COVER SHEET

Paper Number: **1492**

Title: **Hypervelocity Impacts of Shear Thickening Fluid Imbibed Metallic Foam Core Sandwich Panels**

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ABSTRACT

Hypervelocity impact (HVI) experiments were carried out on two configurations of open cell foam core sandwich composite panels both infused with a shear thickening fluid (STF). The first configuration consisted of an aluminum facesheet, 1.27 cm thick 6.35 pores per cm open cell aluminum foam core, and a rear aluminum facesheet. The second configuration consisted of an aluminum facesheet, 1.27 cm thick aluminum honeycomb core, an intermediate aluminum sheet, 0.64 cm thick 6.35 pores per cm open cell aluminum foam core, and a rear aluminum facesheet. The open cell foam core of each configuration was infused with a STF consisting of 0.225 mass fraction of Aerosil 200 fumed silica in 200 molecular weight polyethylene glycol (PEG). HVI experiments were conducted for two specimens of each configuration employing a 1 mm diameter aluminum projectile and impact velocities of approximately 3-5 km/s. For comparison, the HVI experiments were repeated using additional specimens where the open cell foam cores were infused with the STF's liquid phase only, PEG. All specimens regardless of configuration or imbibed fluid prevented penetration of the rear facesheet. However, the STF infused core of the second configuration was not perforated. For the first configuration, in addition to the projectile entrance holes, the front facesheet sustained out of plane deformation local to the point of impact, and the amount of deformation was similar for the PEG and STF infused specimens. Additionally, the PEG infused specimens sustained a small amount of out of plane deformation of the rear facesheet, while the STF infused specimens did not. Non-destructive computed tomography (CT) scans of the impacted specimens were conducted to investigate the internal damage. Comparisons of the CT scans indicated that the PEG infused specimens sustained a slightly greater volume of core damage than the STF infused specimens.

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INTRODUCTION

Highly energetic impacts from micrometeoroids/orbital debris (MMOD) on the scale of approximately 1 mm in diameter are a major concern for spacecraft operating in the near-Earth space environment [1]. Micrometeoroids usually have masses of less than 1 g but can reach velocities up to 72 km/s with an average velocity of 19 km/s, and they are naturally occurring debris originating from comets and asteroids [1,2]. Orbital debris are manmade objects in orbit around the earth resulting from either collisions or discarded remnants of past space missions that serve no useful function. Orbital debris have an average velocity of 8 km/s but can reach 14 km/s [1, 2]. The amount of orbital debris is continually increasing, especially in the orbits which are most commonly utilized [1, 2]. Ultimately, spacecraft whose missions are of significant duration will experience MMOD impacts [2]. Thus MMOD damage mitigation is a crucial aspect in the design of space structures, especially those meant for human habitation.

The first concept for mitigating MMOD impacts was proposed by Whipple in 1947 and consisted of a single, thin aluminum shielding layer placed at some standoff distance away from the spacecraft hull [3]. Several notable MMOD shielding configurations have been developed since then including the multi-shock concept [4], the mesh double bumper [5], and the stuffed Whipple shield [6]. These all feature sacrificial layers outside of the spacecraft structural hull with standoff distances between each layer. Depending on the impact pressure generated, each shielding layer will fracture, melt or vaporize the incoming projectile as well as portions of the shield local to the point of impact forming a debris cloud [7]. The standoff distances allow the debris cloud to expand as it moves toward the next layer, thereby dispersing its energy over a larger area once it contacts the adjacent layer.

This study was a continuation of work investigating the applicability and HVI response of MMOD shielding concepts employing sandwich composite panels with porous core materials imbibed with a STF. STFs are composed of a particulate phase suspended in a liquid phase and display remarkable non-Newtonian shear rate and temperature dependent viscosity. With an increasing rate of shearing deformation the viscosity of a STF can increase multiple orders of magnitude after a critical shear rate. Several novel concepts have successfully employed this dramatic increase in viscosity and include improving the ballistic impact resistance of aramid fiber soft-body armor by changing the dominate energy absorption mechanism or damping the vibration of alpine skies [8, 9]. The NASA Johnson Space Center has performed HVI testing on MMOD shielding with STF impregnated aramid fiber fabric [10].

Figure 1 shows two sandwich composite specimens with 0.064 cm thick aluminum facesheets and 1.27 cm thick aluminum honeycomb cores from a recent study investigating the use of STFs as a component of MMOD shielding [11]. The top specimen was impacted at 4.74 km/s by a 1 mm diameter stainless steel sphere projectile (kinetic energy of 391 J), and its honeycomb core was filled with a STF consisting of 0.3 mass fraction (MF) Aerosil 200 fumed silica (A200 silica) in 200 molecular weight polyethylene glycol (PEG). The bottom specimen was impacted at 3.1 km/s with the same projectile type (kinetic energy of 154 J), and its

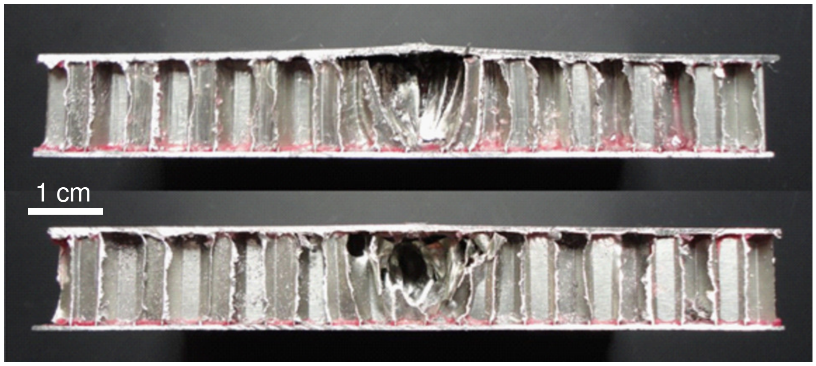

Figure 1. Two MMOD shielding specimens impacted with a 1 mm diameter stainless steel sphere, Top) honeycomb core filled with 0.3 MF Aerosil 200 fumed silica in 200 molecular weight polyethylene glycol (PEG) STF and impacted at 4.94 km/s (kinetic energy of 391 J), Bottom) honeycomb core filled with PEG only and impacted at 3.1 km/s (kinetic energy of 154 J) [11]

honeycomb core was filled with PEG only. Given the significantly disparate impact velocities and kinetic energies, it is remarkable that both specimens exhibited approximately the same amount of damage.

The lateral crushing of the honeycomb cell walls seen in Figure 1 lead to the choice of open cell aluminum foam as another sandwich panel specimen core material of to be infused with a STF and subjected to HVI experiments. Lateral flow of the STF through the open cell foam could cause shear thickening behavior. Figure 2 shows a three dimensional (3D) rendering of two dimensional (2D) computed tomography (CT) scans of a 0.064 cm thick aluminum facesheet sandwich composite specimen with a 1.27 cm thick 12.7 pores per cm open cell aluminum foam core infused with a STF composed of 0.2 MF A200 silica in PEG [12]. The specimen in Figure 2 was impacted with a 1 mm diameter stainless steel sphere at 4.15 km/s resulting in minimal out of plane deformation of the impact-side and rear facesheets as well as very little discernable core damage local to the center of impact. The rear facesheet was perforated by the stainless steel projectile, which remained largely intact after perforating the front facesheet. The exit hole isn’t visible due to the projectile’s path being altered after impacting the foam ligaments. The HVI responses for both the STF and PEG infused specimens was largely similar o the above description. However, the small amount of damage to the witness plates placed behind the specimens during HVI experiments suggested that most of the projectile’s kinetic energy was dissipated within the specimen. The minimal damage to the facesheets and core of the specimen in Figure 2 implies that most of the sandwich panel’s load bearing ability would be retained. However, a configuration capable of preventing perforation of the rear facesheet was of interest and resulted in the choice of experiments undertaken in the present study.

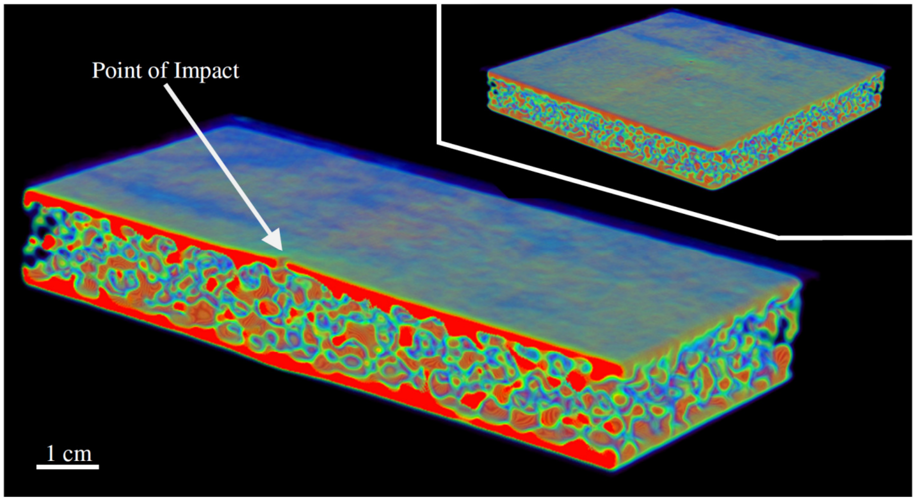

Figure 2. Three dimensional rendering of computed tomography scans of an aluminum facesheet and 1.27 cm thick 12.7 pores per cm open cell aluminum foam sandwich composite impacted with a 1 mm diameter stainless steel sphere at 4.15 km/s (kinetic energy of 276 J) sectioned through the center of impact, Inset) Rendering of entire specimen (Note: rear facesheet was perforated, but the exit hole is not visible due the projectile's path altering after impacting foam ligaments) [12]

Materials and Experiments

The STF that was infused into the open cell foam core of the specimens in this study was made of the same components as the STFs mentioned above (i.e. A200 and PEG), but the MF of particles was 0.225. The A200 silica particles were dried in a 105 ° oven for at least twenty four hours previous to mixing to remove any absorbed moisture, and the particles were dispersed in the PEG using a high shear mixer. The shear rate and temperature dependent behavior of this STF can be seen in Figure 3, which shows the results of steady shear rheology experiments conducted on a TA Instruments DH-2 rheometer employing parallel plate fixtures with a 1 mm gap and a Peltier device for temperature control. The viscosities of PEG alone at 0 °C, 20 °C, and 40 °C are 0.23 Pa.s, 0.065 Pa.s, and 0.019 Pa.s, respectively.

The particle interactions that lead to shear thickening behavior are governed by a force balance between repulsive forces (Brownian, steric, electrostatic, etc) and hydrodynamic forces [13]. Upon initial shearing deformation, the viscosity of a STF will decrease (i.e. shear thin) as the equilibrium microstructure of the suspended particles is broken down and particles align to move past each other more freely. Repulsive forces dominate the system during shear thinning, but the hydrodynamic forces acting on particles increase as the shear rate increases. At some critical shear rate the magnitude of the hydrodynamic forces overtake the repulsive forces resulting in particles coming into close proximity. As the shear rate increases further, transient groups of particles form called hydroclusters which increase the energy dissipation rate of the STF leading to the increase in viscosity. Simulations have shown that these hydroclusters grow in size and numbers as the shear rate is increased and the STF continues to thicken [14].

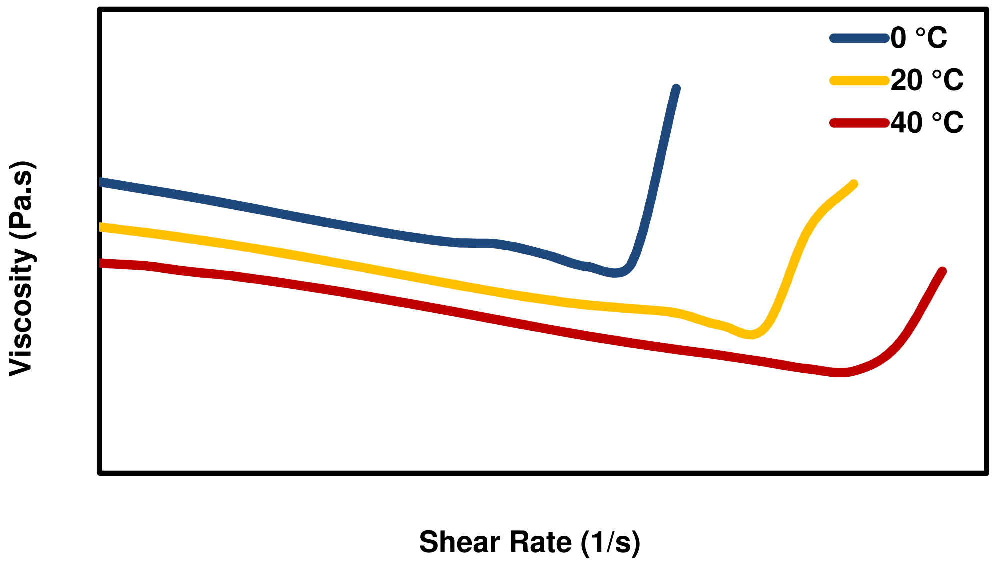

Figure 3. Steady shear experiments of a STF consisting of 0.225 mass fraction of Aerosil 200 fumed silica in 200 molecular weight polyethylene glycol

Two specimen configurations made of 6061 aluminum components were chosen for the present study. The first configuration consisted of a 0.064 cm thick aluminum facesheet, 1.27 cm thick 6.35 pores per cm open cell aluminum foam core, and a rear aluminum facesheet (i.e. facesheet, foam, rear facesheet). This configuration is identical to that of the specimen in Figure 2 except that the pore size of the foam was decreased by four hundred percent. Cell size and pore size are differentiated in Figure 3. The cell size was reduced to increase the shearing deformation of the imbibed fluid when flowing through the pores and hence, affect the shear thickening behavior of the STF. The second configuration consisted of a 0.064 cm thick aluminum facesheet, 1.27 cm thick aluminum honeycomb core, an intermediate 0.064 cm thick aluminum sheet, 0.64 cm thick 6.35 pores per cm open

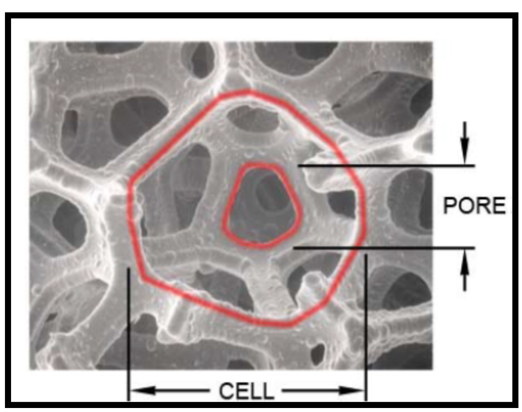

Figure 4. Relationship between open cell foam cell size and pore size [ERG Aerospace]

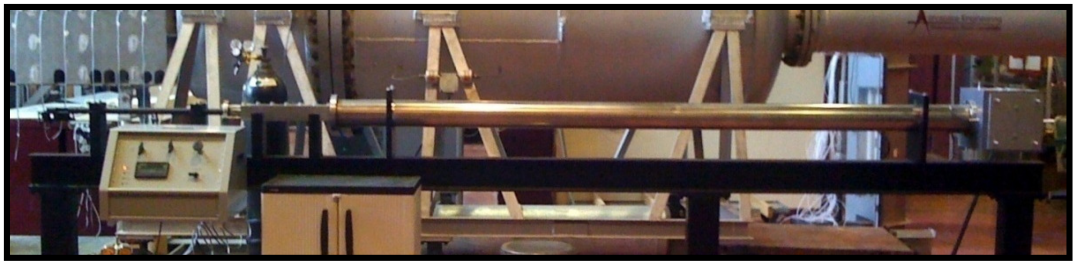

Figure 5. Mississippi State University micro two-stage light gas

cell aluminum foam core, and a rear 0.064 cm thick aluminum facesheet (i.e. facesheet, honeycomb, sheet, foam, rear facesheet). The second configuration was identical to the honeycomb core specimens in Figure 1 with the exception that i) the honeycomb cells were not filled with a fluid and ii) a second core of open cell aluminum foam (to be infused with a fluid) and a rear facesheet were added. A moisture resistant film adhesive, AF 163-2 manufactured by 3M, was employed to bond all components.

The open cell foam core specimens were infused with either the STF or PEG alone and degassed to remove any air bubbles. The specimen edges were sealed using fiber reinforced adhesive tape. All HVI testing was conducted using the Mississippi State University micro two-stage light gas gun seen in Figure 5. The projectiles were 1 mm diameter 2017 aluminum spheres, and the impact velocities were approximately 3-5 km/s. All impacts were perpendicular to the front facesheet of the specimens.

RESULTS

Table I lists the impact velocity and impact kinetic energy for each specimen. Specimens 1through 4 were the first configuration (foam core), and their impact velocity and corresponding kinetic energy ranged from 3.2 – 4.63 km/s and 59.8 – 125.3 J, respectively. Specimens 5 through 8 were the second configuration (honeycomb and foam core), and their impact velocity and corresponding kinetic energy ranged from 2.9 – 4.74 km/s and 49.1 – 131.3 J, respectively.

TABLE I. HVI EXPERIMENTAL RESULTS

Specimen	Infused Fluid	Core Material	Impact Velocity (km/s)	Kinetic Energy (J)
1	PEG alone	foam	4.42	114.2
2	PEG alone	foam	4.63	125.3
3	STF	foam	3.20	59.8
4	STF	foam	4.58	122.6
5	PEG alone	Honeycomb/Foam	2.96	51.2
6	PEG alone	Honeycomb/Foam	2.90	49.1
7	STF	Honeycomb/Foam	4.74	131.3
8	STF	Honeycomb/Foam	n/a	n/a

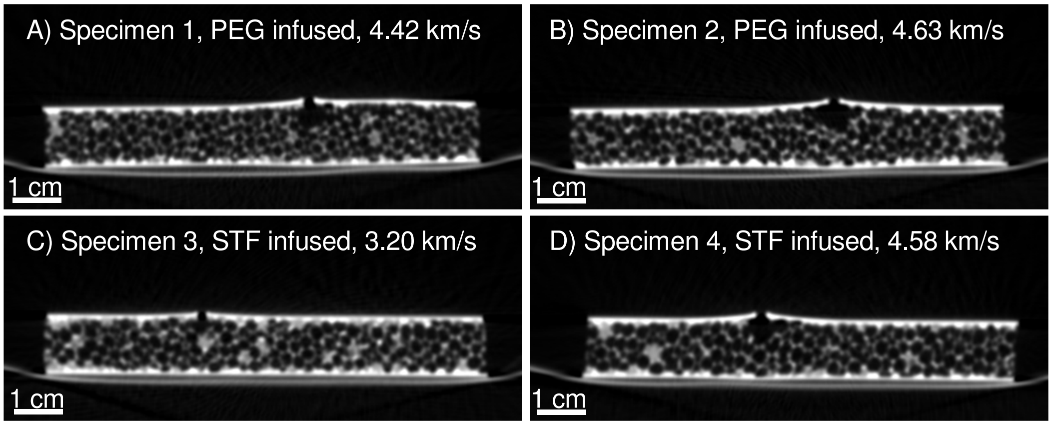

Figure 6. Computed tomography (CT) scans through the center of impact for the first configuration specimens with imbibed fluid and impact velocity of each (Note: curved white line below each specimen is related to the CT scanning process)

Computed tomography (CT) scans were taken of the impacted specimens. Figure 6 shows the CT scans through the center of impact for specimens 1 through 4 (first configuration). Note the impact hole present on the top facesheet of each specimen. Figure 6A and 6B were infused with PEG while Figure 6C and Figure 6D were infused with the STF. Specimens 1 and 2 (Figures 6A and 6B) and specimen 4 had comparable impact velocities of 4.42 km/s, 4.63 km/s, and 4.58 km/s, respectively and can be compared. All three experienced a similar magnitude of out of plane deformation of the front facesheet (upper facesheet in Figure 6) local to the center of impact resulting from pressure developed within the core. This bulging behavior of the impact-side facesheet likely indicates some amount of facesheet delamination and/or in plane tearing of the open cell foam core ligaments near the impact hole. A volume of the foam core of each of these three specimens was crushed by the debris cloud entering the core, but the extent of core damage seen for these three specimens in Figure 6 is very similar. The STF infused specimen (Figure 6D, 4.58 km/s) has a smaller volume of crushed core than the PEG infused specimen in Figure 6C (4.63 km/s) but about the same amount as the PEG infused specimen in Figure 6A with the slightly lower impact velocity (4.42 km/s). This comparison tentatively indicates that an STF infused specimen might sustain less crushing damage of the core due to the debris cloud. Destructive sectioning of the specimens to further investigate core crushing would likely distort the areas of crushed core. Additionally, the rear facesheet (bottom facesheet in Figure 6) of the two PEG infused specimens (Figure 6A and 6B) is slightly bulged out of plane, while the rear facesheet of the STF infused specimen (Figure 6D) bulges out of plane a smaller amount. The STF infused specimen in Figure 6C was impacted at a much smaller velocity (3.20 km/s) than the other three specimens in Figure 6, but it experienced similar trends in damage although to a much lesser extent (i.e. impact hole and slight core crushing).

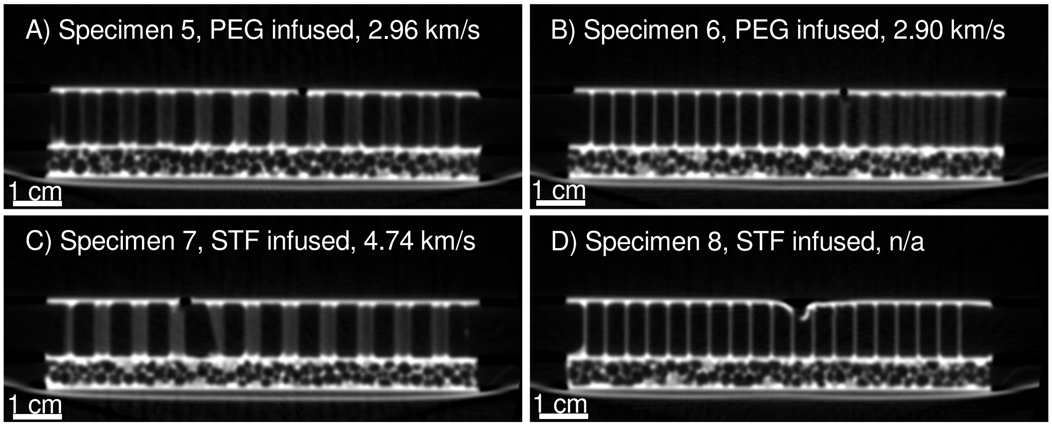

Figure 7. Computed tomography scans through the center of impact for the second configuration specimens with imbibed fluid and impact velocity of each (Note: curved white line below each specimen is related to the CT scanning process)

Figure 7 shows the CT scans through the center of impact for specimens 5 through 8 with the second core configuration of non-infused honeycomb and infused open cell foam separated by an intermediate aluminum sheet. Note the impact hole present on the top facesheet of each specimen. Figure 7A and 7B were infused with PEG while Figure 7C and Figure 7D were infused with the STF. Unfortunately, the CT images in Figure 7 do not indicate that the intermediate aluminum facesheet of any of the specimens was perforated.

CONCLUSIONS

HVI experiments were performed on two configurations of sandwich composite specimens with fluid infused open cell aluminum foam cores. The first configuration had a core of liquid infused open cell foam only, while the second configuration employed an empty honeycomb core followed by a liquid infused open cell foam core. Half of the specimens of each configuration were infused with an STF and the other half with the STF's liquid phase only, PEG. The projectiles were 1 mm aluminum spheres. Impact velocities and kinetic energies ranged from approximately 3-5 km/s and 50-130 J, respectively.

Unfortunately, there was no evidence that the fluid infused foam core of the second configuration was perforated by the projectile. However, the HVI results for the first configuration indicated that the STF infused core specimens might be better able to mitigate the highly energetic impacts. The rear facesheet was not perforated for any of the fist configuration specimens, and CT imaging was performed through the center of impact of each to investigate interior damage. Comparing PEG and STF infused first configuration specimens impacted at comparable velocities, the trends in damage were similar, but the STF infused specimen sustained slightly less damage than the PEG infused specimens. Out of plane deformation of the front facesheet local to the center of impact was present, which indicated facesheet delamination and/or tearing of the open cell foam core ligaments near the impact point. Foam core in the area directly beneath the impact sustained crushing damage but only through a portion of the thickness of the core. There was also out of plane deformation of the rear facesheet.

This work was supported by a NASA Space Technology Research Fellowship.

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