 8 depicts LS-DYNA results showing the ice projectile penetrating the foam layer. Four snapshots are shown progressing from time=0 to time=0.0006 sec. Beyond 0.0006 sec the ice travels below the surface of foam, and in this view cannot be seen, until after the ice rebounds off the Al plate and travels back up towards the surface of the foam. Up until near 0.0006 sec, the ice is not damaged by the foam, and the ice slices a relatively clean path through the foam layer.

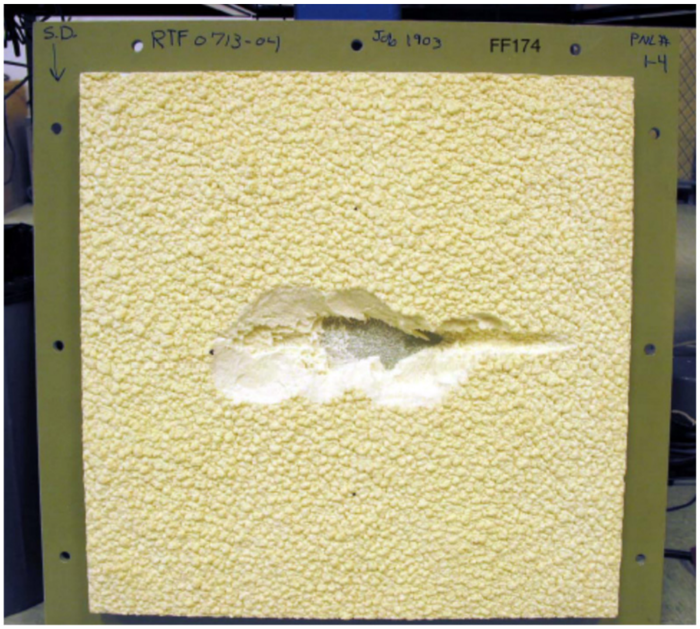


Figure 7.—Damaged foam and exposed Al for test FF174

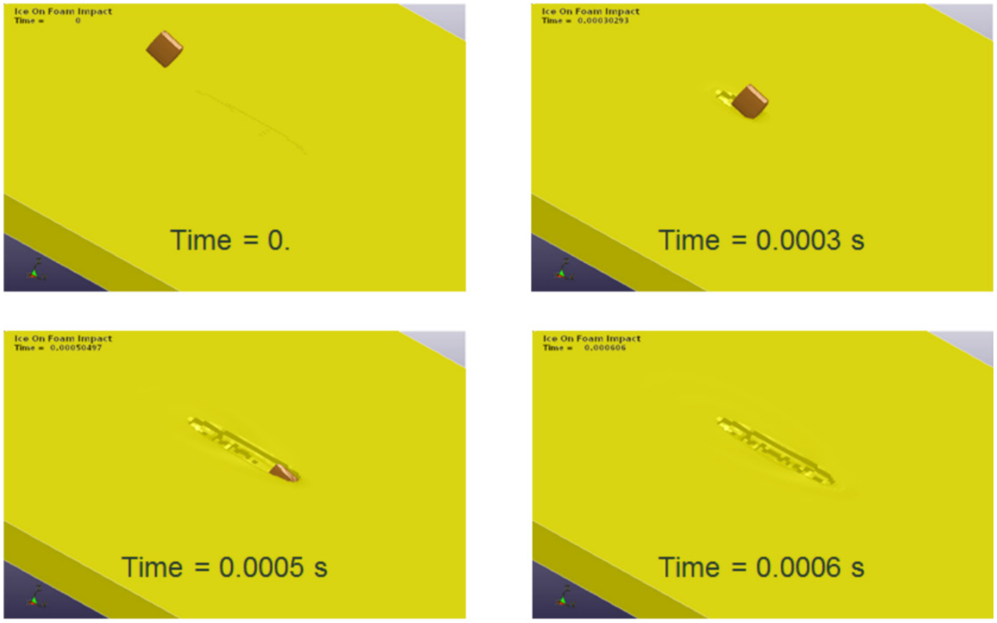


Figure 8.—LS-DYNA results showing ice projectile penetrating foam.

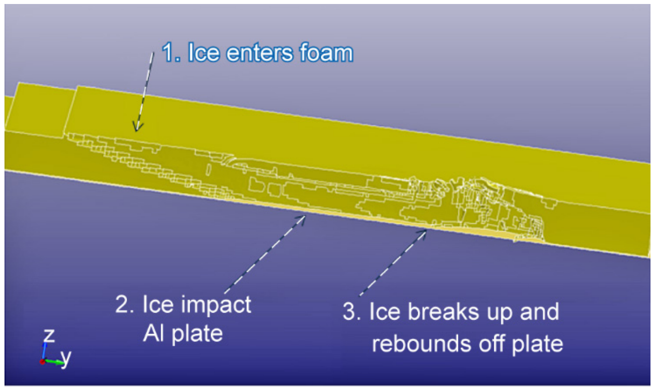


Figure 9.—LS-DYNA cross section showing damaged foam.

Figure 9 shows a cross section with the progression of ice and the resulting damaged foam. As shown in the previous figure during initial ice entry into the foam a damaged path roughly the size and shape of the ice projectile is formed. After the ice impacts the Al plate, the ice begins to break apart, and rebounds off the plate. During rebound the damaged ice spreads out and the resulting damage to the foam is much broader than during ice entry. (Note that for Figure 8 and Figure 9, the ice travels from left to right in the simulations while in the actual tests the ice travels from right to left. This does not affect the results, merely the viewing of the results.)

Figure 10 shows a comparison between the FF174 test and LS-DYNA results. The damage is somewhat complex since the total damage is a combination of the damage through the thickness of the foam, as well as the surface area of the exposed Al plate. In practice, damage to the foam and exposure of the Al plate leads to thermal effects which produce the potential for higher stress levels in the underlying structures, and an increase in possible structural failures. For the present comparison, the combined damaged area is used as the measure to compare test to analysis. Figure 10(a) shows the damage in the top layer foam at the test completion. Exposed Al plate can be seen in the photo, however the extent of the exposure is not captured in the photo since there is separation between the foam and plate in areas where the top layer of foam is not damaged. Figure 10(b) shows the damage in the top layer of foam predicted from the LS-DYNA simulation. While the overall length of the damage is consistent with the test results, the LS-DYNA results do not show foam damage in the region where the ice projectile rebounds off the Al plate. Figure 10(c) shows the LS-DYNA predicted exposure of the Al plate as a result of failure in the interface layer. In reality, the top foam layer cannot remain intact if the underlying layer has been damaged, so it is sensible to combine the damage to the top foam layer with the damage to the interface layer. Once these damage areas are combined, they can be compared to the test results (Figure 10(d)).

A quantitative comparison between test and analysis is made by approximating the damaged areas using an ellipsoid fit. Figure 11 shows the actual combined damage area for FF174, and an ellipsoid fit to that area. Once the ellipsoid is fit, then a quantitative approximation can be made for the length and width of the damaged area, and the area of the damage can be calculated.

Figure 12 shows the damaged foam and exposed Al for test FF172. For this test, the impact velocity is similar to test FF174; however the ice projectile is close to twice as large, leading to far more foam damage. Figure 13 shows a comparison between the FF172 test and LS-DYNA results. Figure 13(a) shows the damage in the top layer foam at the test competition. Similar to test FF174 exposed Al plate is produced as a result of the ice impact. Figure 13(b) shows the damage in the top layer of foam predicted from the LS-DYNA simulation while Figure 13(c) shows the LS-DYNA predicted exposure of the Al plate as a result of failure in the interface layer. Figure 13(d) shows the comparison between the area of foam damage in the test and the analysis.

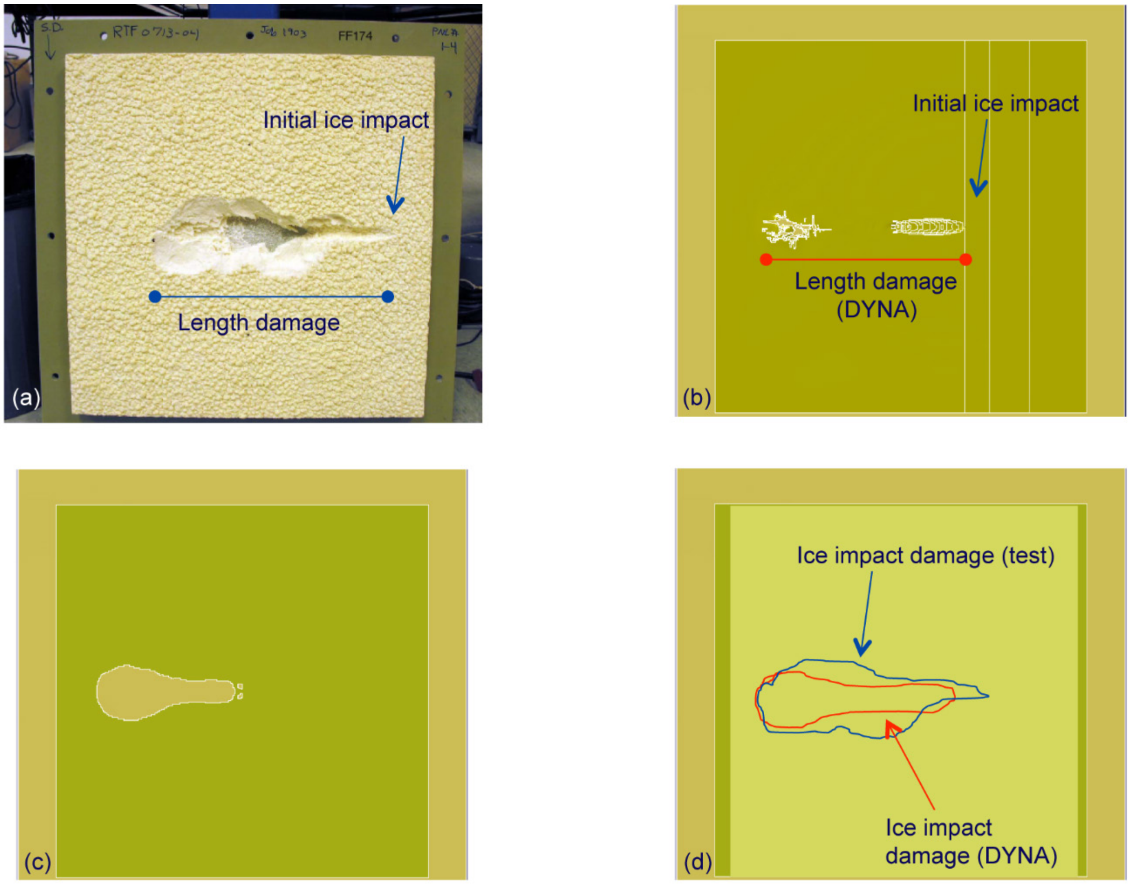


Figure 10.—Test FF174: test and LS-DYNA results. (a) Impact test FF174 at 15°. (b) Damage in 1-in.-foam layer. (c) Damage in interface foam layer. (d) Combined damaged areas.

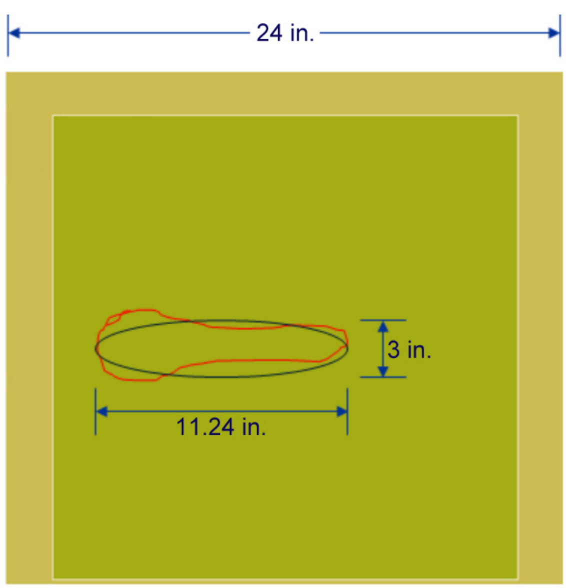


Figure 11.—Use of ellipsoid to estimate damages area

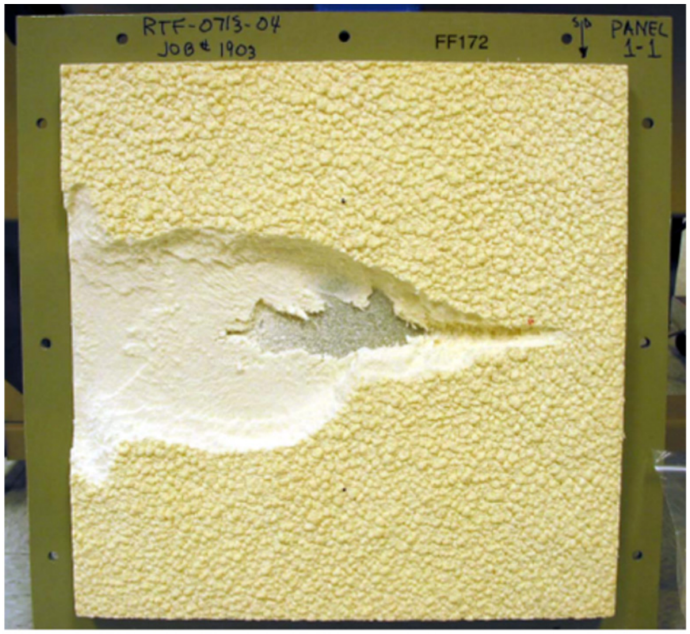


Figure 12.—Damaged foam and exposed Al for test FF172.

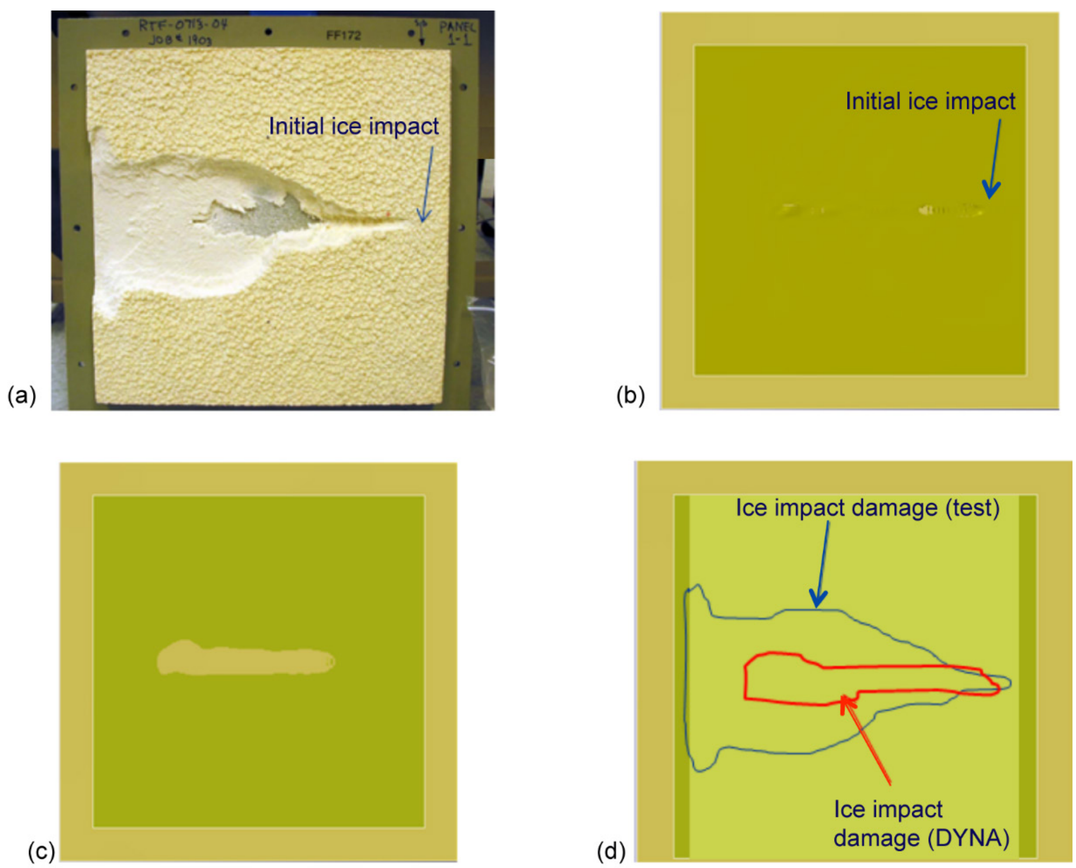


Figure 13.—Test FF172: test and LS-DYNA results. (a) Impact test FF172 at 15°. (b) Damage in 1-in.-foam layer. (c) Damage in interface foam layer. (d) Combined damaged areas.

While LS-DYNA predicts more damage for FF172 compared to FF174, LS-DYNA does not predict damage as extensive as exhibited in the actual test. It can be seen in Figure 12 that the region of foam loss in test FF172 extends to the edge of the acreage foam. Unfortunately, this means that both the foam edge and the boundary conditions of the Al substrate participate in the response of the panel to the projectile. In turn, this non-homogeneous condition can lead to highly varied foam loss. The variability is demonstrated by considering additional tests, documented in Table 7. For these additional tests, there were two tests performed for each projectile impact angle and ice weight. Repeatability of the damage for each specific set of conditions is lacking, i.e. repeat test conditions often produce dissimilar resulting damage. In particular, the 15° impacts showed the highest variability in the amount of acreage foam which was lost.

Test results FF162 and FF163, which both had a 0.089 lb projectile impacting at 15°, are shown in Figure 14(a) and (b). As can be seen there is a significant difference in the amount of foam loss between the two tests, and that the damage extended to the edge of the foam. Test FF162 resulted in a foam loss of 95 in.^{2} and test FF163 resulted in foam loss of 143 in.^{2}, a difference of ~33 percent. Test results FF165 and FF166, which both had a ~0.030 lb projectile impacting at 15°, are shown in Figure 14(c) and (d). Test FF165 resulted in a foam loss of 73 in.^{2} and test FF165 resulted in foam loss of 91 in.^{2}, a difference of ~20 percent. It is evident that credible and precise analytical predictions of foam loss area in these low angle tests are not possible, given the large variability in the test results.

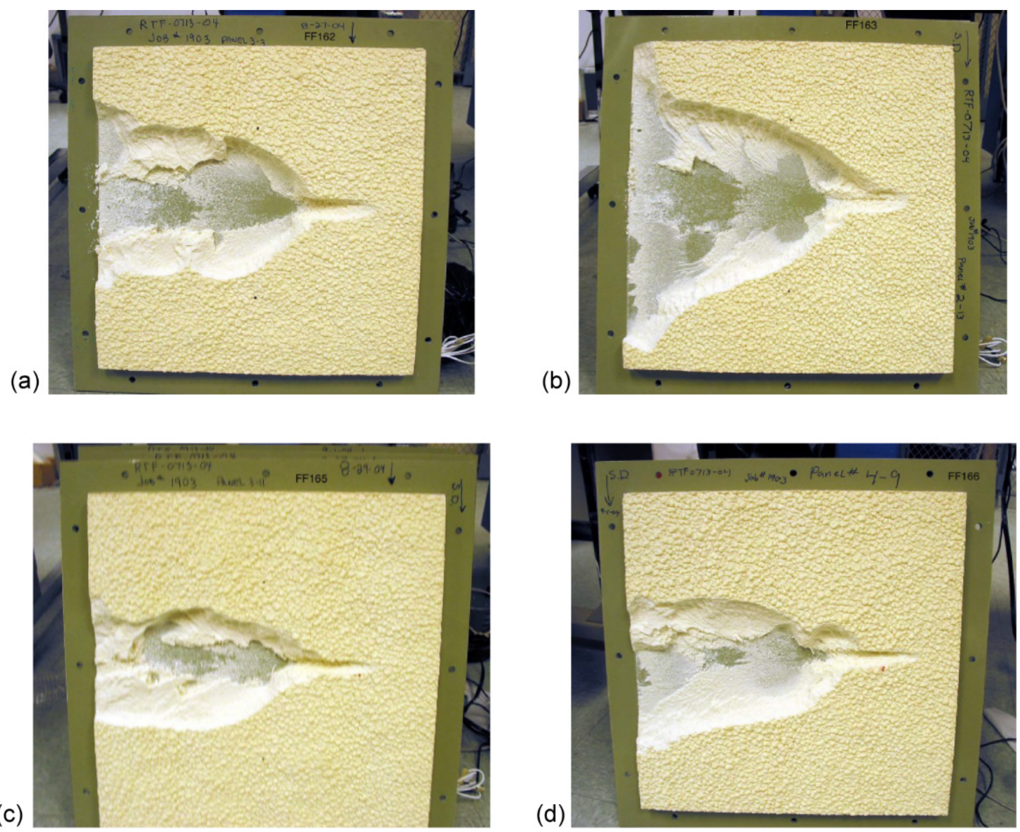


Figure 14.—Damaged foam and exposed Al from low angle ice impacts. (a) Test FF162 (0.089 lb ice). (b) Test FF163 (0.089 lb ice). (c) Test FF165 (0.032 lb ice). (d) Test FF166 (0.030 lb ice).

TABLE 8.—SUMMARY ANALYTICAL RESULTS FOR ICE IMPACT VALIDATION TESTS, FF174 AND FF172

Test	Ice projectile, in.	Ice projectile (test), lb	Ice projectile ([a]LS-DYNA), lb	Impact angle, deg.	Velocity, fps	L2/W2, in.	Area, $in.^2$
FF174	0.75 diam. by 0.72 length	0.008	0.010	15	872	11.25/3	26.5 35.8 test
FF172	0.75 diam. by 1.125 length	0.015	0.016	15	865	13.5/3.75	39.5 (86.9 test)

[a]0.0324 $lb/in.^3$

Table 8 shows summary results for LS-DYNA analysis of test cases FF174 and FF172. The ice model used in this analysis was the certified model discussed in Section 2.0, and the density was not adjusted to match the slightly lower density of the test projectiles. As can be seen, using a slightly higher ice density in the analysis did not result in greater damage than in the test. Considering both the variability in the area of tested foam loss and that the damage in test FF172 extended to the edge of the foam, the analytical results represent a reasonable match to the test results. The difference between the analytical and test foam loss in FF174 was ~26 percent, less than the difference observed between tests FF162 and FF163.

3.2 PDL-1034 Foam Verification Results

Modeling foam projectiles impacting foam targets is somewhat more straightforward than modeling ice impacts, in that both the foam projectile and foam target can be modeling using Lagrangian meshes. However, in addition to the general impact analysis complexities, such as stability, contact and mesh size, with foam there are large distortions to the mesh, making test verification a requirement.

Table 9 shows the PDL foam impact tests performed under the Return-to-Flight program (Ref. 4, Table 3), and the resulting volume of NCFI foam removed. For the purpose of validating the present model, two cases (FF100 and FF109) were modeled, and the results of the model were compared to the test data. FF100 and FF109 were selected since they represent two distinct shallow impact angles (15° and 30°), which are closest to the shallow impact angles expected for SLS. Modeling two distinct angles gives an additional layer of verification. All of the PDL foam impact tests were performed with the same nominal size projectile.

Figure 15 shows the damaged foam and exposed Al for test FF100. For this test, the PDL foam projectile enters from the right side of the image and travels to the left. Near the center of the test plate, the PDL foam fully penetrates the NCFI foam, hits the Al plate, and then rebounds off the plate. During impact with the plate, the PDL foam breaks into multiple pieces, causing a large area of NCFI foam to detach from the plate.

Figure 16 depicts LS-DYNA results showing the PDL foam projectile penetrating the NCFI foam. Four snapshots are shown progressing from time=0 to time=0.0015 sec, which shows both the PDL foam projectile breaking apart and damage to the NCFI foam. There is damage to the NCFI foam which extends beyond that visible in Figure 16. This is shown in the cross section close-up of Figure 17, where the NCFI foam has been detached from the Al plate in an area larger than the immediate area around the impact.

TABLE 9.—PDL FOAM IMPACT TEST MATRIX AND AREA AFFECTED FROM REFERENCE 4 (TABLE 3)

Test No.	Projectile material	Projectile number	Projectile data			Panel material	Panel ID	Substrate thickness, in.	Impact angle, deg.	Gun pressure psi	Velocity, fps	Volume removed, in.^{3}
			Diam., in.	Length, in.	Mass, gram							
FF078	BX-265	1907BX265-8-01	2.957	4.987	18.2	NCFI24-124	1-16	0.375	15	20	1357	90
FF080	BX-265	1907BX265-8-15	2.957	4.987	18.2	NCFI24-124	1-12	0.375	15	20	1346	35
FF081	BX-265	1907BX265-8-26	2.961	4.769	18.21	NCFI24-124	1-15	0.375	15	20	1372	35
FF082	BX-265	1907BX265-8-28	2.964	5.02	18.25	NCFI24-124	1-11	0.375	15	20	1346	36
FF085	BX-265	1907BX265-8-06	2.965	4.657	18.16	NCFI24-124	2-07	0.375	30	19.7	1355	92
FF086	BX-265	1907BX265-8-07	2.961	4.6225	18.22	NCFI24-124	1-03	0.375	30	19.7	1367	121
FF087	BX-265	1907BX265-8-04	2.973	4.692	18.15	NCFI24-124	1-09	0.375	30	19.5	1354	80
FF088	BX-265	1907BX265-8-09	2.966	4.998	18.15	NCFI24-124	2-03	0.375	45	19.5	1350	118
FF089	BX-265	1907BX265-8-02	2.9613	4.985	18.23	NCFI24-124	2-06	0.375	45	19.5	1353	114
FF090	BX-265	1907BX265-8-12	2.9641	4.832	18.14	NCFI24-124	3-01	0.375	45	19.5	1382	111
FF091	BX-265	1907BX265-8-05	2.9652	4.629	18.19	NCFI24-124	2-14	0.375	45	19.3	1367	97
FF094	NCFI24-124	1855B-P7-189	2.9716	4.213	18.18	NCFI24-124	3-07	0.375	30	20	1325	73
FF095	NCFI24-124	1855B-P7-171	2.993	4.211	18.17	NCFI24-124	3-16	0.375	30	20.1	1365	84
FF096	NCFI24-124	1855B-P7-181	2.9833	4.233	18.17	NCFI24-124	1-07	0.375	30	20.1	1337	129
FF097	NCFI24-124	1855B-P7-169	2.9836	4.2325	18.19	NCFI24-124	3-13	0.375	30	20.1	1364	91
FF099	PDL-1034	PDL-12-02	2.486	3.745	18.18	NCFI24-124	2-16	0.375	30	20	1191	91
FF100	PDL-1034	PDL-12-07	2.4917	3.72	18.19	NCFI24-124	1-06	0.375	30	20.2	1023	76
FF101	PDL-1034	PDL-12-13	2.4868	3.675	18.16	NCFI24-124	3-10	0.375	30	22	1326	100
FF102	PDL-1034	PDL-12-04	2.4895	3.766	18.18	NCFI24-124	3-06	0.375	30	21	1285	84
FF103	PDL-1034	PDL-12-29	2.4908	3.777	18.14	NCFI24-124	2-01	0.375	30	20.5	1270	135
FF104	PDL-1034	PDL-12-01	2.4897	3.701	18.18	NCFI24-124	1-05	0.375	45	20	1258	113
FF105	PDL-1034	PDL-12-30	2.4928	3.6685	18.15	NCFI24-124	1-10	0.375	45	19.5	1261	129
FF106	PDL-1034	PDL-12-27	2.4901	3.6655	18.15	NCFI24-124	2-12	0.375	45	18.5	1224	133
FF107	PDL-1034	PDL-12-03	2.4875	3.702	18.19	NCFI24-124	2-11	0.375	15	22	1314	41
FF108	PDL-1034	PDL-12-14	2.487	3.711	18.17	NCFI24-124	2-15	0.375	15	21.5	1287	46
FF109	PDL-1034	PDL-12-06	2.487	3.679	18.18	NCFI24-124	1-13	0.375	15	21.5	1280	38

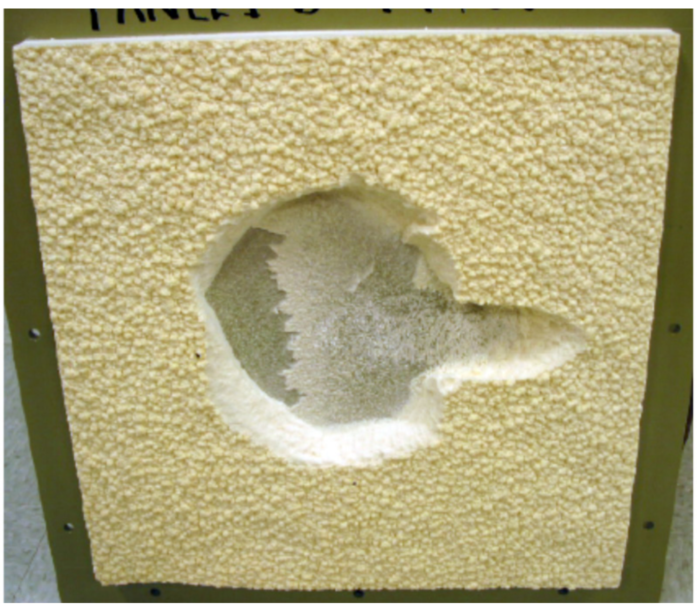


Figure 15.—Damaged foam and exposed Al for test FF100.

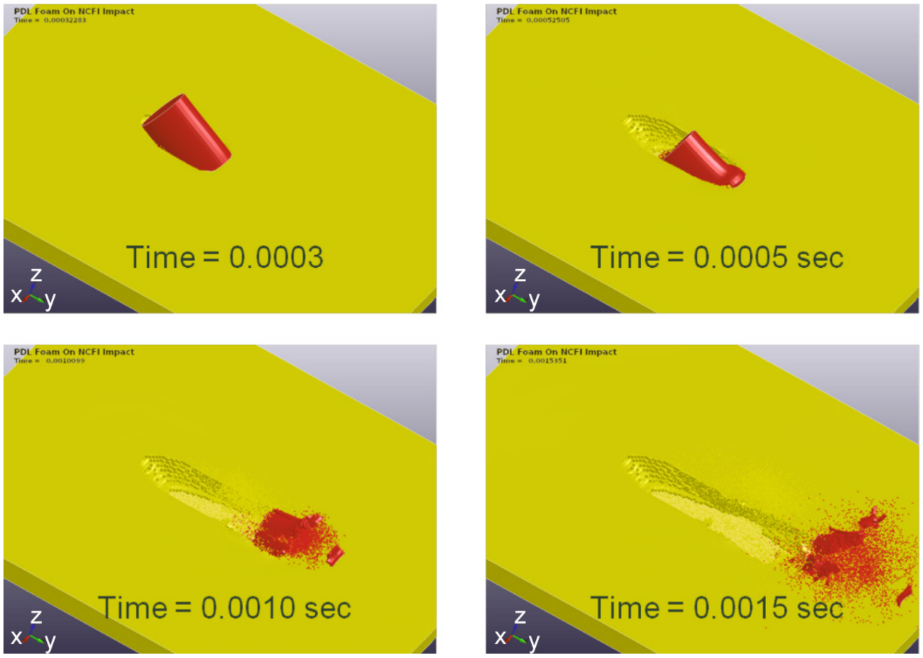


Figure 16.—PDL foam projectile impacting NCFI foam covered Al plate.

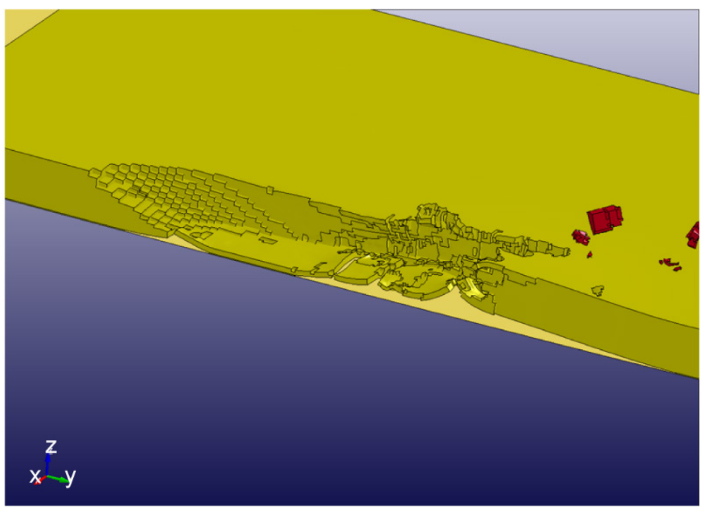


Figure 17.—Cross section of panel showing damaged NCFI foam.

Figure 18 shows a comparison between the FF100 test and LS-DYNA results. As in the ice projectile verification, the combined damaged area is used as the measure to compare test to analysis. Figure 18(a) shows the damage in the top layer foam at the test completion. Figure 18(b) shows the damage in the top layer of NCFI foam predicted from the LS-DYNA simulation. Figure 18(c) shows the LS-DYNA predicted exposure of the Al plate as a result of failure in the interface layer. As discussed previously, the top NCFI foam layer cannot remain intact if the underlying layer has been damaged, so the damage in the two layers is combined. Once these damage areas are combined, they can be compared to the test results (Figure 18(d)).

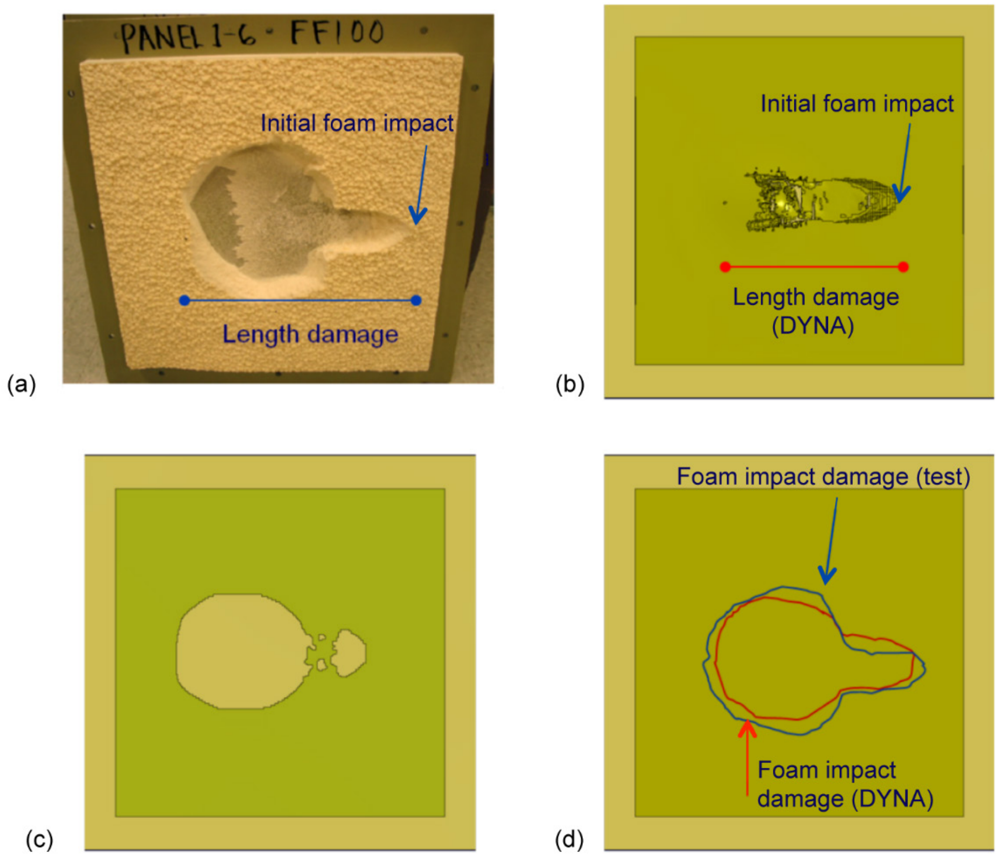


Figure 18.—Test FF100: test and LS-DYNA results. (a) Impact test FF100 at 30°. (b) Damage in 1-in.-foam layer. (c) Damage in interface foam layer. (d) Combined damaged areas.

For test FF109, the impact velocity is greater than test FF100 and the impact angle is shallower (15° versus 30° and 1280 fps versus 1023 fps). Figure 19 shows a comparison between the FF109 test and LS-DYNA results. Figure 19(a) shows the damage in the top layer foam at the test competition. Similar to test FF100, exposed Al plate is produced as a result of the foam impact. Figure 19(b) shows the damage in the top layer of foam predicted from the LS-DYNA simulation while Figure 19(c) shows the LS-DYNA predicted exposure of the Al plate as a result of failure in the interface layer. Figure 19(d) shows the comparison between the area of foam damage in the test and the analysis.

The variability in damage area resulting from the PDL foam impacts onto the NCFI acreage foam plates was not as great as that observed in the ice impacts. This is partially because the damage did not extend to the edge of the acreage foam. Even so, significant variability did occur in these tests. For example, Figure 20 shows a comparison between the damage resulting from test FF109, FF108, and FF107. Tests FF107 and FF108 used the same PDL foam projectile size and impact angle as FF109. In Reference 4, the volume of foam loss reported for FF107 was 41 $in.^3$, for FF108 was 46 $in.^3$, and for FF109 was 38 $in.^3$. Obviously, the sample size in this test series is not large enough to perform reliable statistical analysis on the variability of foam loss. So, simply comparing the largest foam loss in FF108 to the smallest in FF109 shows a difference of ~17 percent.

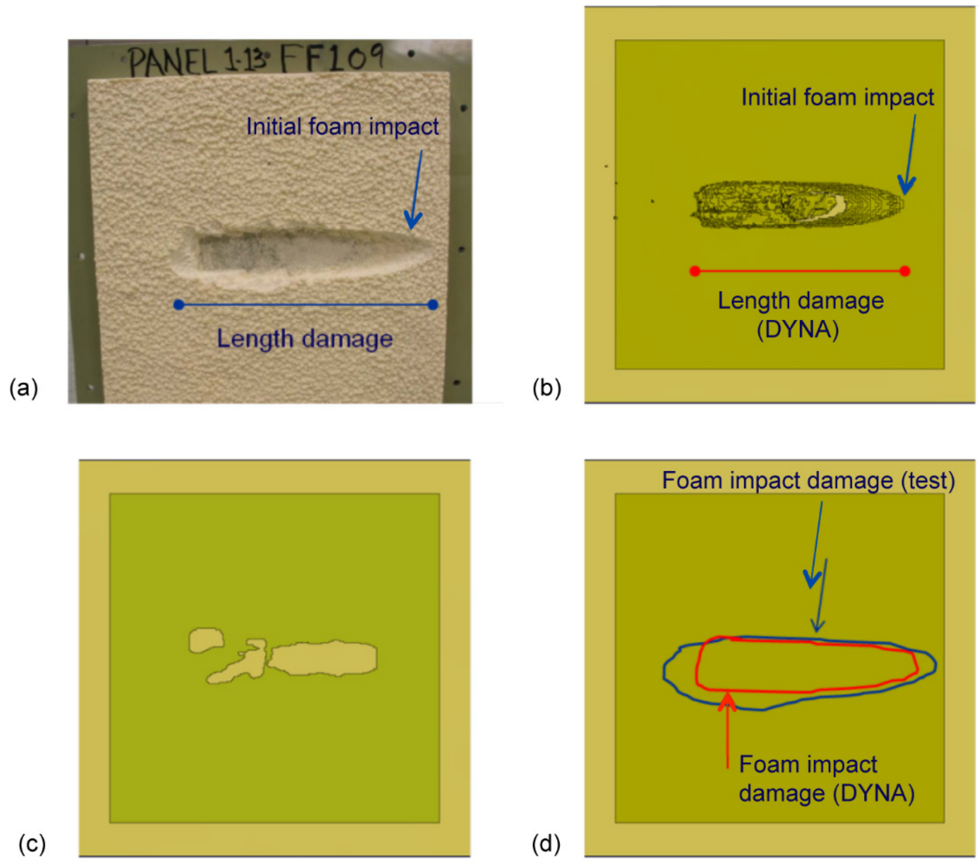


Figure 19.—Test FF109: test and LS-DYNA results. (a) Impact test FF109 at 15°. (b) Damage in 1-in.-foam layer. (c) Damage in interface foam layer. (d) Combined damaged areas.

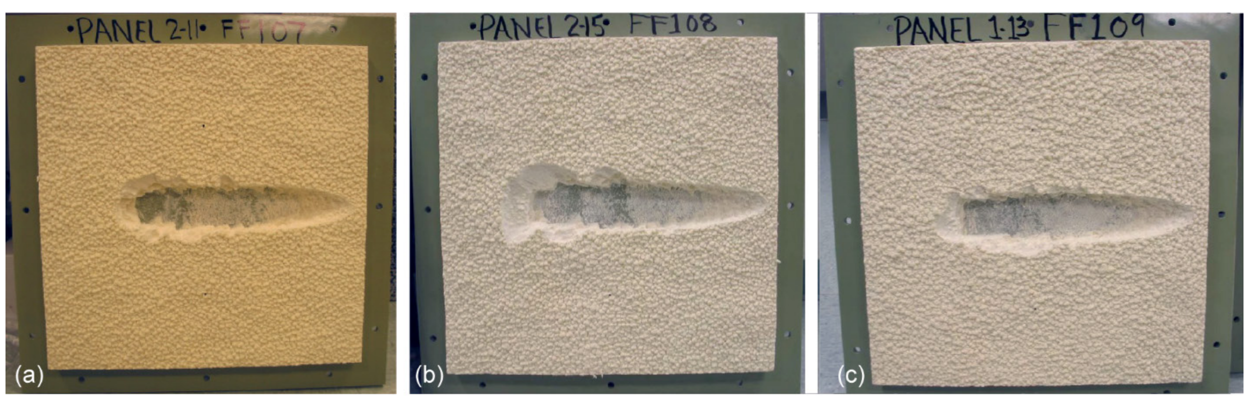


Figure 20.—Damaged foam and exposed Al from low angle foam impacts. (a) Test FF107. (b) Test FF108. (c) Test FF109.

Table 10 summarizes both the ice and PDL foam projectile validation comparisons between test and analysis. The damage area measurements for the PDL foam analysis results were performed in the same manner as for the ice tests. Only the volume of the NCFI foam damage in the tests was given in Reference 4, and not the area. So the area was calculated based upon the photographic documentation. As a result, the test damaged areas in Table 10 are approximate. The difference between the analytical and test foam loss in FF100 was ~8 percent, less than the difference observed between tests FF108 and FF109. The

TABLE 10.—SUMMARY RESULTS FOR BOTH ICE AND PDL FOAM IMPACT VALIDATION TESTS

Test	Projectile, in.	Impact angle, deg.	Velocity, fps	L2/W2, in.	Area, $in.^2$
FF172	Ice 0.75 diam by 1.125 length	15	865	13.5/3.75	39.5 (86.9 test)
FF174	Ice 0.75 diam by 0.72 length	15	872	11.25/3	26.5 35.8 test
FF100	PDL 2.5 diam by 3.72 length	30	1023	13.5/3.75	69.7 (86.9 test)
FF109	PDL 2.5 diam by 3.72 length	15	1280	13/3	30.6 (~38 test)

difference between the analytical and test foam loss in FF109 was ~19 percent, approximately the same difference observed between tests FF108 and FF109. For both PDL foam and ice impacts to the NCFI acreage foam plates, considering the variability in the test results, the analytical results represent an acceptable match to the tests.

4.0 Impact Assessment Results

For this study, two allowable damage criteria are utilized; both the total damaged surface area, and exposed substrate below foam. Total damaged surface area is defined as the surface area damage in the top surface of the top layer of foam combined with the area of damage to the interface layer of foam. As discussed previously, in many cases the projectile burrows below the top layer of foam and damages the interface layer without damage to the top layer just above the location of the projectile. In these cases, while the simulation predicts the top foam layer remaining intact, it is not reasonable to expect that the top layer retains structural integrity in this region, so this region is considered as damaged area. The limit for allowable total foam loss is 16.0 $in.^2$, and was derived from Return-to-Flight limits for the external tank (Ref. 4). For Return-to-Flight it was determined that beyond 16.0 $in.^2$ of foam loss, thermal effects would lead to exceeding allowable stress limits in the underlying structures.

The second criteria; exposed substrate is determined by measuring the area of the damaged interface layer of foam sandwiched between the top layer of foam and the Al plate. Once this layer is damaged, it is assumed that all of the foam in the top layer will lose its structural integrity, and the underlying Al plate will be exposed to the outside environment. The limit for exposed substrate is 1.7 $in.^2$, and similarly to the total foam loss limit, was derived from Return-to-Flight limits for the external tank (Ref. 4). For Return-to-Flight it was determined that beyond 1.7 $in.^2$ of exposed substrate, thermal effects would lead to exceeding allowable stress limits in the underlying structures.

The allowable damage criteria based on Shuttle limits is a reasonable starting point for SLS, however, the specific limits for SLS may differ from Shuttle. Therefore, SLS limits will need to be determined before the results of this study may be applied to SLS.

Two different impact angles were used for both the ice and PDL foam SLS impact study; 5° and 10°. For SLS, it is expected that the impact angles on acreage foam will be small because the vehicle generally possesses a smooth contour in the direction of flight. Therefore, impact angles greater than 10° were not evaluated.

TABLE 11.—SLS ICE IMPACT CONDITIONS

Impact angle, deg.	PDL foam cylinder		
	Diameter, in.	Length, in.	Weight, lb
10	0.75	0.72	0.011
10	0.946	0.907	0.021
10	1.189	1.142	0.041
10	1.499	1.4387	0.082
5	0.75	0.72	0.011
5	0.946	0.907	0.021
5	3.547	5.25	0.041
5	1.502	1.440	0.082

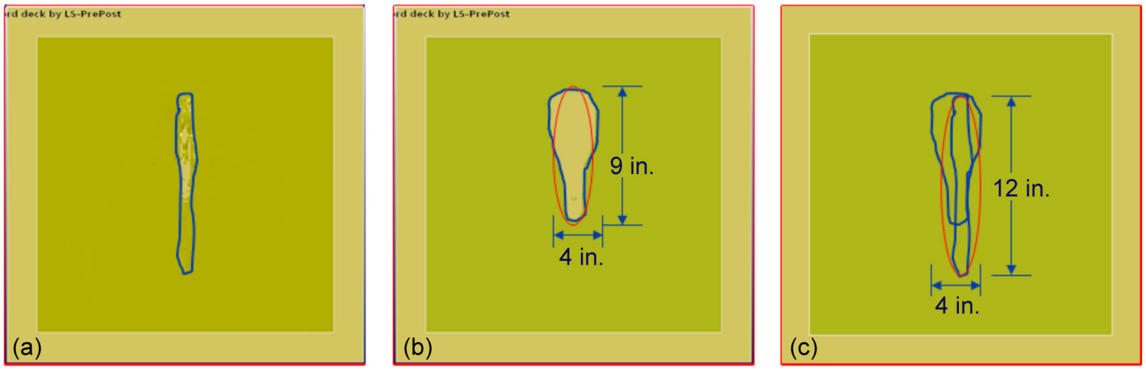
4.1 Ice Impact Results

To determine ice impact limits which can be used by the SLS project, damage predicted by LS-DYNA for combinations of impact angles, projectile size, and projectile velocities, is compared to the allowable limits, and the boundary of impact conditions that do not exceed the limits can be generated. The combinations of size and angle which were analyzed are reported in Table 11. The damaged area of acreage foam due to ice impact for each of these conditions is also reported.

The small ice projectile size was initially used, and then the projectile size was increased until projectile size did not affect the maximum allowable impact velocity. Once the ice projectile diameter becomes larger than the thickness of the top foam layer, increasing the projectile size has little effect on the damaged area.

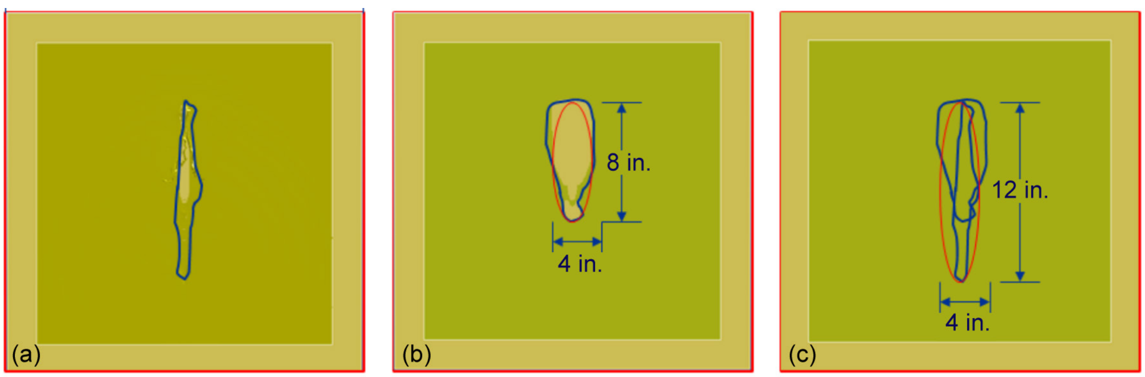
It is important to mention that only cylindrically shaped ice projectiles were studied. The same dimension cylinder that was used for the FF174 was used for the smallest SLS projectile (0.011 lb). For subsequent ice projectile sizes, the ratio of diameter to length was held constant, and the size was increased so the mass of the ice was double that of the previous size projectile. Projectile shape will have some effect of damage, however it was not practical, at this time, to study multiple projectile shapes. Another important item to note is that for the results presented below, the LS-DYNA simulations were sometimes terminated before the projectile completed its trajectory, and before all of the damage was completed. The reason for this was that once the allowable damage limits were exceeded, the runs were sometimes terminated to free up computer resources to enable subsequent impact conditions to be analyzed. Performing the analysis in this way did not affect the resulting impact limits; however for the runs that were terminated early, the actual damage may have been underestimated.

Figure 21 to Figure 26 show the LS-DYNA results for the 0.011 lb projectile impacting with a 10° impact angle. For the 872 fps impact velocity (Figure 21), both the exposed substrate, and the total foam loss, exceeds the allowable values, and the impact velocity must be reduced to determine the allowable Impact velocity limit. At 700 fps, both limits are still exceeded (Figure 23), and the impact velocity is further reduced. At 500 fps, only the exposed substrate limit is exceeded, and once again, the impact velocity is reduced. It is not until 400 fps that neither the exposed substrate nor the total foam loss limits are exceeded, and the maximum allowable impact velocity is identified.



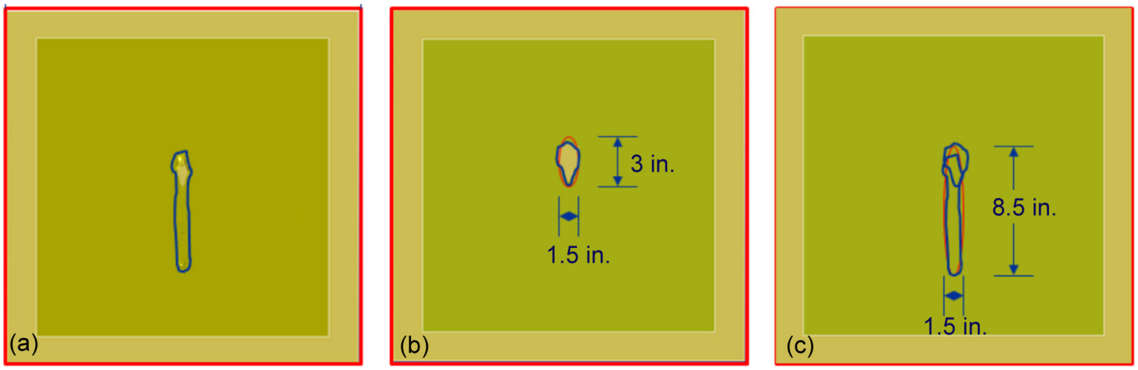
Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}
0.75 diam by 0.72 L	10	872	9/4	28 Exceeds	1.7	12/4	38 Exceeds	16.1

Figure 21.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 872 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.



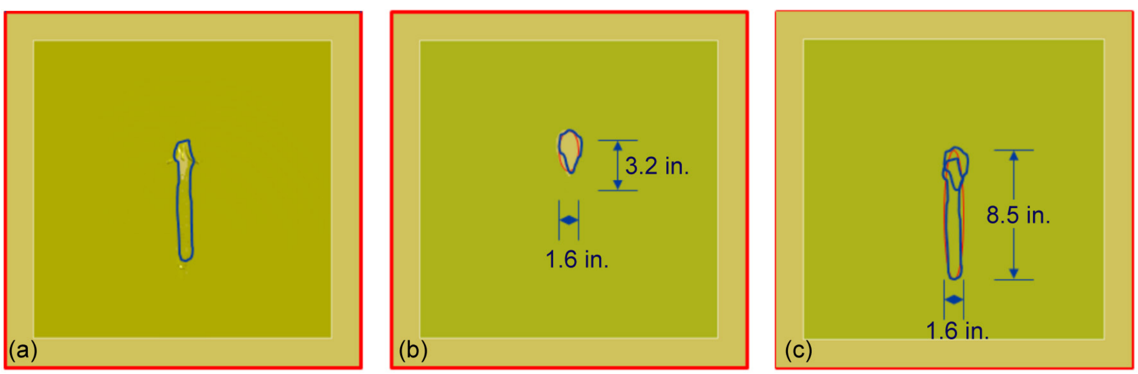
Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}
0.75 diam by 0.72 L	10	700	8/4	25 Exceeds	1.7	12/4	38 Exceeds	16.1

Figure 22.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 700 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.



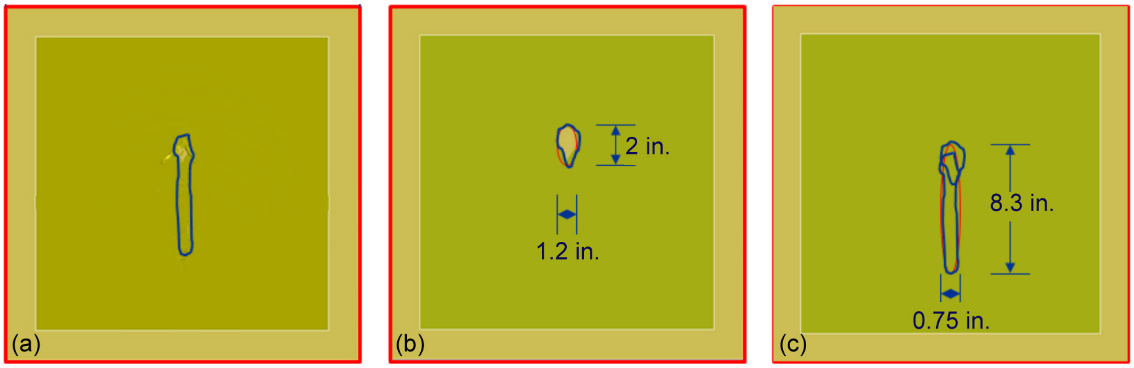
Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}
0.75 diam by 0.72 L	10	500	3/1.5	3.5 Exceeds	1.7	8.5/1.5	10 OK	16.1

Figure 23.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 500 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.



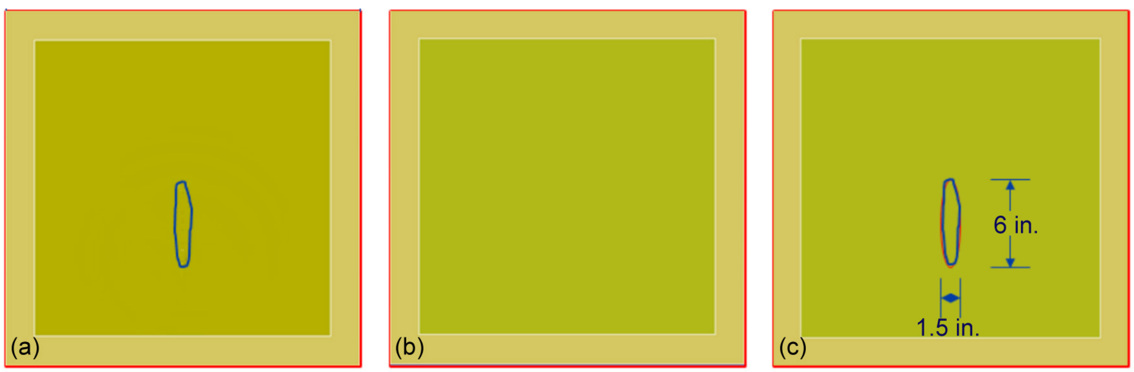
Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} $\pi/4(L2*W2)$	Target area, in.^{2}
0.75 diam by 0.72 L	10	450	3.2/1.6	4.0 Exceeds	1.7	8.5/1.6	10.7 OK	16.1

Figure 24.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 450 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.



Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} π/4(L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4(L2*W2)	Target area, in.^{2}
0.75 diam by 0.72 L	10	425	2/1.2	1.9 Exceeds	1.7	8.3/0.75	4.9 OK	16.1

Figure 25.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 425 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.



Parameters		Interface foam (exposed Al plate)				Total foam loss		
Ice projectile, in.	Impact angle, deg	Velocity, fps	L2/W2, in.	Area, in.^{2} π/4(L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4(L2*W2)	Target area, in.^{2}
0.75 diam by 0.72 L	10	400	0/0	0 OK	1.7	6/1.5	7 OK	16.1

Figure 26.—Ice projectile: 0.75-in.-diameter by 0.72-in.-length, 10° impact angle, 400 fps impact velocity. (a) Damage in 1-in.-thick foam layer. (b) Interface foam (exposed Al plate). (c) Total foam loss.

Figure 27 shows a summary for the 0.75-in.-diameter by 0.72-in.-length. Ice projectile, 10° impact angle. As discussed above, the total damaged area criterion is exceeded when the impact velocity is greater than 540 fps. The exposed substrate criterion is exceeded at only 425 fps, and therefore dictates the critical impact velocity. In general there is less damaged foam and exposed substrate as the impact velocity is decreased; however the trend is not completely linear. At the lowest impact velocities, minimal amounts of the projectile reach the substrate, limiting the creation of exposed substrate. This trend is largely linear, and exposed substrate is required to create large amounts of damage. This effect minimizes the non-linear pattern at the lowest velocities.

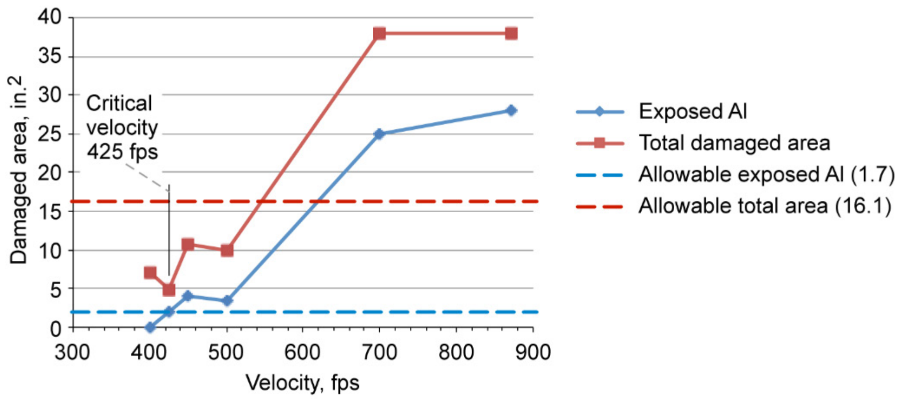


Figure 27.—Summary for 0.75-in.-diameter by 0.72-in.-length ice projectile, 10° impact angle.

TABLE 12.—LS-DYNA RESULTS FOR 0.946-in. DIAMETER BY 0.907-in. LENGTH (0.021 lb) ICE PROJECTILE, 10° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, In.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, In.^{2}
-	0.946 diam. by 0.907 length	10	300	0/0	0 OK	1.7	9.3/1.0	7.3 OK	16.1
-	0.946 diam. by 0.907 length	10	325	7.8/2.0	12.2 NG	1.7	13.1/1.5	15.4 OK	16.1
-	0.946 diam. by 0.907 length	10	350	8.3/1.6	10.4 NG	1.7	12.4/2.0	19.5 NG	16.1
-	0.946 diam. by 0.907 length	10	400	7.6/1.7	10.1 NG	1.7	12.9/1.3	13.2 OK	16.1
-	0.946 diam. by 0.907 length	10				1.7			16.1

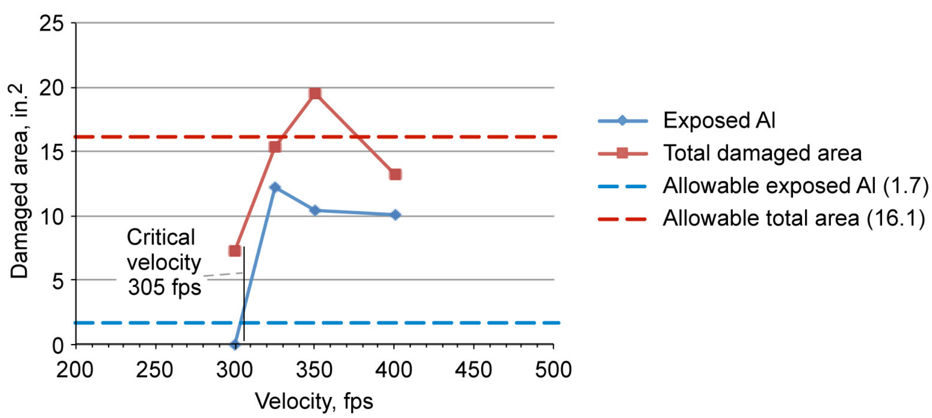


Figure 28.—Summary for 0.946-in.-diameter by 0.907-in.-length (0.021 lb), 10° impact angle.

The next step was to maintain the impact angle, and to double the weight of the ice projectile. Table 12 shows a summary of the LS-DYNA results for 0.946-in.-diameter by 0.907-in.-length (0.021 lb) ice projectile. At an impact velocity of 400 fps, the exposed substrate criterion was exceeded while the total foam loss was within the allowable limit. When the speed was reduced to 350 fps, both the exposed substrate and total foam loss criteria were exceeded. The total foam loss actually increased at the slower speed because at the slower speed the ice projectile did not travel directly to the substrate. Instead, the projectile was ‘caught’ in the foam layer, began to tumble, and did more damage to the foam top layer than at the higher impact velocity. The impact velocity had to be lowered to 300 fps before both the exposed substrate and total foam loss were both within the allowable criteria. Figure 28 shows the results of Table 12 graphically.

The ice projectile weight was doubled, once again, and the resulting LS-DYNA predictions are shown in Table 13 and Figure 29. As expected, the impact velocity had to be lowered even further to meet the damage criteria compared to the smaller sized ice projectiles. At first look, it is surprising that the damage incurred at 200 fps is greater than the damage predicted at 300 fps. After closer examination (Figure 30), it was observed that at the higher velocity, the ice projectile slices a longer path through the foam, but less of the ice breaks-up, so the path is narrower than for the 200 fps impact. For the 200 fps impact, the ice projectile does not travel as far, but the ice breaks up more extensively, so the damage done to the foam is broader. It is important to note that the exact quantitative value for damage for the 200 and 300 fps conditions is not overly critical since both impact conditions exceed the allowable limits. What is more important is the velocity where the damage is equal to the limit since this velocity defines the critical impact velocity. Regardless of the actual damage values for the 200 and 300 fps impacts, so long as these conditions exceed the allowable, the critical velocity would still be reasonably close to 180 fps.

TABLE 13.—LS-DYNA RESULTS FOR 1.189 in. DIAMETER BY 1.142 in. LENGTH (0.041 lb) ICE PROJECTILE, 10° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}
-	1.189 diam. by 1.142 length	10	150	0/0	0 OK	1.7	9.6/1.0	7.5 OK	16.1
-	1.189 diam. by 1.142 length	10	175	0/0	0 OK	1.7	12.5/1.1	10.8 OK	16.1
-	1.189 diam. by 1.142 length	10	200	7.6/6.8	40 NG	1.7	7.6/6.8	40 NG	16.1
-	1.189 diam. by 1.142 length	10	300	9.1/2.4	17.2 NG	1.7	9.1/2.4	17.2 NG	16.1

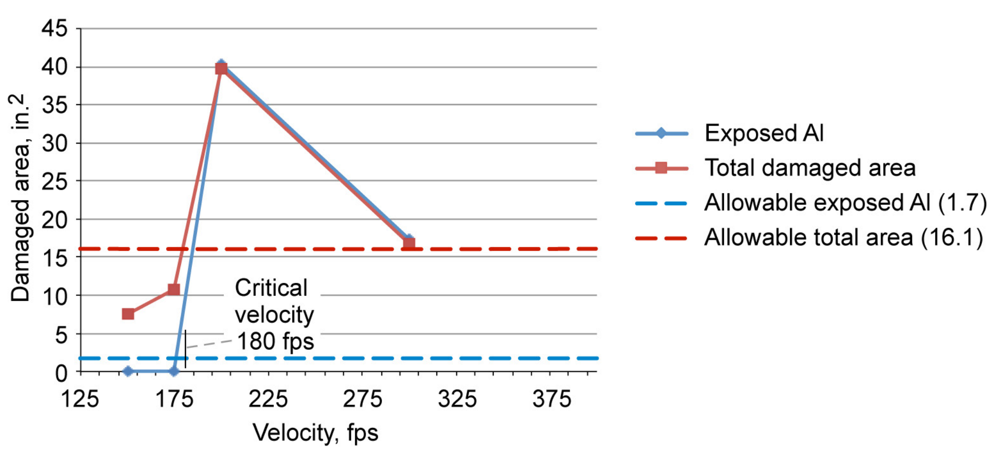


Figure 29.—Summary for 1.189-in.-diameter by 1.142-in.-length (0.041 lb) ice projectile, 10° impact angle.

The weight of the fourth and final ice projectile size that was investigated was 0.082 lb. It was only necessary to run two conditions to locate the critical impact velocity, and as expected since this was the largest projectile size, the critical impact velocity was less than for the previous ice projectile sizes. These results are shown in Table 14 and Figure 31.

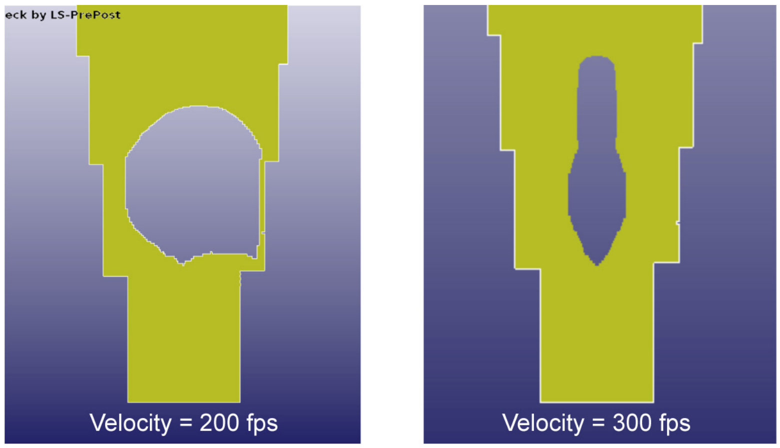


Figure 30.—Exposed substrate for 1.189-in.-diameter by 1.142-in.-length (0.041 lb) ice projectile, 10° impact angle.

TABLE 14.—LS-DYNA RESULTS FOR 1.499-in.-DIAMETER BY 1.4387-in.-LENGTH (0.081 lb) ICE PROJECTILE, 10° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}
-	1.499 diam. by 1.4387 length	10	150	0/0	0 OK	1.7	12.5/1.4	13.7 OK	16.1
-	1.499 diam. by 1.4387 length	10	200	12.5/3.3	32 NG	1.7	16.8/2.5	33 NG	16.1

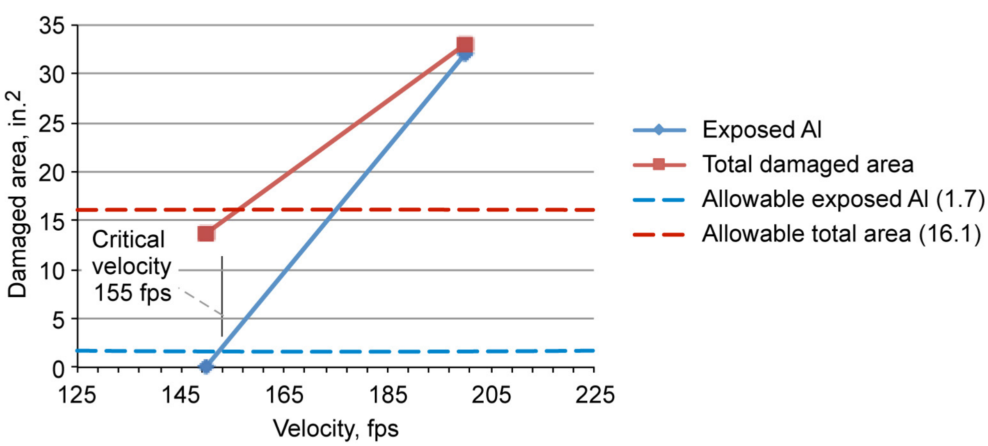


Figure 31.—Summary for 1.499-in.-diameter by 1.4387-in.-length (0.081 lb) ice projectile, 10° impact angle.

After completion of the 10° impact analyses with a range of ice projectile sizes, the impact angle was reduced to 5°, and the analyses were repeated with the same size projectiles. The LS-DYNA results for the smallest, 0.011 lb, projectiles are shown in Table 15 and Figure 32. For this shallow impact angle, and small sized ice projectile, the projectile never caused enough damage to exceed the allowable, regardless of the impact velocity. At higher impact velocities, the ice tends to inflict slightly more damage to the top layer of foam, but, at higher velocities the ice also breaks up faster which tends to limit the total amount of damage. Regardless of the impact velocity, the ice projectile never penetrates through to the substrate, so there is never any damage to the exposed substrate.

TABLE 15.—LS-DYNA RESULTS FOR 0.75-in.-DIAMETER BY 0.72-in.-LENGTH (0.011 lb) ICE PROJECTILE, 5° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}
-	0.75 diam. by 0.72 length	5	500	0/0	0 OK	1.7	8/1.5	9.4 OK	16.1
-	0.75 diam. by 0.72 length	5	600	0/0	0 OK	1.7	14/.8	8.8 OK	16.1
-	0.75 diam. by 0.72 length	5	700	0/0	0 OK	1.7	15.4/.9	10.9 OK	16.1
-	0.75 diam. by 0.72 length	5	800	0/0	0 OK	1.7	15.6/.95	11.5 OK	16.1
-	0.75 diam. by 0.72 length	5	1000	0/0	0 OK	1.7	12.7/.94	9.4 OK	16.1
-	0.75 diam. by 0.72 length	5	1200	0/0	0 OK	1.7	12.7/1.1	11 OK	16.1
-	0.75 diam. by 0.72 length	5	1800	0/0	0 OK	1.7	13.6/1.1	11.7 OK	16.1
-	0.75 diam. by 0.72 length	5	2500	0/0	0 OK	1.7	14.4/1.1	12.4 OK	16.1

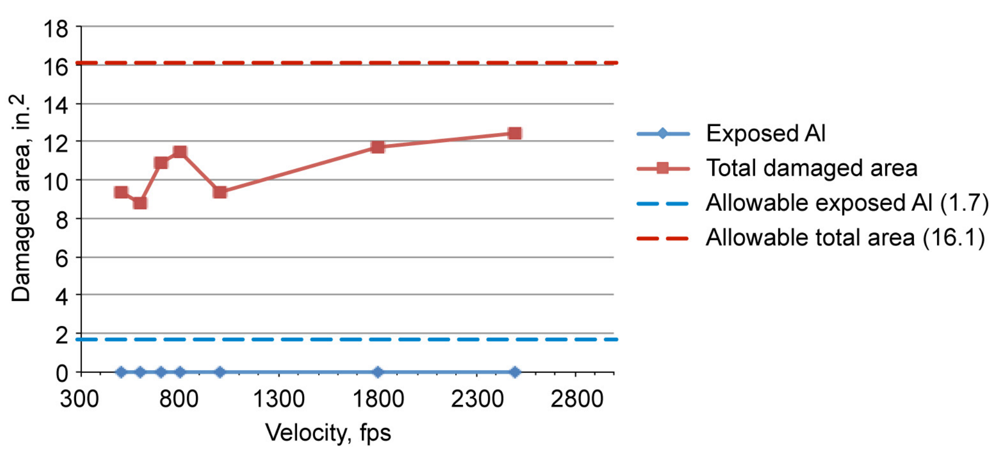


Figure 32.—Summary for 0.75-in.-diameter by 0.72-in.-length (0.011 lb) ice projectile, 5° impact angle.

Table 16 and Figure 33 show the LS-DYNA results for the 0.946-in.-diameter by 0.907-in.-length (0.021 lb) ice projectile at 5° impact angle. For these impact conditions, and the range of impact velocities examined, the total foam loss never exceeds the allowable limit. Up until close to 1900 fps impact velocity, the ice projectile does not penetrate all the way to the substrate so there is no exposed substrate. At the critical velocity of 1950 fps, the exposed substrate just reaches the allowable limit. Figure 34 shows the total damage in the foam layer and exposed substrate.

TABLE 16.—LS-DYNA RESULTS FOR 0.946-in.-DIAMETER BY 0.907-in.-LENGTH (0.021 lb) ICE PROJECTILE, 5° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} $\pi/4$ (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} $\pi/4$ (L2*W2)	Target area, in.^{2}
-	0.946 diam. by 0.907 length	5	800	0/0	0 OK	1.7	16.7/.95	12.5 OK	16.1
-	0.946 diam. by 0.907 length	5	1500	0/0	0 OK	1.7	17.2/1.2	16.2	16.1
-	0.946 diam. by 0.907 length	5	1750	0/0	0 OK	1.7	17.4/1.1	15.0 OK	16.1
-	0.946 diam. by 0.907 length	5	1900	0/0	0 OK	1.7	17.8//1.1	15.4 OK	16.1
-	0.946 diam. by 0.907 length	5	2000	1.4/1.9	2.1 NG	1.7	17.9/1.1	15.5 OK	16.1

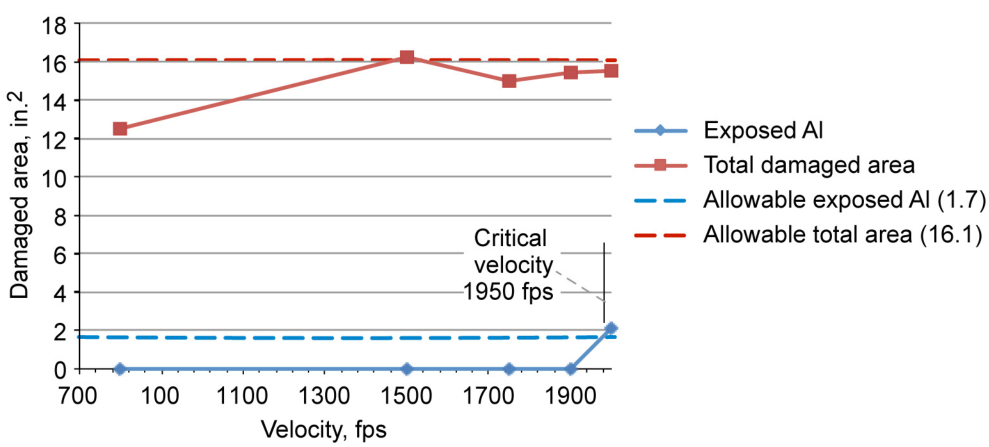


Figure 33.—Summary for 0.946-in.-diameter by 0.907-in.-length (0.021 lb) ice projectile, 5° impact angle.

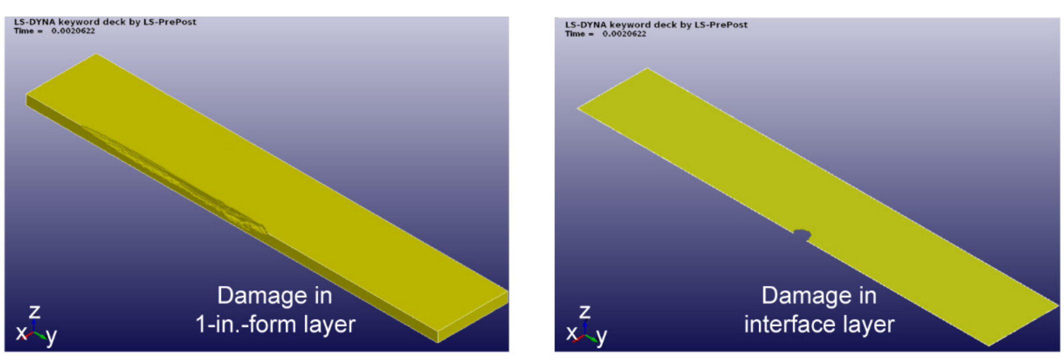


Figure 34.—Damage in foam layer and exposed substrate for 0.946-in.-diameter by 0.907-in.-length (0.021 lb) ice projectile, 5° impact angle.

Table 17 and Figure 35 show the LS-DYNA results for the 1.192-in.-diameter by 1.1428-in.-length (0.041 lb) ice projectile at 5° impact angle. For this size projectile, the damage is highly nonlinear in that the damage does not decrease linearly with impact velocity. Instead, the damage is maximum at an intermediate impact velocity (~600 fps), and is less at higher and lower impact velocities. The critical impact velocity is 350 fps.

TABLE 17.—LS-DYNA RESULTS FOR 1.192-in.-DIAMETER BY 1.1428-in.-LENGTH (0.041 lb) ICE PROJECTILE, 5° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}
-	1.192 diam. by 1.1428 length	5	300	0/0	0 OK	1.7	15/1.2	14.1 OK	16.1
-	1.192 diam. by 1.1428 length	5	350	0/0	0 OK	1.7	17.2/1.2	16.2 NG	16.1
-	1.192 diam. by 1.1428 length	5	400	6.8/2.6	13.9 NG	1.7	18.8/1.1	16.2 NG	16.1
-	1.192 diam. by 1.1428 length	5	600	13.9/3.7	40.4 NG	1.7	22.5/1.2	21.2 NG	16.1
-	1.192 diam. by 1.1428 length	5	800	4.1/1.9	6.1 NG	1.7	12.4/1.3	12.7 OK	16.1
-	1.192 diam. by 1.1428 length	5	1000	13.7/1.8	19.4 NG	1.7	24.2/1.1	20.9 NG	16.1
-	1.192 diam. by 1.1428 length	5	1500	8.5/.83	5.5 NG	1.7	21.6/1.6	27.1 NG	16.1

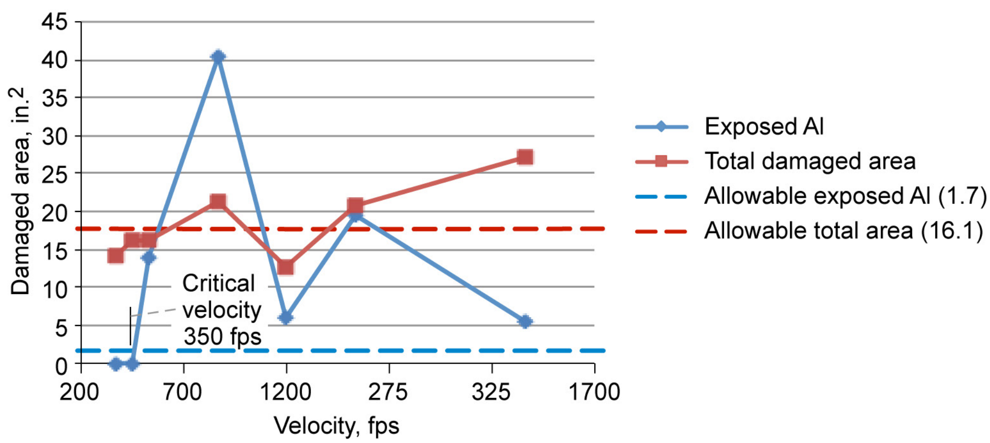


Figure 35.—Summary for 1.192-in.-diameter by 1.1482-in.-length (0.041 lb) ice projectile, 5° impact angle.

Table 18 and Figure 36 show the LS-DYNA results for the 1.502 in. diameter x 1.440 in. length (0.082 lb) ice projectile at 5° impact. For this size projectile the damage to the foam and the quantity of exposed substrate is extensive above an impact velocity of 400 fps. Both types of damage decrease below 400 fps, and reach an allowable impact velocity at 275 fps.

Table 19 shows the ice summary results for both the 10° and 5° impact angles and the four sizes of projectiles. Figure 37 shows the Ice projectile critical velocity vs. projectile size. As expected, the critical impact velocity decreases as the size of the projectile increases, and the steeper impact angle (10° has lower critical velocities than the more shallow (5°) impact angle. As mentioned earlier, the critical impact velocity levels off for larger ice projectiles since the diameter of the larger size projectile exceeds the thickness of the top layer of foam, so part of the projectile does not make contact with the foam. It is also interesting to note that for all but one impact condition, the exposed Al (exposed substrate) criteria drives the allowable impact velocity since this criteria is exceeded before the total foam loss criteria is reached.

TABLE 18.—LS-DYNA RESULTS FOR 1.502-in.-DIAMETER BY 1.440-in.-LENGTH (0.082 lb) ICE PROJECTILE, 5° IMPACT

Test	Ice projectile, in.	Impact angle, deg.	Velocity, fps	Interface foam (exposed Al plate)			Total foam loss		
				L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}	Combined foam L2/W2, in.	Area, in.^{2} π/4 (L2*W2)	Target area, in.^{2}
-	1.502 diam. by 1.440 length	5	250	0	0 OK	1.7	13.9/1.3	14.2 OK	16.1
-	1.502 diam. by 1.440 length	5	275	0	0 OK	1.7	15.4/1.3	15.7 OK	16.1
-	1.502 diam. by 1.440 length	5	300	0	0 OK	1.7	16.7/1.4	18.8 NG	16.1
-	1.502 diam. by 1.440 length	5	400	6.4/2.9	14.6 NG	1.7	19.3/1.2	18.2 NG	16.1
-	1.502 diam. by 1.440 length	5	600	16.5/5	65 NG	1.7	25/3.75	74 NG	16.1

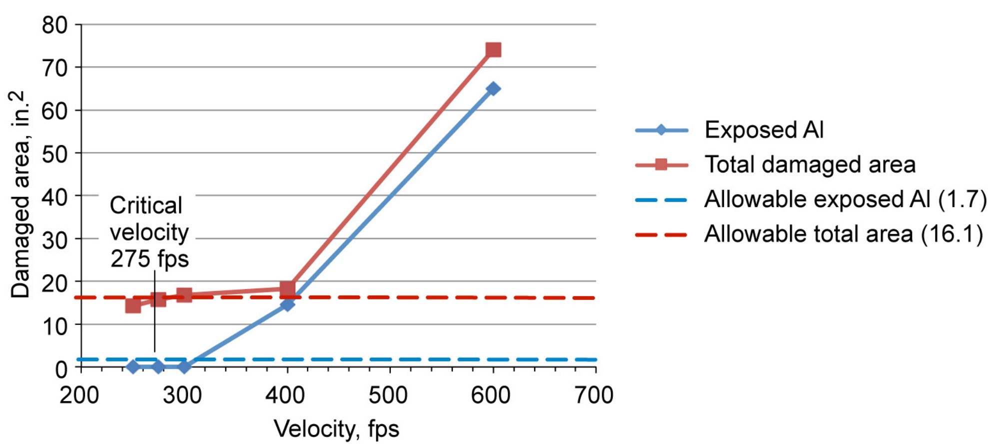


Figure 36.—Summary for 1.502-in.-diameter by 1.440-in.-length (0.082 lb) ice projectile, 5° impact angle.

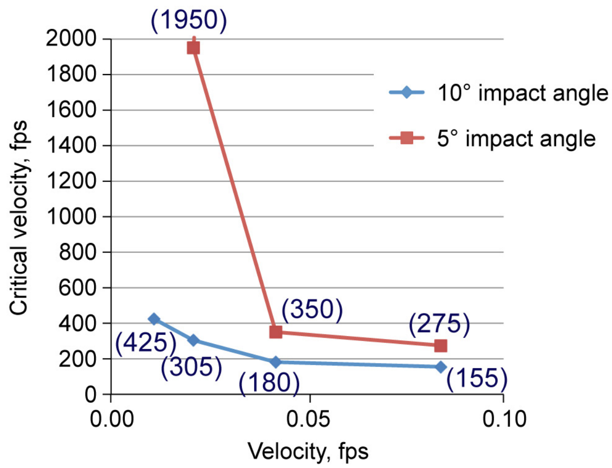


Figure 37.—Ice projectile critical velocity versus projectile size.

TABLE 19.—ICE PROJECTILE SUMMARY RESULTS

Impact angle, deg	Ice cylinder			Critical impact velocity, fps	Criteria Exceeded	
	Diameter, in.	Length , in.	Weight ice, oz.		Exposed Al	Total foam loss surface area
10	0.75	0.72	0.011	425	Yes	---
10	0.946	0.907	0.021	305	Yes	---
10	1.189	1.142	0.041	180	Yes	---
10	1.499	1.4387	0.082	155	Yes	---
5	0.75	0.72	0.011	No limit	---	---
5	0.946	0.907	0.021	1950	Yes	---
5	1.192	1.1428	0.041	350	Yes	---
5	1.502	1.440	0.082	275	---	Yes

4.2 PDL Foam Impact Results

PDL foam impact results for SLS are determined for combinations of impact angles, projectile size, and projectile velocities, then compared to the allowable limits, so the boundary of impact conditions that do not exceed the limits can be generated.

TABLE 20.—SLS PDL FOAM IMPACT CONDITIONS

Impact angle, deg.	PDL foam cylinder		
	Diameter, in.	Length, in.	Weight, lb
10	1.646	2.437	0.010
10	2.5	3.72	0.035
10	3.547	5.25	0.100
5	1.646	2.437	0.010
5	2.5	3.72	0.035
5	3.547	5.25	0.100
5	4.47	6.614	0.200

The combinations of size and angle which were analyzed are reported in Table 20. The damaged area of acreage foam due to PDL foam impact for each of these conditions is also reported.

It is important to mention that, as in the ice assessment, only cylindrically shaped PDL foam projectiles were studied. The medium weight projectile (0.035 lb) that was assessed had the same dimensions as the cylindrical projectile used in the verification tests. For the other projectile sizes, the ratio of diameter to length was held constant, while the size was varied. Projectile shape will have an effect on damage. In particular, with foam masses of 0.1 lb and greater, not all of the foam in a cylindrical or square projectile would necessarily interact with the NCFI acreage foam. A higher aspect ratio rectangular foam projectile shape, with the same larger mass, will remove more acreage foam than the geometry studied. However, as in the ice assessment, it was not practical to study multiple projectile shapes.

The general procedure for measuring damaged areas and selecting velocities to analyze is essentially the same as discussed previously in the ice impact assessment. Table 21 shows a summary of LS-DYNA results for 1.646-in.-diameter by 2.437-in.-length (0.01 lb) PDL foam projectile impacting at a 10° angle. For the 1600 fps impact velocity, both the exposed substrate, and the total foam loss, exceeds the allowable values, and the impact velocity must be reduced to determine the allowable impact velocity limit. At 1250 fps, only the exposed substrate limit is exceeded, and once again, the impact velocity is reduced. At 1100 fps neither the exposed substrate nor the total foam loss limits are exceeded, and the maximum allowable impact velocity is identified. In general there is less damaged foam and exposed substrate as the impact velocity is decreased; however the trend is clearly not linear. Figure 38 shows the results of Table 21 graphically.

TABLE 21.—LS-DYNA RESULTS FOR 1.646-in.-DIAMETER BY 2.437-in.-LENGTH (0.01 lb) PDL FOAM PROJECTILE, 10° IMPACT

Velocity, fps	10° impact angle		PDL foam mass 0.01 lb		Diameter = 1.646 in.		Length = 2.437 in.		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
750	7.30	1.77	10.15	OK	0.00	0.00	0.00	OK	0.24
900	9.36	1.77	13.02	OK	0.00	0.00	0.00	OK	0.19
1000	7.92	1.77	11.02	OK	0.00	0.00	0.00	OK	0.25
1100	7.86	1.90	11.75	OK	0.00	0.00	0.00	OK	0.19
1250	8.22	1.87	12.08	OK	2.81	2.64	5.83	Exceeds	0.00
1500	9.48	1.90	14.13	OK	5.36	1.25	5.27	Exceeds	0.00
1550	10.11	1.90	15.12	OK	7.26	2.72	15.53	Exceeds	0.00
1600	11.18	1.91	16.74	Exceeds	3.09	1.97	4.79	Exceeds	0.00
1650	10.81	1.91	16.17	Exceeds	6.92	2.88	15.66	Exceeds	0.00
1700	11.93	1.90	17.84	Exceeds	8.16	2.49	15.95	Exceeds	0.00
1800	12.06	1.97	18.61	Exceeds	4.37	1.32	4.52	Exceeds	0.00

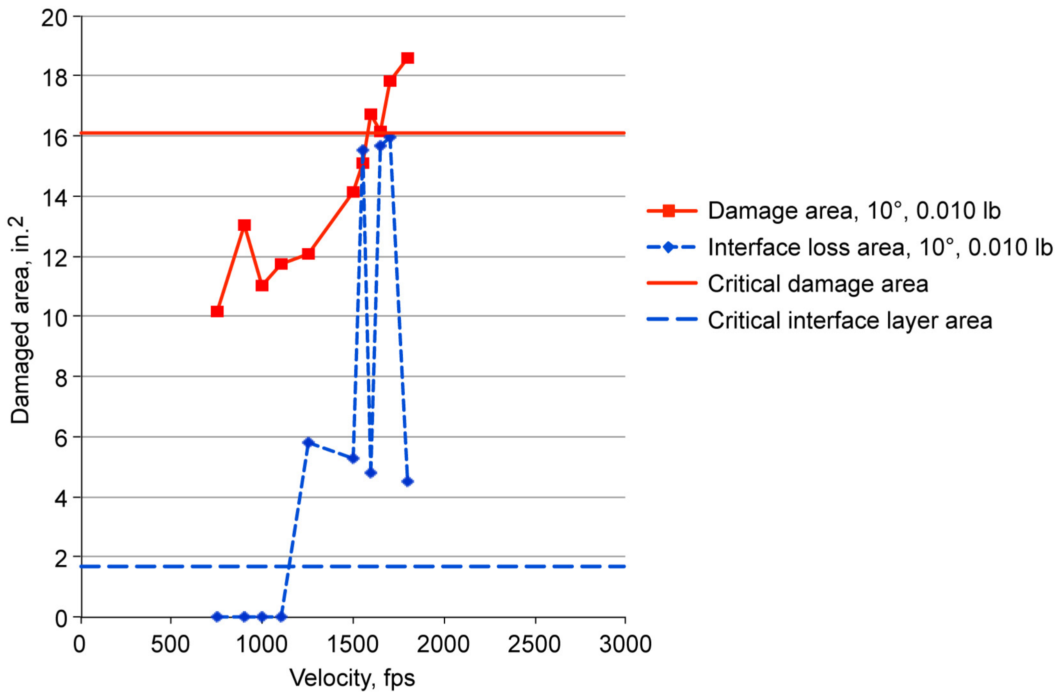


Figure 38.—Summary for 1.646-in.-diameter by 2.437-in.-length (0.01 lb) PDL foam projectile, 10° impact angle.

Given the highly non-linear nature of the physics, including the non-linear material behavior of the foams (Figure 1 and Figure 2), it is expected that the damage area versus velocity trends would also not be linear. The non-linear nature of these trends has been clearly visible in the ice impact results. However, the degree of sensitivity that foam loss in the interface layer shows to small changes in velocity is extreme (Figure 38). The PDL projectile foam has a similar density and strength as the NCFI acreage foam. As a result, it does not burrow into the NCFI foam while remaining largely intact as the ice does. Therefore, whether or not the NCFI foam interface layer fails depends on the velocity of the complex shock waves traveling through the foam, and whether or not they are in in-phase with the reflection from the Al backing plate. In other words, the foam on foam impact may create a non-linear resonance condition. When the resonance condition is created, the interface layer failure area is large. When not in resonance, the interface layer area is smaller. This behavior is also seen in the 5° tests with the 0.035 lb PDL projectile (Figure 42), and the 5° tests with the 0.1 lb PDL projectile (Figure 43).

The next step was to maintain the impact angle, and to increase the weight of the PDL foam projectile. Table 22 shows a summary of LS-DYNA results for 2.5-in.-diameter by 3.72-in.-length (0.035 lb) PDL foam projectile impacting at a 10° angle. The total foam loss exceeded the allowable value at very velocity analyzed, and the exposed substrate allowable was exceeded when the velocity was at or greater than 750 fps. Figure 39 shows the results of Table 22 graphically.

TABLE 22.—LS-DYNA RESULTS FOR 2.5-in.-DIAMETER BY 3.72-in.-LENGTH (0.035 lb) PDL FOAM PROJECTILE, 10° IMPACT

Velocity, fps	10° impact angle		PDL foam mass 0.035 lb		Diameter = 2.5 in		Length = 3.72 in		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
250	13.07	2.80	28.74	Exceeds	0.00	0.00	0.00	OK	0.13
500	15.55	2.79	34.07	Exceeds	0.00	0.00	0.00	OK	0.07
600	14.42	2.79	31.60	Exceeds	0.00	0.00	0.00	OK	0.07
650	13.86	2.79	30.37	Exceeds	0.00	0.00	0.00	OK	0.07
700	13.92	2.79	30.50	Exceeds	0.00	0.00	0.00	OK	0.07
725	14.23	2.80	31.29	Exceeds	0.00	0.00	0.00	OK	0.07
750	14.86	2.64	30.81	Exceeds	5.24	1.62	6.67	Exceeds	0.00
1000	13.65	2.80	30.02	Exceeds	10.68	2.34	19.63	Exceeds	0.00
1500	14.85	2.95	34.41	Exceeds	9.67	1.97	14.96	Exceeds	0.00

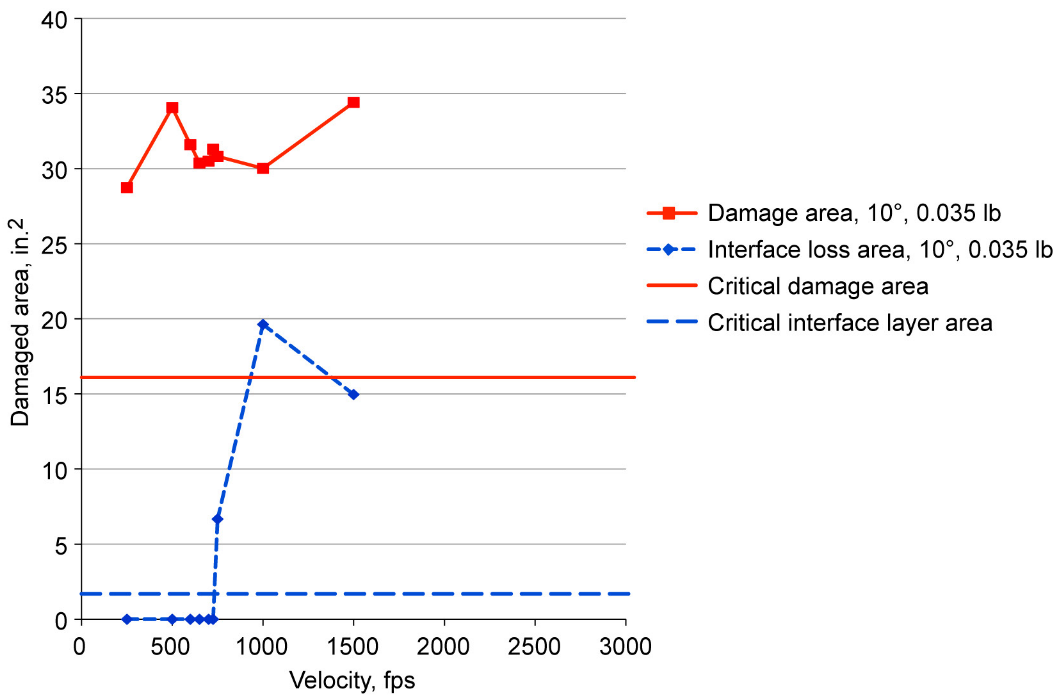


Figure 39.—Summary for 2.5-in.-diameter by 3.72-in.-length (0.035 lb) PDL foam projectile, 10° impact angle.

The weight of the PDL foam projectile was increased again to 0.1 lb Table 23 shows a summary of LS-DYNA results for 3.547-in.-diameter by 5.25-in.-length (0.1 lb) PDL foam projectile impacting at a 10° angle. The total foam loss exceeded the allowable value at every velocity analyzed, and the exposed substrate allowable was exceeded when the velocity was at or greater than 725 fps. Note that while the velocity at which the exposed substrate criterion was exceeded does not vary significantly from the 0.035 lb assessment, the area of damage is much greater with the larger, 0.1 lb projection. Figure 40 shows the results of Table 23 graphically.

TABLE 23.—LS-DYNA RESULTS FOR 3.547-in.-DIAMETER BY 5.25-in.-LENGTH (0.1 lb) PDL FOAM PROJECTILE, 10° IMPACT

Velocity, fps	10° impact angle		PDL foam mass 0.1 lb		Diameter = 3.547 in.		Length = 5.25 in.		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
500	17.32	3.53	48.01	Exceeds	0.00	0.00	0.00	OK	0.19
600	17.55	4.14	57.06	Exceeds	0.25	0.17	0.03	OK	0.00
700	17.36	4.06	55.32	Exceeds	0.00	0.00	0.00	OK	0.07
710	16.67	3.79	49.60	Exceeds	1.65	0.88	1.14	OK	0.00
725	17.16	3.87	52.19	Exceeds	6.54	1.97	10.14	Exceeds	0.00
750	23.61	6.28	116.51	Exceeds	17.05	6.28	84.14	Exceeds	0.00
1000	20.36	4.05	64.73	Exceeds	14.60	4.05	46.40	Exceeds	0.00
1500	25.25	4.07	80.78	Exceeds	19.59	3.96	60.93	Exceeds	0.00
2000	25.22	7.22	143.08	Exceeds	13.36	7.22	75.76	Exceeds	0.00
2500	24.21	5.01	95.32	Exceeds	12.06	5.01	47.47	Exceeds	0.00
3000	27.17	4.76	101.60	Exceeds	14.85	4.76	55.54	Exceeds	0.00

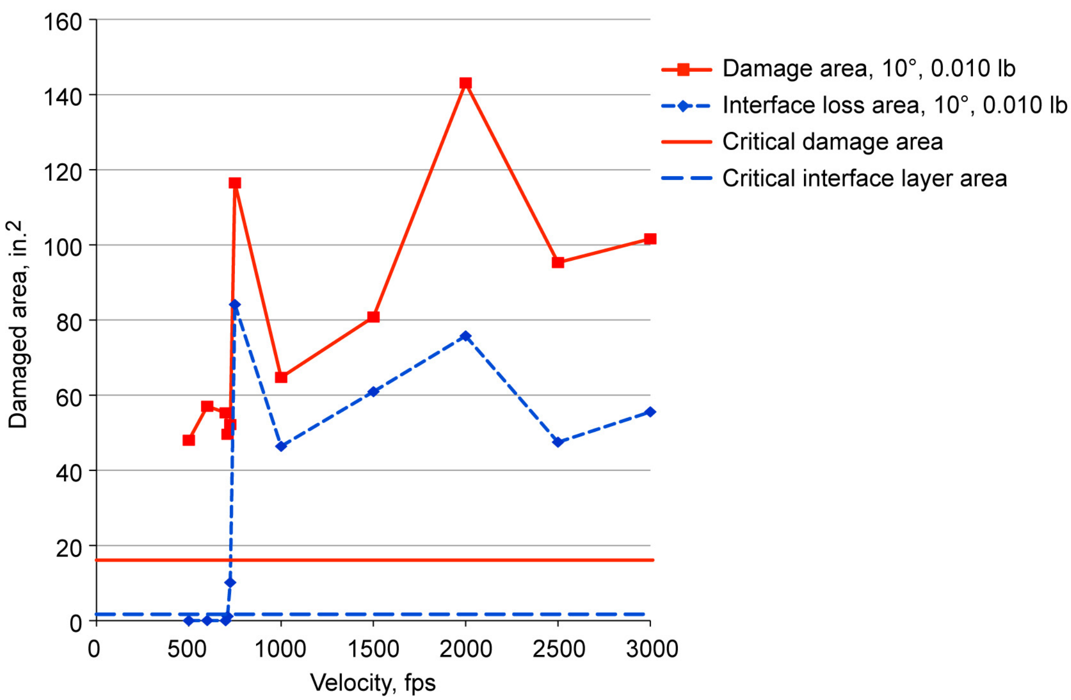


Figure 40.—Summary for 3.547-in.-diameter by 5.25-in.-length (0.1 lb) PDL foam projectile, 10° impact angle.

After completion of the 10° impact analyses with a range of PDL foam projectile sizes, the impact angle was reduced to 5°, and the analyses were repeated with the same size projectiles. The LS-DYNA results for the smallest, 0.01 lb, projectile is shown in Table 24 and Figure 41. For this shallow impact angle, and small sized PDL foam projectile, the projectile never caused enough damage to exceed the exposed substrate allowable, regardless of the impact velocity.

TABLE 24.—LS-DYNA RESULTS FOR 1.646-in.-DIAMETER BY 2.437-in.-LENGTH (0.01 lb) PDL FOAM PROJECTILE, 5° IMPACT

Velocity, fps	5° impact angle		PDL foam mass 0.01 lb		Diameter = 1.646 in.		Length = 2.437 in.		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
1700	12.27	1.77	17.03	Exceeds	0.00	0.00	0.00	OK	0.38
1800	13.49	1.77	18.75	Exceeds	0.99	0.89	0.69	OK	0.00
1850	13.74	1.77	19.09	Exceeds	0.00	0.00	0.00	OK	0.45
2000	13.56	1.83	19.53	Exceeds	0.00	0.00	0.00	OK	0.45
2200	15.04	1.90	22.45	Exceeds	0.00	0.00	0.00	OK	0.46
2500	15.48	1.78	21.59	Exceeds	0.00	0.00	0.00	OK	0.45
2800	14.78	1.91	22.12	Exceeds	0.00	0.00	0.00	OK	0.54
3000	13.43	1.90	20.08	Exceeds	0.00	0.00	0.00	OK	0.46
3500	13.22	1.90	19.76	Exceeds	0.00	0.00	0.00	OK	0.46
4000	14.09	1.97	21.79	Exceeds	0.00	0.00	0.00	OK	0.53

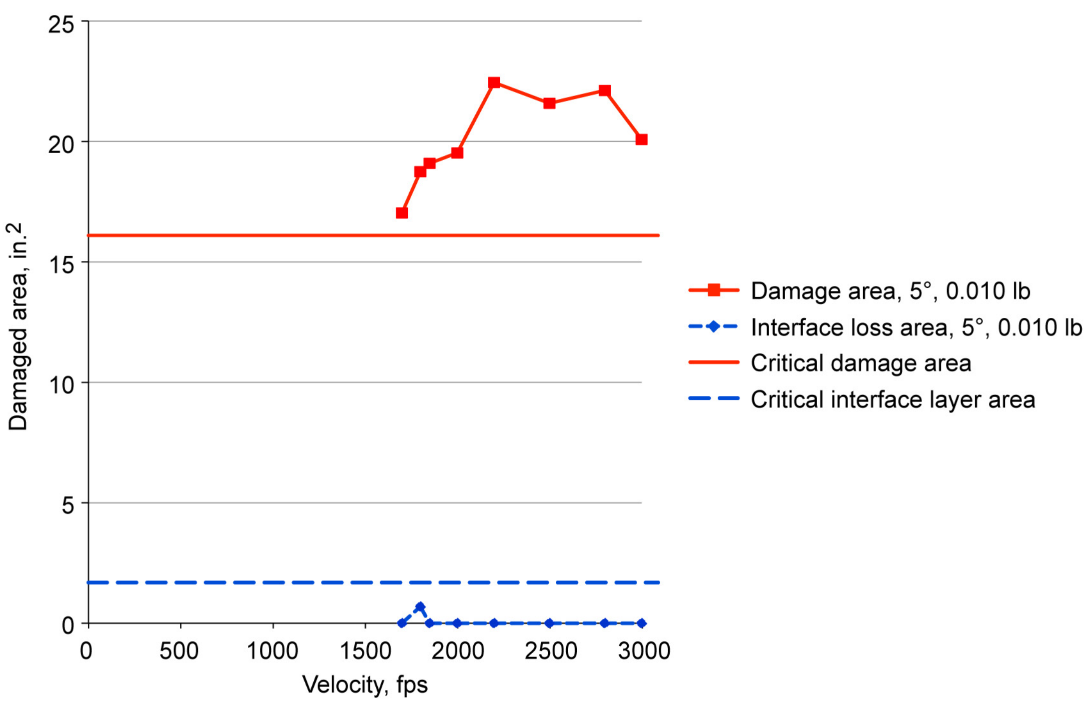


Figure 41.—Summary for 1.646-in.-diameter by 2.437-in.-length (0.01 lb) PDL foam projectile, 5° impact angle.

As in the 10° analyses, the weight of the PDL foam projectile was increased to 0.035 lb Table 25 shows a summary of LS-DYNA results for 2.5-in.-diameter by 3.72-in.-length (0.035 lb) PDL foam projectile impacting at a 5° angle. The total foam loss exceeded the allowable value at every velocity analyzed, and the exposed substrate allowable was exceeded when the velocity was at or greater than 1050 fps. There is some sensitivity in the interface layer foam loss to specific dynamic conditions. This can be seen in the results of the 1150 and 1151 fps impact results, where the stress waves produced by the PDL foam projectile at these specific velocities did not couple with the response of the NCFI foam to produce complete insulating foam loss in any small area. This degree of general sensitivity was also seen in the test results, although not enough tests were conducted at these shallow angles to demonstrate this exact result. Figure 42 shows the results of Table 25 graphically.

TABLE 25.—LS-DYNA RESULTS FOR 2.5-in.-DIAMETER BY 3.72-in.-LENGTH (0.035 lb) PDL FOAM PROJECTILE, 5° IMPACT

Velocity, fps	5° impact angle		PDL foam mass 0.035 lb		Diameter = 2.5 in		Length = 3.72 in		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
700	13.91	2.05	22.40	Exceeds	0.00	0.00	0.00	OK	0.26
900	14.17	1.97	21.92	Exceeds	0.00	0.00	0.00	OK	0.31
1000	13.10	2.11	21.71	Exceeds	0.00	0.00	0.00	OK	0.25
1025	13.40	2.04	21.47	Exceeds	0.84	0.86	0.57	OK	0.00
1050	12.91	2.05	20.79	Exceeds	7.19	1.97	11.12	Exceeds	0.00
1075	13.16	2.04	21.09	Exceeds	4.19	2.27	7.47	Exceeds	0.00
1100	13.60	2.11	22.54	Exceeds	9.26	2.16	15.71	Exceeds	0.00
1125	13.92	2.13	23.29	Exceeds	9.92	2.89	22.52	Exceeds	0.00
1150	13.41	2.11	22.22	Exceeds	0.00	0.00	0.00	OK	0.25
1151	14.04	2.12	23.38	Exceeds	0.00	0.00	0.00	OK	0.31
1175	13.10	2.11	21.71	Exceeds	9.12	2.42	17.33	Exceeds	0.00
1200	13.78	2.18	23.59	Exceeds	4.86	1.78	6.79	Exceeds	0.00
1300	14.62	2.50	28.71	Exceeds	10.19	2.12	16.97	Exceeds	0.00

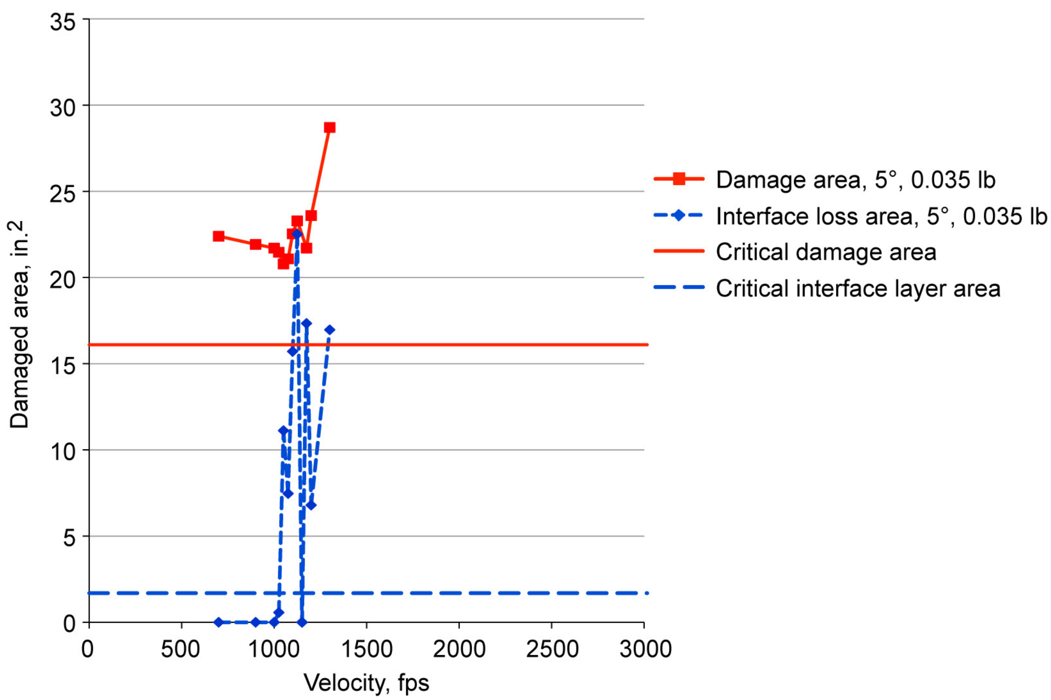


Figure 42.—Summary for 2.5-in.-diameter by 3.72-in.-length (0.035 lb) PDL foam projectile, 5° impact angle.

The weight of the PDL foam projectile was increased to 0.1 lb Table 26 shows a summary of LS-DYNA results for a 3.547-in.-diameter by 5.25-in.-length (0.1 lb) PDL foam projectile, impacting at a 5° angle. The total foam loss exceeded the allowable value at every velocity analyzed, and the exposed substrate allowable was exceeded when the velocity was at or greater than 760 fps. As in the 0.035 lb PDL foam impact at 5°, there is some interesting dynamic sensitivity in the results. At 3000 fps, the projectile's contact time with the target was short enough that stress waves which would cause interface foam damage were not created. Figure 43 shows the results of Table 26 graphically.

TABLE 26.—LS-DYNA RESULTS FOR 3.547-in.-DIAMETER BY 5.25-in.-LENGTH (0.1 lb) PDL FOAM PROJECTILE, 5° IMPACT

Velocity, fps	5° impact angle		PDL foam mass 0.1 lb		Diameter = 3.547 in.		Length = 5.25 in.		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
700	20.77	3.71	60.48	Exceeds	0.00	0.00	0.00	OK	0.13
750	20.92	3.20	52.54	Exceeds	0.00	0.00	0.00	OK	0.19
760	24.11	5.41	102.47	Exceeds	16.82	5.41	71.48	Exceeds	0.00
775	21.80	5.52	94.53	Exceeds	17.97	5.52	77.95	Exceeds	0.00
800	17.32	3.53	48.01	Exceeds	11.29	2.95	26.16	Exceeds	0.00
900	24.03	4.52	85.27	Exceeds	16.62	4.52	58.99	Exceeds	0.00
1000	20.59	3.03	49.05	Exceeds	13.51	2.42	25.64	Exceeds	0.00
1500	30.13	3.63	85.87	Exceeds	11.61	2.57	23.40	Exceeds	0.00
2000	29.77	3.79	88.62	Exceeds	15.81	2.58	31.97	Exceeds	0.00
2500	34.48	3.96	107.29	Exceeds	15.00	2.20	25.92	Exceeds	0.00
3000	34.78	3.96	108.23	Exceeds	0.00	0.00	0.00	OK	0.19

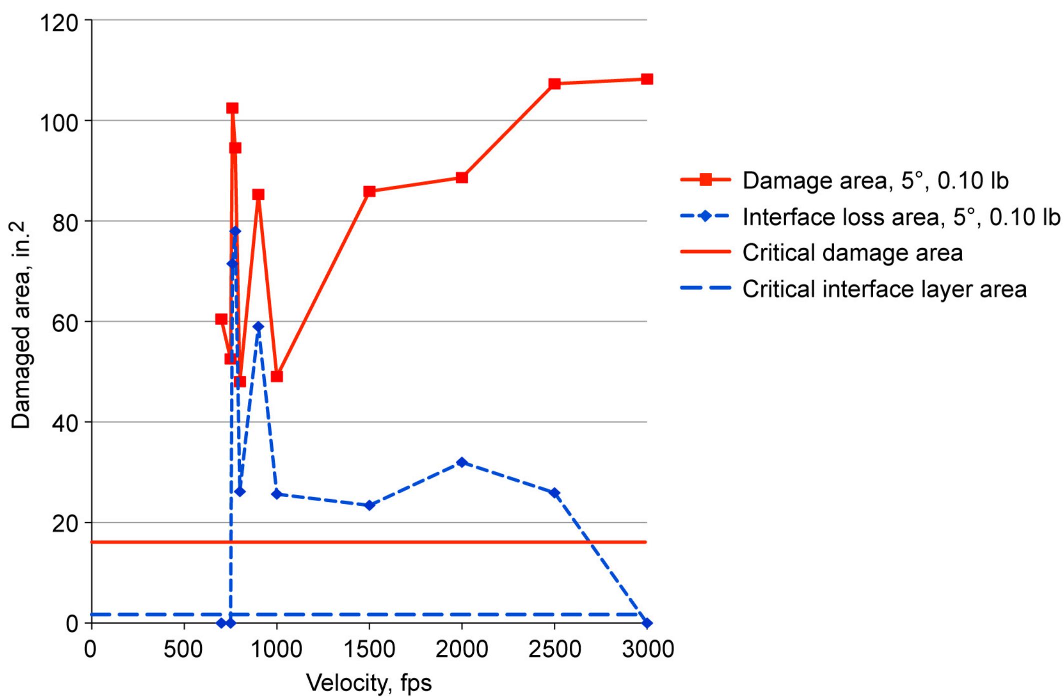


Figure 43.—Summary for 3.547-in.-diameter by 5.25-in.-length (0.1 lb) PDL foam projectile, 5° impact angle.

As the ice projectile mass was increased, the critical velocity did not decrease significantly, approaching convergence (Figure 38). Comparing the critical velocities for 10° PDL foam projectile, the same trend is evident, with the critical velocity of the 0.035 lb projectile at 750 fps and that of the 0.1 lb projectile at 725 fps. At 5°, the critical velocity of the 0.035 projectile is 1050 fps and the critical velocity of the 0.1 lb projectile is 760 fps. Therefore, the weight of the PDL foam projectile was increased to 0.2 lb, to determine if the trend holds for the PDL foam impacting at 5°. Table 27 shows a summary of LS-DYNA results for a 4.469-in.-diameter by 6.615-in.-length (0.2 lb) PDL foam projectile, impacting at a 5° angle. With the critical velocity of 675 fps, the critical velocity has ceased decreasing significantly. Figure 44 shows the results of Table 27 graphically.

TABLE 27.—LS-DYNA RESULTS FOR 4.469-in.-DIAMETER BY 6.615-in. LENGTH (0.2 lb) PDL FOAM PROJECTILE, 5° IMPACT

Velocity, fps	5° impact angle		PDL foam mass 0.2 lb		Diameter = 4.469 in.		Length = 6.615 in.		
	Total damaged area		Critical total damage area = 16.1 in.^{2}		Removed interface layer area (exposed Al)		Critical removed interface area = 1.69 in.^{2}		Min remaining foam thickness, in.
	Length, in.	Width, in.	Damage area, in.^{2}	Failure criteria	Length, in.	Width , in.	Interface area, in.^{2}	Failure criteria	
600	29.97	4.15	97.61	Exceeds	0.00	0.00	0.00	OK	0.07
650	29.29	4.52	104.07	Exceeds	0.19	0.17	0.02	OK	0.00
675	29.54	3.97	92.01	Exceeds	12.19	3.80	36.32	Exceeds	0.00
700	30.86	4.15	100.58	Exceeds	14.63	1.58	18.09	Exceeds	0.00
750	26.98	4.07	86.33	Exceeds	13.55	4.76	50.63	Exceeds	0.00

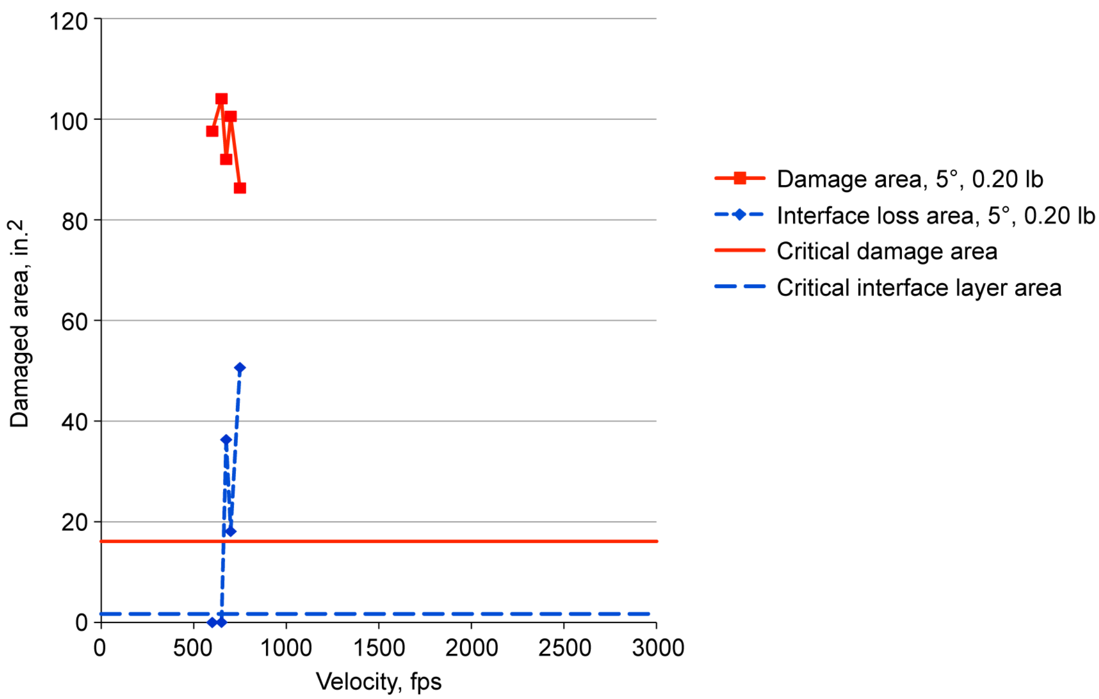


Figure 44.—Summary for 4.469-in.-diameter by 6.615-in.-length (0.2 lb) PDL foam projectile, 5° impact angle.

A summary of the critical velocities for the PDL foam, at both the 10° and 5° impact angles, and for the assessed projectile masses is shown in Figure 45. As in the ice study, the critical impact velocity decreases as the size of the projectile increases, and for the steeper impact angle. (The 10° impacts have lower critical velocities than the more shallow, 5° impacts.) Also as in the ice study, the critical impact velocity levels off with larger PDL foam projectiles. Here too, the diameter of the larger size PDL foam projectiles exceeds the thickness of the top layer of insulting foam, so part of the projectile does not make contact with the foam. As a result, some of the PDL cylindrical foam mass is not an effective projectile, and other projectile geometries might yield larger damage areas for the same mass and impact velocity.

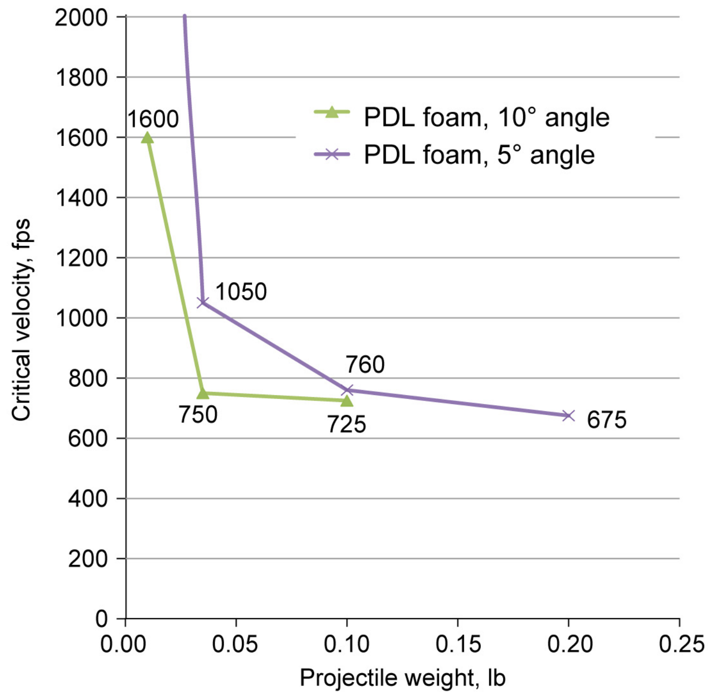


Figure 45.—PDL foam projectile critical velocity versus projectile size.

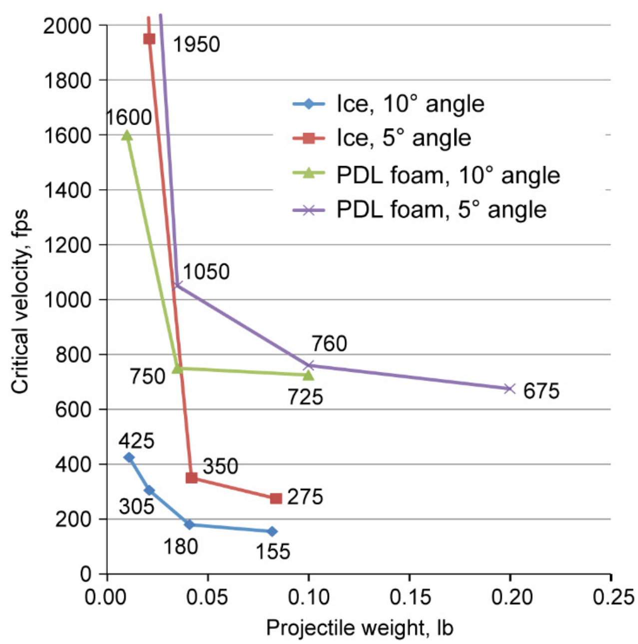


Figure 46.—Ice and PDL foam projectile critical velocity versus projectile size.

4.3 Impact Results Summary

A summary of the critical velocities for both the ice and the PDL foam projectiles, and at both the 10° and 5° impact angles, versus the assessed projectile masses is shown in Figure 46. As shown in this figure, the same trend of critical impact velocity leveling off with larger mass projectiles occurs with both ice and PDL foam projectiles.

The difference in critical velocity for the same mass and impact angles between ice and PDL foam is also demonstrated in Figure 46. Here, the greater density of ice results in a lower critical velocity than the same mass projectile of less dense PDL foam. This effect of density, along with the previously discussed effects of projectile shape and localized dynamics, demonstrate why simple ice and foam impact assessments, using limited formulas such as kinetic energy, do not yield reliable results.

5.0 Summary

A large amount of testing and analysis were conducted with both ice and PDL foam impacts on NCFI acreage foam for the Space Shuttle Project (SSP) External Tank (ET). Test verified material models and techniques that resulted from this testing were utilized for this study to perform a parametric study for the Space Launch System (SLS) to determine critical impact velocities for given projectile weights

The testing, test verified material models and techniques were reviewed in Section 2.0. In Section 3.0, an updating repetition of the test verification analysis was presented. In Section 4.0 impact assessments of both ice and PDL foam impacts for NCFI acerage foam for multiple projectile masses, and for 5 and 10° impacts were documented. The presented damage areas and comparisons to SSP ET critical areas can be used by SLS to assess potential damage due to debris. In addition, should additional analysis be required, the presented results can serve as an accuracy benchmark for any subsequent studies.

The allowable damage criteria based on Shuttle limits is a reasonable starting point for SLS, however, the specific limits for SLS may differ from Shuttle. Therefore, SLS limits will need to be determined before the results of this study may be applied to SLS.

References

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