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Executive Summary

Interplanetary spacecraft are exposed to meteoroid fluxes that range in speeds from 10 to 72 km/sec, far above the capability of today's test facilities to provide predictions for the likelihood of spacecraft critical penetration. Of special interest are sample return missions, which (though protected by shielding) must often survive years of exposure to the meteoroid environment in order to re-enter Earth's atmosphere with their scientific cargo.

This paper describes the simulation of meteoric material damage to thermal protection systems (TPS) of the planned Mars Sample Return Mission sample return vehicle, housed beneath a protective "garage" (shielding) enclosure. The simulations use the Smooth Particle Hydrodynamics Code (SPHC) to predict breakup of impacting meteoroids within the garage structure, as well as their subsequent penetration into the underlying TPS heat shield covering the Earth-return vehicle.

The study outlined in this paper considered the impact effect of both meteoric materials, such as iron, ice, and chondrites (dunnite), and non-meteoric materials, such as aluminum and nylon, against both external shielding materials (single and dual aluminum bumpers) and heat shield for Extreme Entry Environments Technology (HEEET) TPS materials, used alone and in conjunction with shielding. A general predictive damage equation to HEEET TPS developed from these SPHC simulations for velocities up to 70 km/sec matched the predicted shield performance within 5%.

Recommendations

IDA recommended changes to the shielding design of the Mars Sample Return Mission based on these results.

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PREDICTION AND ENHANCEMENT OF THERMAL PROTECTION SYSTEMS FROM METEOROID DAMAGE USING A SMOOTH PARTICLE HYDRODYNAMIC CODE

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ABSTRACT

Interplanetary spacecraft are exposed to meteoroid fluxes that range in speeds from 10 to 72 km/sec, far above the capability of today's test facilities to provide predictions for the likelihood of spacecraft critical penetration. Of special interest are sample return missions, which (though protected by shielding) must often survive years of exposure to the meteoroid environment in order to re-enter Earth's atmosphere with their scientific cargo.

This paper describes the simulation of meteoric material damage to thermal protection systems (TPS) housed beneath protective "garage" (shielding) enclosures using the Smooth Particle Hydrodynamics Code (SPHC) operated by the Institute for Defense Analyses and Stellingwerf Consulting in support of ongoing NASA tasks. The study outlined in this paper considered the impact effect of both meteoric materials such as iron, ice, and chondrites (dunnite), and non-meteoric materials such as aluminum and nylon against both external shielding materials (single and dual aluminum bumpers) and Heat shield for Extreme Entry Environments Technology (HEEET) TPS materials, used alone and in conjunction with shielding. A general predictive damage equation to HEEET TPS is developed from these SPHC simulations for velocities up to 70 km/sec.

Keywords: orbital debris, hypervelocity impact, thermal protection system

1. INTRODUCTION

Interplanetary spacecraft are exposed to meteoroid fluxes that range in speeds from 10 to 72 kilometers per second (kps), far above the capability of today's test facilities to provide predictions for the likelihood of spacecraft critical penetration. Of special interest are sample return missions, which (though protected by shielding) must often survive years of exposure to the meteoroid environment in order to re-enter Earth with their scientific cargo. A key element to ensure spacecraft re-entry survival is to understand the potential damage to thermal protection systems (TPS) that may be housed beneath protective "garage" (shielding) enclosures.

This paper summarizes a series of meteoroid impact simulations of such a spacecraft protective system using the Smooth Particle Hydrodynamics Code (SPHC), originally developed by Stellingwerf, et al [1], and now operated by the Institute for Defense Analyses and Stellingwerf Consulting in support of ongoing National Aeronautics and Space Administration Engineering Safety Center (NESC) tasks. The study outlined in this paper considered the impact effect of both meteoric materials such as iron, ice, and chondrites (dunnite), and non-meteoric materials such as aluminum and nylon against both external shielding materials (single and dual aluminum bumpers) and Heat shield for Extreme Entry Environments Technology (HEEET) TPS materials, used alone and in conjunction with shielding. It also discusses validation of the code in the testable regime, as well as general hydrocode limitations.

2. APPROACH

SPHC is a gridless Lagrangian hydrodynamic computation technique developed by Stellingwerf Consulting in 1987–1990. Initially used for projects at Mission Research Corp., Air Force Weapons Lab, and Los Alamos National Lab, it is closely related to the widely used LANL code SPHINX. It was specially designed to accommodate large translations of material, large deformations, and large void fractions, and is an ideal candidate for modelling asteroid impact, spacecraft shield modeling, and planetary accretion. Figure 1 shows a flash x-ray of a debris cloud created by impact of an aluminum sphere at 6.62 kps compared to an experiment performed by the University of Dayton Research Institute (UDRI) under similar conditions[2].

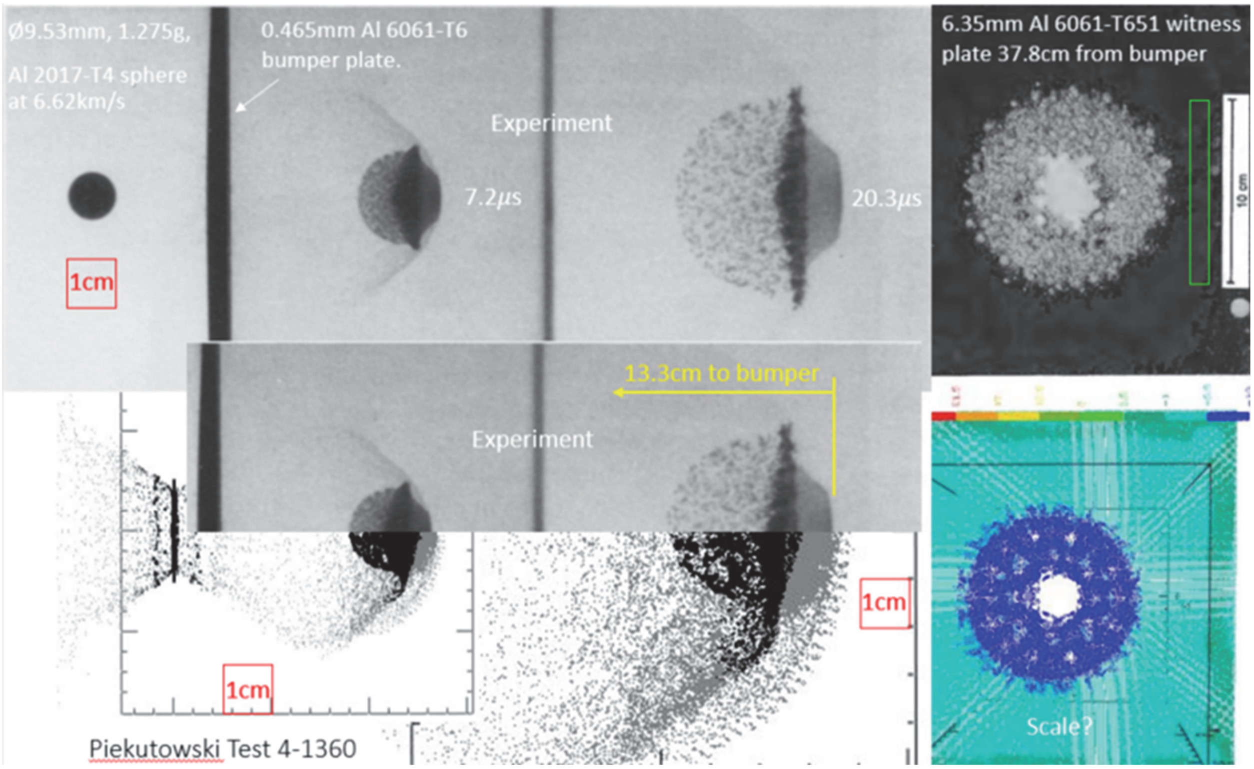


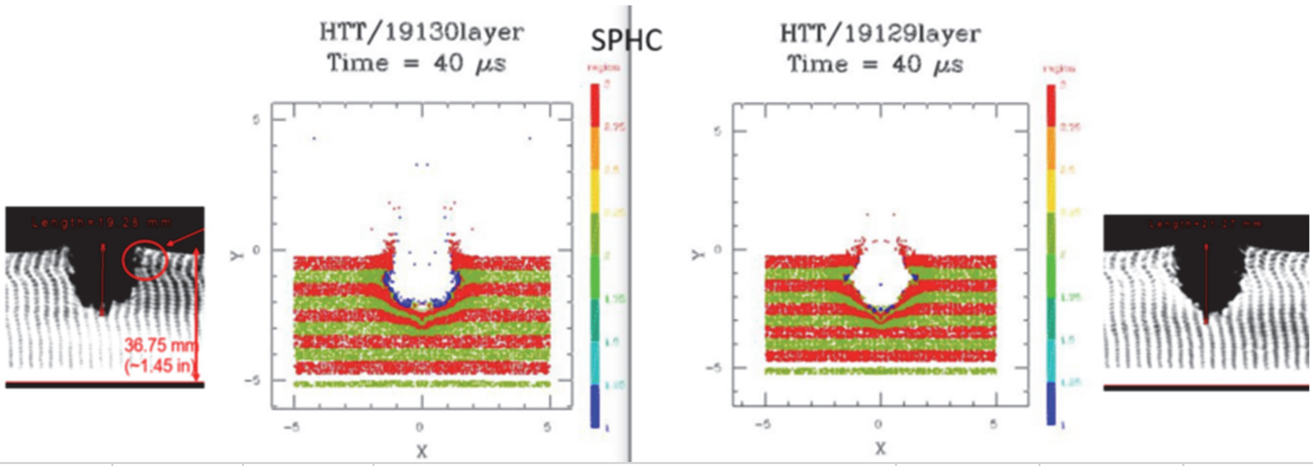
FIGURE 1: COMPARISON OF SPHC-PREDICTED DEBRIS CLOUD TO EXPERIMENTAL DEBRIS CLOUD [2]

The 3D model result is shown as the bottom half of the lower images (shaded on density), compared to the UDRI radiograph shown at top and at the top half of the lower series. We observe that the model accurately reproduces the flat disk of fractured projectile material, the dome of spalled fragments at the rear of the debris field, the thin "veil" surrounding the debris field, and the light gray disk of uniform gray density at the front edge of the debris cloud. Examination of the model explains this feature as a region of melted aluminum. The witness plate damage pattern is shown at right, showing a good match of the damaged region and penetration hole size between model and experiment.

Figure 2 shows a comparison of SPHC results (table at bottom) to a test of HEEET-type TPS, consisting of a complex 3D woven structure of carbon fiber and nylon phenolic fiber materials. The SPHC model attempts to capture some of the aspects of this blend by using alternating carbon fiber and nylon fiber layers, 10 in all, plus simulating the porosity of the material by randomly omitting about 20% of the SPH particles in each of these layers. Carbon layers are shown in red in Figure 2; nylon layers are green. Comparison of the modeled craters with two experiments are shown, with good agreement.

3. RESULTS AND DISCUSSION

Figure 3 shows the setup and results from an impact simulation consisting of a 4mm Al sphere impacting a dual-wall shield consisting of two 0.5mm Al 6061-T6 layers separated by 2cm, suspended 10cm above a 13mm layer of HEEET-type TPS, impacted at 30 kps at a 30 deg impact angle. The debris cloud expands within the shield, penetrates it, and then expands to create damage within the TPS at a maximum depth of approximately 7.5mm. Although a great amount of vapor is created in the debris cloud due to the intense kinetic energy of the impact, most of the damage is actually from the liquid and solid particles generated within the cloud, which sometimes work together to cause closely spaced craters in the TPS to coalesce into larger craters. In the far-right image, a "cross section" of damage at a level of 4mm into the TPS is shown (white areas are where material is missing, forming craters).



			IL Only Test Data				Inner	Inner	
Test	Date	Pen Matl	Pen Diam	Vel kps	Obliq	Depth	Diameter 1	Diameter 2	Energy
21045		AL	2.38	7.26	0	Not Given	8.4	6.6	514
19130		Nylon	4.78	6.68	0	19.3			1451
19131		Nylon	4.78	6.86	70	10			1531
19129		Al	3.55	6.83	0	21.3			1531

FIGURE 2: COMPARISON OF SPHC-PREDICTED TPS DAMAGE TO EXPERIMENTAL DAMAGE [3]

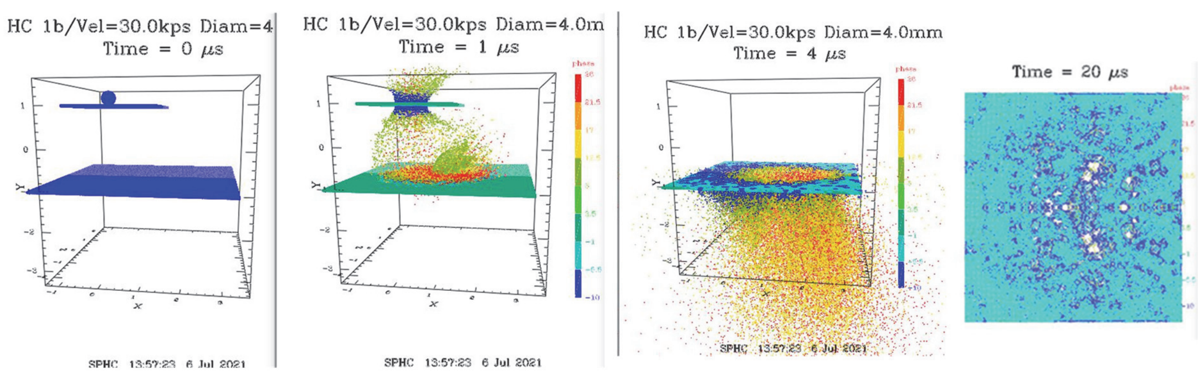


FIGURE 3: SIMULATION RESULTS FOR 4MM ALUMINUM SPHERE IMPACTING DUAL WALL AT 30 KPS, 30 DEG (CASE 1B)

Table 1 shows the results of a “cluster” file for this impact that describes the condition of the debris cloud below the dual shield, including the mass, speed, and position of each solid, liquid, and gas particle cluster that is created by the impact. Note that the largest contributors to damage in the TPS are solid and liquid aluminum debris from the second plate of the shield travelling under 7 kps. It is also noteworthy that at these impact velocities, the kinetic energy from the vapor portion of the cloud is 20 times the energy of the solid and liquid portions, but does not drive visible cratering damage.

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TABLE 1. CLUSTER FILE DESCRIBING DEBRIS CLOUD CHARACTERISTICS BEHIND SHIELD AT 30 KPS, 30 DEG (CASE 1B)

clusters	parts	mass(g)	x	y	z(cm)	vx	vy	vz(kmps)	V(kmps)	material	phase	Dsph(mm	L(mm)	Shape	KE(J)
136	233140	2.46794	1.44969	-1.09004	-0.00574	0.050665	-0.22293	-0.00503	0.228667	al_bot	SOLID	12.0415	73.686	6.11935	64.5227
1787	245	0.002593	2.36436	-1.88904	0.137704	2.30268	-3.08308	0.102278	3.84944	al_bot	LIQUID	1.22451	10.5309	8.60013	19.2154
1915	117	0.001237	2.70418	-2.06426	-0.08162	3.36506	-3.87952	-0.12757	5.13718	al_bot	LIQUID	0.956736	6.73276	7.03722	16.3216
1998	128	0.001355	1.92301	-2.21642	-0.90054	1.72755	-4.10119	-1.65798	4.74901	al_bot	LIQUID	0.986247	6.70382	6.7973	15.2793
2212	26	0.000275	2.64788	-3.08681	-0.34526	4.74572	-7.37237	-0.96529	8.82074	al_bot	LIQUID	0.57978	5.11835	8.82808	10.7071
1977	73	0.000773	2.26852	-2.16958	0.724932	2.49915	-4.05269	1.51018	4.99507	al_bot	LIQUID	0.817896	3.3703	4.1207	9.64035
2030	52	0.00055	1.04979	-2.33024	-1.6021	0.19458	-4.5336	-3.26115	5.58807	al_bot	LIQUID	0.73046	9.19651	12.59	8.59438
2171	29	0.000307	2.25674	-2.82696	-0.59502	3.11392	-6.23346	-1.39675	7.10657	al_bot	LIQUID	0.60127	8.115	13.4964	7.75186
1996	95	0.001006	0.324267	-2.21019	-0.5804	-0.62548	-3.80005	-0.57414	3.89375	al_bot	LIQUID	0.892952	11.6194	13.0124	7.62336
2274	5	5.29E-05	-3.77458	-4.34873	-0.08719	-8.98025	-13.7207	-0.54621	16.4073	al_top	LIQUID	0.334672	16.7346	50.0031	7.12415
1973	52	0.00055	2.36786	-2.16399	0.312828	2.85115	-4.12629	0.525444	5.04295	al_bot	LIQUID	0.73046	2.61057	3.57387	6.9994
1981	2	2.12E-05	6.81843	-2.17542	-5.65446	18.6913	-7.8718	-15.0744	25.2699	al_top	LIQUID	0.246596	10.8312	43.9229	6.75964
2277	8	8.47E-05	0.290172	-4.52753	-0.88187	-1.87463	-11.9003	-2.74876	12.3567	al_bot	LIQUID	0.391429	8.47765	21.6582	6.46519
2291	3	3.18E-05	1.13721	-6.49601	1.03831	1.03977	-18.6189	2.93359	18.8773	al_bot	LIQUID	0.282278	12.8781	45.622	5.6583
2251	13	0.000138	-0.11523	-3.59994	0.423293	-2.61839	-8.59998	0.888438	9.03354	al_bot	LIQUID	0.460182	11.2715	24.4935	5.61496
2267	2	2.12E-05	3.10463	-3.9635	-6.82809	8.177	-12.3345	-17.3438	22.7994	al_top	LIQUID	0.246596	14.1563	57.4068	5.50253
2137	19	0.000201	2.55311	-2.66913	0.314692	3.79445	-5.79336	0.820482	6.97382	al_bot	LIQUID	0.522229	1.38469	2.65149	4.89082
1944	63	0.000667	0.557737	-2.10953	-1.09976	-0.46204	-3.44172	-1.48298	3.776	al_bot	LIQUID	0.778705	13.9366	17.8971	4.75436
2199	10	0.000106	1.1557	-3.01542	-2.00555	0.605631	-6.84296	-6.09311	9.18253	al_bot	LIQUID	0.42165	8.31347	19.7165	4.46284
2266	7	7.41E-05	1.70066	-3.93533	-0.93802	2.35003	-10.0192	-2.70663	10.6411	al_bot	LIQUID	0.37439	6.15744	16.4466	4.19527
2110	28	0.000296	0.103421	-2.59978	0.113257	-1.24053	-5.13599	0.089614	5.28444	al_bot	LIQUID	0.594279	7.76914	13.0732	4.1385
2228	7	7.41E-05	3.25577	-3.24988	0.113017	6.97359	-7.86594	0.949836	10.5549	al_bot	LIQUID	0.37439	5.4475	14.5503	4.12757
1878	8	8.47E-05	-2.84609	-2.00652	-0.45848	-6.59958	-7.21182	-1.04674	9.8316	al_top	LIQUID	0.391429	21.43	54.7482	4.09285
1746	45	0.000476	2.59579	-1.85616	0.177504	2.59872	-3.20231	0.354036	4.13926	al_bot	LIQUID	0.696095	4.35871	6.26166	4.0808
2275	5	5.29E-05	2.2819	-4.37519	-0.23134	4.32972	-11.5851	-0.40138	12.3743	al_bot	LIQUID	0.334672	6.23849	18.6406	4.05226
2293	2	1.96E-05	1.20329	-6.92513	0.80297	1.2602	-20.1169	2.15716	20.2715	al_bot	LIQUID	0.240533	8.1315	33.8062	4.03691
2292	2	1.80E-05	1.26136	-6.84761	-1.6188	1.88575	-20.2426	-5.45066	21.0483	al6061	LIQUID	0.233823	7.04494	30.1294	3.99802
2273	4	4.23E-05	2.20413	-4.34322	-1.96156	3.22243	-11.8804	-6.05866	13.7199	al_bot	LIQUID	0.310684	5.84973	18.8285	3.98519
2289	3	3.18E-05	-0.15899	-5.56749	0.542595	-3.67009	-15.0371	0.607877	15.4905	al_bot	LIQUID	0.282278	6.93419	24.5651	3.81011

Largest contributors mass ~ 1mm spheres at 4-5 kps

Most top energy contributors under 7 kps

Note there are a lot of Odd Shapes

Debris Cloud Characteristics:

Solid/Liquid Cloud Mass = 0.133 g   Gas mass = 0.296977 g   Dust mass = 0.0837564

Solid/liquid KE = 702.6 J   Gas KE = 16459 J   Dust KE = 1227.08 J

Cluster KEy = 572.509 J   Gas KEy = 12164 J   Dust KEy = 863.841 J

In developing a model for general penetration depth into the TPS behind the shield, the evaluators performed 60 SPHC hydrocode runs against the MMG shield (0.5mm Al / 2cm space / 0.5mm Al) at various standoffs from the TPS, which resulted in images showing damage extent and estimates of maximum TPS crater depths (see Table 2). Most runs used dunnite (a material similar in density and structure to chondritic meteoroids) and water (ice), but also used aluminum, iron, aluminum oxide (Al2O3), and nylon impactors to develop a general penetration equation. Runs varied from 0 to 45 degrees obliquity, 10 to 40 kps for med/high-density materials (aluminum density and greater), and 25 to 55 kps for low-density impactors (under 2.7 g/cc, such as water and nylon). Only 5 and 10cm standoffs to the TPS were examined due to adverse effects of longer standoffs on computational time. Some tests were also varied to examine the effect of bumper thickness.

In general, the study found that penetrator densities > aluminum produced similar damage in TPS for similar masses and velocities of impact, but densities < aluminum produced far less damage in TPS, due primarily to the creation of more vapor for these less dense materials (and less of the damaging liquid or solid materials) for the same impact energies. There was more damage at longer standoffs, but this was not a strong factor.

TABLE 2: RESULTS OF SPHC HYPERVELOCITY IMPACT HYDROCODE RUNS CONSIDERING SHIELDED TPS

Test	Desc	Dia	Density	Mass	Vel	KJ	Obl	Standoff	Depth
4	AL 1.47	1.5	2.7	0.004	30	2	30	10 cm	2
5	AL 2.0 (Ca	2	2.7	0.011	30	5	30	10 cm	3
6	AL 2.21	2.2	2.7	0.015	30	7	30	10 cm	3.5
7	AL 2.64	2.6	2.7	0.026	30	12	30	10 cm	3.5
8	ALOX 3.55	3.6	3.95	0.092	30	41	30	10 cm	7.5
9	ALOX 4.0	4	3.95	0.131	30	59	30	10 cm	9
10	Nylon 2.0	2	1.15	0.005	50	6	30	10 cm	2
11	Nylon 3.8	3.8	1.15	0.033	50	41	30	10 cm	5
12	Nylon 7.9	8	1.15	0.303	50	379	30	10 cm	7
13	Water 4.0	4	1	0.033	50	42	30	10 cm	5
14	Water 7.9	8	1	0.264	50	330	30	10 cm	7
15	AL 8.42	8.4	2.7	0.842	30	379	30	10 cm	12.7 +
16	ALOX 8.42	8.4	3.95	1.230	30	555	30	10 cm	12.7 +
17	Iron Case	2	8 g/cc	0.032	25	10	30	10 cm	5.5
18	Iron Case	2	8 g/cc	0.032	40	25	30	10 cm	5
19	Iron Case	2	8 g/cc	0.032	25	10	45	10 cm	3.5
20	Iron Case	2	8 g/cc	0.032	40	25	45	10 cm	5
21	Iron Case	2	8 g/cc	0.032	25	10	30	5 cm	6
22	Iron Case	2	8 g/cc	0.032	40	25	30	5 cm	7.5
23	Case 1b AL	4	2.7	0.092	30	41	30	10 cm	7.5
24	Case 1b Ir	2.8	8	0.092	30	41	30	10 cm	6
25	Case 1b Gr	4	2.7	0.092	30	41	30	10 cm	6.5
26	Case 1b Ba	3.9	2.95	0.092	30	41	30	10 cm	7
27	Case 1b Du	3.7	3.3	0.092	30	41	30	10 cm	7.5
28	2mm Duni	2	3.3	0.014	30	6	30	10 cm	2.5
29	Case 2 Alu	2	2.7	0.014	30	5	30	10 cm	1
30	Case 1b Al	4	2.7	0.092	30	41	30	10 cm	6
31	Run 1 Duni	1.8	3.3	0.010	25	3	30	10	2.5
32	Case 2 Alu	2	2.7	0.011	30	5	30	10	2.5
33	Run 2 Duni	1.8	3.3	0.010	40	8	30	10	4
34	Run 1.5 Du	1.8	3.3	0.010	25	3	30	5	3.5
35	Run 2.5 Du	1.8	3.3	0.010	40	8	30	5	3.5
36	Run 1-45	1.8	3.3	0.010	25	3	45	10	2
37	Run 2-45	1.8	3.3	0.010	40	8	45	10	4.5
38	Run 3.5 Du	2.6	3.3	0.032	25	10	30	5	4.5
39	Run 4.5 Du	2.6	3.3	0.032	10	2	30	5	2
40	Run 1 W (V	2.7	1	0.003	40	3	30	10	1
41	Run 2 W (V	2.7	1	0.003	55	5	30	10	1
42	Run 1.5 W	2.7	1	0.003	40	3	30	5	2
43	Run 2.5 W	2.7	1	0.003	55	5	30	5	2.5
44	Dunite Rur	2.6	3.3	0.032	25	10	30	10	4.5
45	Dunite Rur	2.6	3.3	0.032	10	2	30	10	2
46	Run 3W	3.9	1	0.010	40	8	30	10	3
47	Run 4W	3.9	1	0.010	25	3	30	10	2
48	Run 3.5 W	3.9	1	0.010	40	8	30	5	3
49	Run 4.5 W	3.9	1	0.010	25	3	30	5	2.5
50	Run 10.5 C	2	1.15	0.005	50	6	30	5	2.5
51	Run 11.5 C	3.8	1.15	0.033	50	41	30	5	8
52	Dunite Rur	2.6	3.3	0.032	25	10	45	10	2
53	Dunite Rur	2.6	3.3	0.032	10	2	45	10	2
54	Case 2 Al 1	2	2.7	0.011	30	5	30	5	4
55	Run 5 Du 2	2.6	3.3	0.032	40	25	30	10	5.5
56	Run 5-45 D	2.6	3.3	0.032	40	25	45	10	3
57	Run 5W Ic	3.9	1	0.032	55	44	30	10	5
58	Case 1b-0.	4	2.7	0.092	30	41	30	5	8
59	Run 1-0 Du	1.8	3.3	0.010	25	3	0	10	0.5
60	Run 2-0 Du	2.6	3.3	0.032	25	9	0	10	4
61	Run 1-0 W	2.7	1	0.010	40	8	0	10	0.5
62	Run 5.5 W	3.9	1	0.032	55	48	30	5	6.5
63	Run 2-0 W	3.9	1	0.032	40	25	0	10	4.5

Using the data generated from the hydrocode runs, the authors created a general crater depth "Energy Overmatch" prediction model for the shielded TPS, as shown below:

$$\text{Pen Depth (mm)} = K^* [(Ei * Br) / (2 * Ebl*S)]^{\wedge}Exp \tag{1}$$

Where:
K = Constant to account for light density (0.0234) vs medium/heavy particle density (0.0345)
Ei = Impacting energy, joules at a given velocity
Ebl = Ballistic limit energy required to penetrate the shield [4], which includes features such as impacting obliquity and velocity
Br = Bumper ratio of larger MMG areal density to original MMG areal density
S = Standoff, cm > 2 cm
Exp = 0.5 unless Ei over 300 KJ (then 0.45)

Figure 4 shows a plot of the predicted penetration depth of both ice and aluminum impactors into the shielded TPS for various particle impact energies and densities as described in Table 2, and as described in Equation 91. It is clear from the plotted data that the denser penetrators (such as aluminum) produce more damage to the TPS for equal impact energies.

4. CONCLUSION

The use of the SPHC to simulate meteoric material damage to TPS housed beneath protective "garage" (shielding) enclosures offered a fast, economic, and accurate method for exploring the impact effect of materials such as iron, ice, and chondrites (dunnite), and non-meteoric materials such as aluminum and nylon at velocities up to 70 kilometers per second. SPHC's advantages in tracking particles through large standoffs into complex shielding materials (single and dual aluminum bumpers) and targeted materials such as HEEET TPS materials, used alone and in conjunction with shielding, are noteworthy. A general predictive damage equation to predict depth of penetration into HEEET TPS was developed from these SPHC simulations.

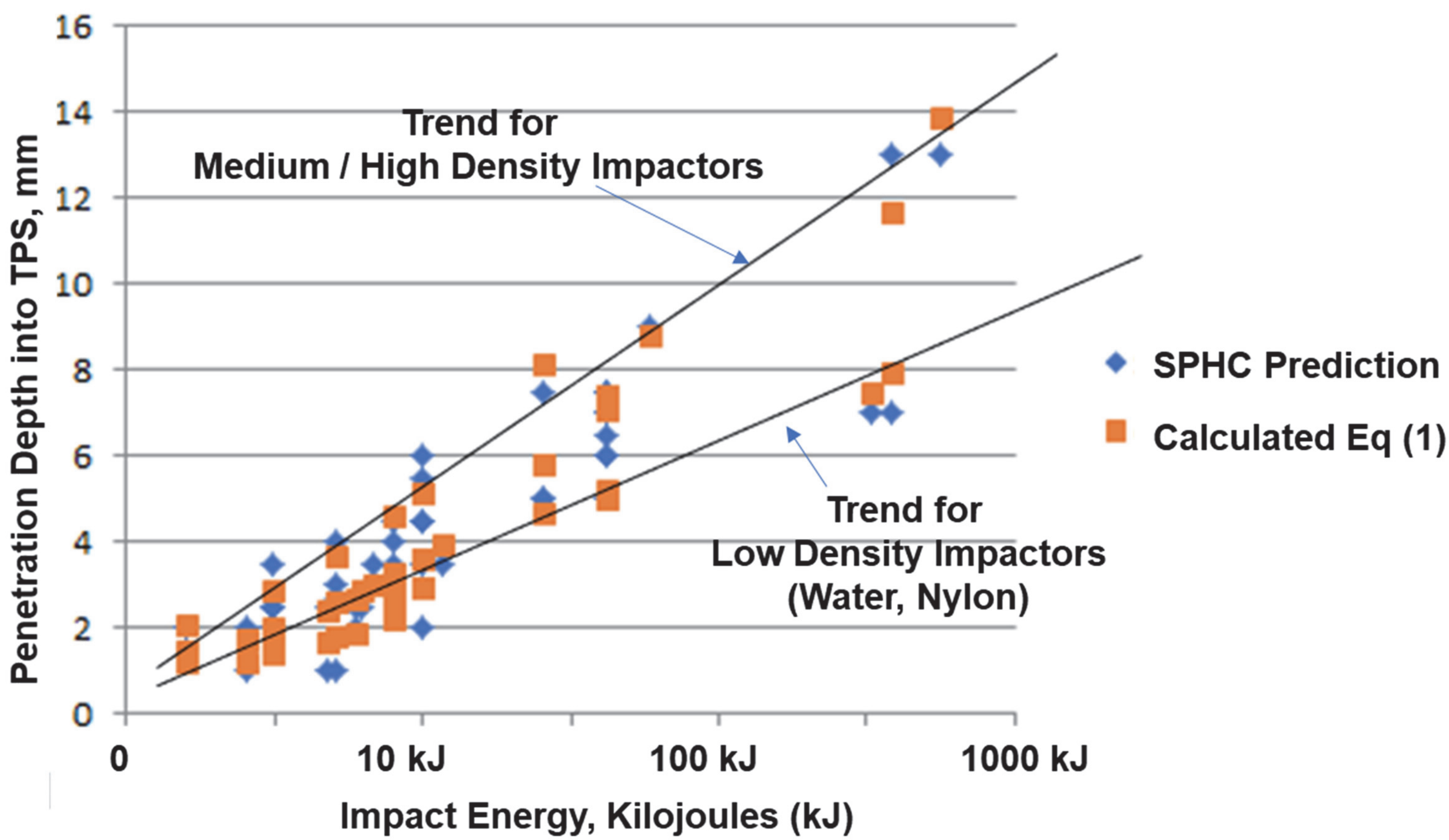

FIGURE 4: PREDICTED PENETRATION DEPTH INTO THE SHIELDED TPS FOR VARIOUS PARTICLE IMPACT ENERGIES AND DENSITIES

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14. ABSTRACT
Interplanetary spacecraft are exposed to meteoroid fluxes that range in speeds from 10 to 72 km/sec, far above the capability of today’s test facilities to provide predictions for the likelihood of spacecraft critical penetration. Of special interest are sample return missions, which (though protected by shielding) must often survive years of exposure to the meteoroid environment in order to re-enter Earth’s atmosphere with their scientific cargo.

This paper describes the simulation of meteoric material damage to thermal protection systems (TPS) housed beneath protective “garage” (shielding) enclosures using the Smooth Particle Hydrodynamics Code (SPHC) operated by the Institute for Defense Analyses and Stellingwerf Consulting in support of ongoing NASA tasks. The study outlined in this paper considered the impact effect of both meteoric materials such as iron, ice, and chondrites (dunnite), and non-meteoric materials such as aluminum and nylon against both external shielding materials (single and dual aluminum bumpers) and Heat shield for Extreme Entry Environments Technology (HEEET) TPS materials, used alone and in conjunction with shielding. A general predictive damage equation to HEEET TPS is developed from these SPHC simulations for velocities up to 70 km/sec.

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