Foam Core Particleboards with Intumescent FRT Veneer: Cone Calorimeter Testing With Varying Adhesives, Surface Layer Thicknesses, and Processing Conditions

Mark A. Dietenberger
USDA Forest Service, Forest Products Laboratory
Madison, Wisconsin
mdietenberger@fs.fed.us

Ali Shalbafan,
Department of Wood and Paper Science and Technology
Faculty of Natural Resources and Marine Sciences
Tarbiat Modares University, Iran

Johannes Welling
Thuenen-Institute (TI) of Wood Research
2103 Hamburg, Germany

***Abstract*—Intumescent FRT Veneers adhered to the surface of foam core particleboard to provide adequate fire protection were evaluated by means of cone calorimeter tests (ASTM E1354). The foam core particleboards were prepared with variations in surface layer treatment, adhesives, surface layer thicknesses, and processing conditions. Ignitability, heat release rate profile, peak of heat release rate, total heat released, effective heat of combustion, mass loss rate, gaseous emissions and specific extinction area were measured with the test specimens exposed to a cone irradiance of 50 kWm^{-2}. Unprotected foam core panels generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the polymeric foam component of tested panels, whereas time to ignition and total heat release were not pronounced from the veneer treated boards. Adding the fire retardant (EnviroGraph Intumescent cloth with veneer) to the surface particleboard provided a dramatic improvement to the measured flammability properties, with the best FRT performance associated with thicker face layer (5mm), lower press temperature (130ºC), and adhered with an acrylic thixotropic adhesive, Intumescent Adhesive. Such protected foam core particleboard is likely to receive a flammability rating that is typical of commercial FRT plywood when tested in accordance with both the SBI (Class B anticipated) and Steiner Tunnel (Class A anticipated) tests.**

***Index Terms*—Intumescent flame retardant, foam core particle board, cone calorimeter, sandwich panels**

I. Introduction

Lightweight, sandwich-type composite panels with particleboard facing and a foam core produced in one single production step [1] are novel replacement for conventional particleboards. They can be produced on standard particleboard production lines using some modifications of the machines. Using Expandable Polystyrene (EPS) for in-situ foaming of the core material constrains the production process. Marketability of these innovative panels can be limited due to their fire safety concerns. The nature of the foam core particleboard construction makes the cone calorimeter optimal for evaluating flammability as compared to other potential laboratory scale tests such as the limiting oxygen index (LOI) and the micro combustion calorimeter (MCC). The cone calorimeter (ASTM E1354-11a) measures the reaction-to-fire parameters having good correlations with the full-scale fire behavior [2, 3]. The ignition time, heat release rate, total heat released, heat of combustion, mass loss rate, combustion products and specific extinction area are the main parameters measured and analyzed. The very limited flammability studies that are available on thin foam core sandwich panels indicate the need for a comprehensive investigation of the fire performance of foam core sandwich panels [4, 5, 6].

The initial study involved the cone calorimeter tests of samples exposed to irradiance of 35 kWm^{-2}. Of the variations in surface layer thicknesses, core foam densities, and processing temperatures for the 19 mm-thick panels, it was the surface layer thicknesses that had the most impact on the fire behavior of sandwich structures [4]. In that study, the heat release rates (HRR) for the sandwich panels were much higher in comparison to the conventional particleboard panel. Since increasing the surface layer thickness was beneficial for reducing the heat release rate, the use of a veneer with fire retardant adhesive or intumescent cloth was suggested to seal in the volatiles and provide insulation to prevent the foam degradation for a relevant period of time. The detailed analysis of evolved gases and temperature profile from such samples when exposed to 50 kWm^{-2} in the cone calorimeter has proved these effects [5]. However, additional study was needed to further reduce the HRR with a systematic variation to the processing temperature, surface layer thickness, adhesive type, and veneer treatment, which is reported in this paper.

II. MATERIALS AND METHODS

A. Production of the panels with face layer variations

The foam core particleboards, with a nominal thickness of 19 mm, were manufactured from a three layered mat without additional gluing between the face and core layers. The wood particles resinated with urea formaldehyde resin (Kaurit 350, BASF, Germany) were used for the face layers. The expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) with a granule size of 0.3 to 0.8 mm were used as the foam core materials. According to the data sheet of Terrapor 4, it contains a small amount of flame retardant. This material also contains 5.7% pentane (by weight) as the blowing agent. Between 2 and 3% of the initial pentane remains in the foam cells after expansion, depending on process parameters.

The three-layered mat was pressed in a lab-scale single opening (Siempelkamp, Germany) hot-press. The press cycle consisted of three consecutive stages: pressing phase, foaming phase, and stabilization phase by the internal cooling of the press plates. For the present study, the temperature of the press plates was set to130˚C (1-EPS; A, B, C panels) and 160˚C (2-EPS, D, E, F panels), respectively. The panels were produced with varying surface layer thicknesses of 3, 4, and 5 mm for each press temperature as shown in Figure 1. For each surface layer thickness, four panel replicates were produced. Shalbafan, et. al. [7] have described in details the pressing schedules and foaming conditions.

Fig. 1. The six different panel constructions

The improvements utilized for this study were the use of a conventional beech veneer without and with intumescent paper underneath the veneer. The fire resistive adhesive used for veneering the samples was Firobond Ultra Adhesive (FUA) and acrylic thixotropic adhesive named Intumescent Adhesive (IA) supplied from ENVIROGRAF, UK. The conventional particle boards and sandwich panels without any veneer were utilized as reference samples in this series of tests. Four panels of each series were produced as replicates and one 100- by 100- mm sample was cut out from each panel to do the fire performance test in triplicates and with one sample retained for other detailed tests [5]. Table 1 provides the identifiers for all the test materials used in this study and listed again in Table 2.

TABLE I. PANEL IDENTIFIER CODE

Identifier	Thickness (mm)	Temperature (Celsius)	Veneer	Adhesive
B02	4	130	none	none
A11	3	130	beech	IA
A21	3	130	beech	FUA
AV1	3	130	FR	IA
BV1	4	130	FR	IA
CV1	5	130	FR	IA
AV2	3	130	FR	FUA
BV2	4	130	FR	FUA
CV2	5	130	FR	FUA
E02	4	160	none	none
D11	3	160	beech	IA
D21	3	160	beech	FUA
DV1	3	160	FR	IA
EV1	4	160	FR	IA
FV1	5	160	FR	IA
DV2	3	160	FR	FUA
EV2	4	160	FR	FUA
FV2	5	160	FR	FUA

B. Sample preparation and testing procedures

All the samples were conditioned at 23°C and 50% relative humidity for at least two weeks prior to testing to meet equilibrium moisture content (EMC). The tests were carried out according to the ASTM E1354 test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, IL) at the Forest Product Laboratory in Madison, USA. Samples were exposed in the horizontal orientation to the irradiance 50 kWm^{-2} upon opening the water-cooled thermal shutter and using an electric spark for piloted ignition.

The specimens were tested in the optional retainer frame with a wire grid over the test specimen. The 100- by 100- mm specimens were wrapped with aluminum foil on the sides and bottom and placed in the specimen holder lined with a ceramic blanket. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause the slight expansion of the foam during the test. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid was used in all the cone tests to restrain the heated surface. Ignitability was determined by observing the time for sustained ignition for a 4 second period of the specimen. Observations of HRR, mass loss rates (MLR), effective heat of combustion

(EHC), and soot extinction area (SEA) as function of time are obtained, although only the HRR profile is examined in detail to evaluate flammability in this paper.

III. RESULTS AND DISCUSSION

A. Heat release rate (HRR) of panels

The size of a fire is correlated positively with the HRR and the HRR will, in turn, increase as the fire is spreading, unless the HRR can be made to decrease rapidly enough or be kept to a low value to counter the increase in pyrolysis surface area [2]. Thus the practical goal for fire retardancy is preventing fire growth rather than merely preventing ignition. Since both ASTM E84 and Single Burn Item (SBI) (EN 13823) last 10 minutes, only the first 600 seconds of the cone calorimeter test were evaluated. In addition, the ASTM E84 specimen is backed by a heavy cement board that will absorb heat from the exposed specimen, thereby drastically reducing the second HRR peak [2] and extending the period of glowing. However, there are real world fires in which the insulation backing is more the norm.

1) *Particle board results*

As a baseline comparison, the conventional particle boards prepared without the foam core were tested in the cone calorimeter. Their HRR profile, as shown in Figure 2, at least during the first 600 seconds, is similar to most untreated wood products. For comparison, the oriented strandboard (OSB) board with similar HRR exponential decay as in Figure 2 was predicted and measured to have a Class C flame spread rating [2,3]. Tsantarideis, Ostman and Hakkarainen [8] have provided the rating Euroclass D to similar materials, particularly if they are straddling around HRR of 100 kWm^{-2}, for the most part. The rule of thumb for Euroclass D criteria using the cone calorimeter data is TTI >15s and PHRR < 250 kWm^{-2}, for at least 900 seconds from the start of heat exposure. Furthermore the simple rules for Euroclass B is with TTI >40s and PHRR<100kWm^{-2} and for Euroclass C is with TTI>30s and PHRR<180kWm^{-2}. These rules are on the safe side, so that a product having these conditions meets the requirements of a certain Euroclass in the SBI test with a high probability.

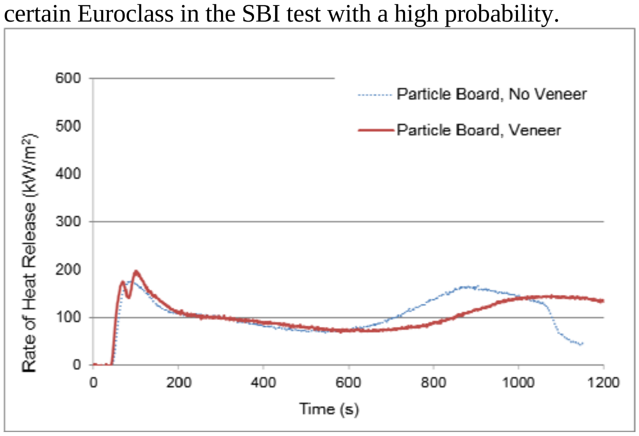

Fig. 2 HRR of the baseline wood product as particleboard

2) *Foam core particle board results*

Figures 3, 4, and 5 show the strong, and yet similar, dual peak HRR profiles of foam core particle board that is predicted to be very flammable. That is, the first PHRR is about 300 kWm^{-2} and the second PHRR is about 500 kWm^{-2}, all of which are within 600 seconds. The first peak is the result of ablating initially the surface exposed to a combined cone heater and flame radiance on the surface. The HRR then decreases as a result of surface charring and the thermal wave process following the ablative process. In essence, the pyrolysis front develops and is decreasing in speed and, with the char density staying constant; the volatization mass rate is also decreasing. Since the volatile heat of combustion is fairly constant for initially dry wood, the HRR is also decreasing [9,10]. The HRR eventually begins to rise as a result of the thermal wave termination at the insulated rear surface, which means the sample is entering the thermally thin regime and broadens and speeds up the thin pyrolysis zones. For a surface layer sufficiently thin and backed by an insulation board, such as EPS, the dual peaks in the HRR merge together into a single initial peak, such that the surface is treated as thermal capacitance that control the heating process, and thus the pyrolysis process [9,10]. However, since there is a second, backside surface layer of particle board, it is just a matter of time after the EPS has fully melted and charred remains of the exposed surface layer heats the backside surface layer by contact or radiation. Further volatization occurs when the backside particle board reaches its volatization temperatures after a period of heating. The glowing from the infusion of air takes over at some point at a peak HRR, and, as the material is consumed, the HRR will decrease once again. Figures 4 and 5 show that adhering a beech veneer with either FUA or IA resulted in no improvement to the HRR profiles.

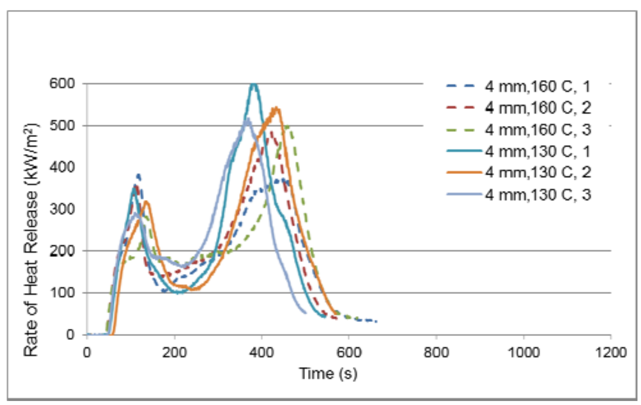

Fig. 3. HRR of foam particle boards of type E and B in Fig. 1 with no veneer as exposed to 50 kWm^{-2}

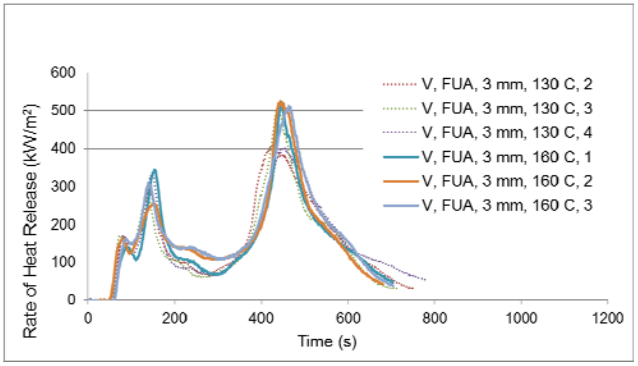

Fig. 4. HRR profile of foam particle boards of type A and D with beech veneer adhered with FUA as exposed to 50 kWm^{-2}

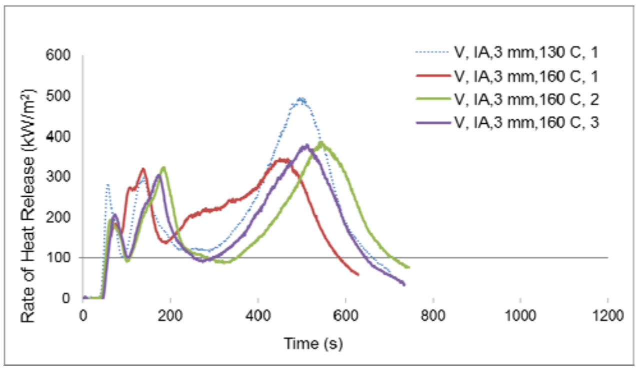

Fig. 5. HRR profile of foam particle boards of type A and D with beech veneer adhered with IA as exposed to 50 kWm^{-2}

3) Fire retarded surface layers

Since the detailed temperature measurements in an earlier study [5] showed that the foam core easily reached degradation temperatures, even with ordinary veneers, it was suggested to use a commercial veneer with an intumescent layer to protect the panel during fire exposures. The EnviroGraph Intumescent cloth with veneer of 1 mm thickness was found suitable, although other similar products can be utilized. The results of using fire retardant veneer (FRV) with various panel constructions are shown in Figures 6 to 9. All tests had the similar first and narrow PHRR of about 220 kWm^2 due to the FRV degradation occurring at 50 seconds. The presence of the second peak HRR of varying magnitudes at around 200 to 300 seconds is due to the surface layer degrading and emitting combustible volatiles through the degraded FRV. The third HRR peak for all the tests occurred after 600 seconds indicating that the FRV resulted in much reduced HRR resulting in the improved flammability overall as compared to the unprotected panels in relation to the Steiner Tunnel test and SBI test.

To compare the effects of adhesives, surface layer thickness, and processing temperatures, the second PHRR is worth further examination. The least improvement was obtained with FRV adhered with FUA and processing temperature of 160^{o}C, as shown in Figure 6. Our microscopic observation of the surface layer revealed a relatively low density surface layer or lower compacted surface layer in which some of the adhesive can penetrate the layer resulting in a relatively weaker bond as well as in higher porosity for the volatiles to flow. Additionally, the FUA is described by Envirograph as to not give the adhesive strength at high temperatures. As Figure 6 shows, even though the second peak HRR is reduced and somewhat delayed as compared to that in Figure 4, the improvement now is somewhat comparable to Figure 2 for particleboard.

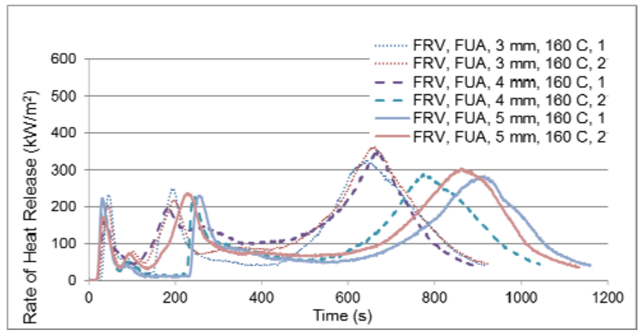

Fig. 6. HRR of foam particle boards for types D, E, and F of FRV adhered with FUA and processing temperature of 160 C.

The next level of improvement is shown in Figure 7 where a lower processing temperature of 130^{o}C resulted in a denser surface layer. Despite the repeated use of FUA, there is a further delay in the second peak HRR by about 100 s and the improvement in the overall HRR is somewhat better than that of the particleboard in Figure 2. Since the second and third PHRR are around 200 kWm^{-2} or higher, it would still be Euroclass D [8]. However, considering the quite low valleys of HRR between the peak HRRs as far below 100 kWm^{-2}, and with the third peak HRR occuring greater than 600 seconds, this sandwich panel construction could provide an anticipated Class A or B FSI.

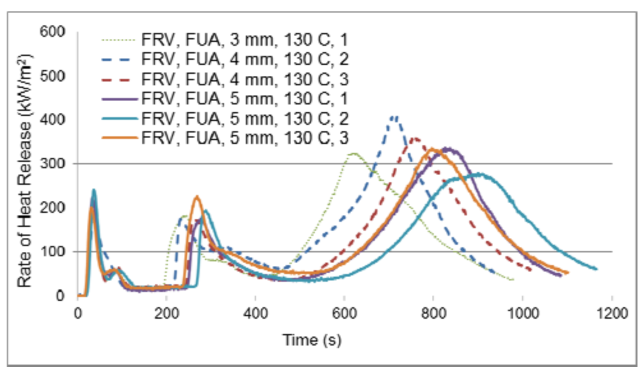

Fig. 7. HRR of foam particle boards for types A, B, and C of FRV adhered with FUA and processing temperature of 130 C.

A somewhat better improvement in reducing the HRR is shown in Figure 8 where the FRV is adhered with IA on the less densed surface layer with processing temperature of 160ºC. Envirograph describes this adhesive as adhering wood joints for a long period of high temperature exposure time around at least 60 minutes. The thickest surface layer of 5 mm has the longest delay for the second peak HRR at approximately 400 s. With its HRR tending to hover around 100 kWm^2, the maximum HRR less than 180 kW/m^2, and ignoring the initial first peak HRR, a Class B flame spread index (FSI) is predicted [2,3] as well as Euroclass C [8].

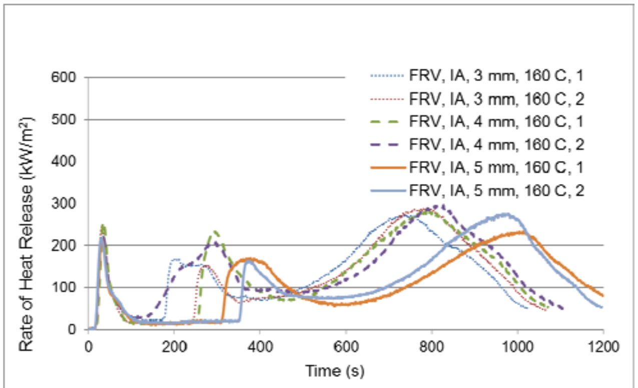

Fig. 8. HRR of foam particle boards for types D, E, and F of FRV adhered with IA and processing temperature of 160 C.

The best performance in reducing the HRR is shown in Figure 9 in which the second peak HRR has been eliminated by using FRV adhered with IA to the thickest and densest surface layer tested. This quite low HRR lasted a full 600 s until the back surface layer began burning. If the narrow peak HRR due to the FRV degradation is ignored, it is expected that a Class A FSI and Euroclass B are attainable [2,8]. It is likely that if FRV is adhered with IUA to conventional particle board, the similar level of reduction of HRR will also occur, but with the third peak HRR occuring at even a later time than 900 seconds.

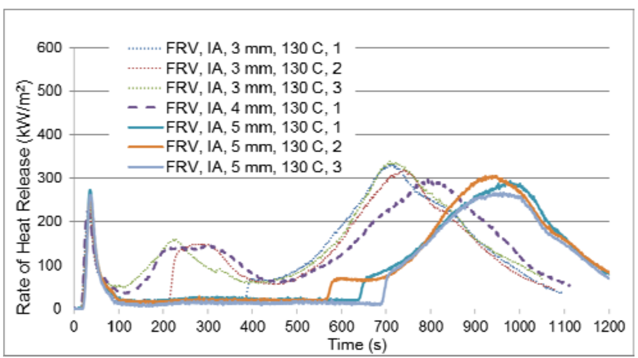

Fig. 9. HRR of foam particle boards for types A, B, and C of FRV adhered with IA and processing temperature of 130ºC.

B. Cone calorimeter summary results

Table 2 reports the average of three replicates for the time to ignition (TTI), Peak HRR (PHRR), effective heat of combustion (EHC), mass loss rate (MLR), and specific extinction area (SEA) for the panels considered for this study. It is seen that the panels without the FRV tend to have comparatively higher values of TTI, PHRR, EHC, MLR and SEA. Despite these differences, the propensity to flame spread as indicated by the Beta calculation as described in [2], or by plotting THR/TTI versus PHRR, show that all the panels are predicted to obtain a Class C FSI. Evidently, the narrow peak HRR due to burning of the fire retarded veneer has distorted the results of the summary data. To correct this predictive problem the flame spread modeling will need to be more comprehensive.

IV. Conclusions

The best fire performance for a foam core particleboard is offered by a processing panel temperature of 130ºC, a 5 mm surface layer thickness, an IA adhesive with an intumescent veneer. This optimal panel is predicted to meet the Euroclass B (SBI) and a Class A FSI (ASTM E84) via the cone calorimetry HRR data at irradiance of 50kW/m^2 and with piloted ignition. Other combinations of FRV with alternative adhesives, surface layer thicknesses, and processing temperature also resulted in much reduced HRR to the point that they would be an equivalent replacement to the conventional particle board. The cone calorimeter summary data proved not helpful when predicting flammability ratings, which implies that flame spread modeling may need to be revisited.

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Table 2. Cone Calorimeter Summary Data for Averages of Three Replicates and Standard Deveiation, Beta, and THR/TTI ratio

Identifier	TTI		PRHR		THR		EHC		MLR (10% to 90%)		SEA		Beta	THR/TTI
	(s)	Std.dev	(kWm^{-2})	Std.dev	(MJm^{-2})	Std.dev	(MJ/kg)	Std.dev	(g/s)	Std.dev	(m^2kg^{-1})	Std.dev		(kWm^{-2})
B02	55.5	6.6	320.2	29.6	118.8	4.9	17.4	0.3	16.1	0.2	545.0	56.2	0.326	2141
A11	38.1		284.0		147.9		18.7		13.5		579.0		0.355	3877
A21	54.5	0.6	300.8	43.7	113.0	6.7	15.7	0.0	12.5	0.2	461.8	25.5	0.295	2071
AV1	17.6	1.5	234.0	10.6	138.9	11.3	16.9	1.6	9.1	0.2	621.1	62.6	0.317	7874
BV1	16.9	2.3	240.8	17.1	147.8	7.4	13.8	4.4	11.0	2.1	404.0	123.0	0.332	8741
CV1	18.9	1.3	265.5	6.7	117.9	9.9	11.6	1.1	9.5	0.2	347.7	75.8	0.360	6242
AV2	19.5	1.6	245.1	25.1	119.8	7.4	16.0	1.4	8.7	0.3	832.0	358.9	0.325	6143
BV2	19.0	0.6	201.9	37.5	120.7	3.7	14.2	0.1	10.0	0.8	971.5	60.1	0.254	6336
CV2	19.8	2.4	221.3	20.4	125.3	3.8	13.2	0.7	9.8	0.4	391.9	15.3	0.286	6319
E02	48.8	2.9	342.6	52.2	118.2	2.5	16.9	0.3	14.8	0.4	497.9	43.6	0.379	2421
D11	44.0	2.9	240.2	68.9	128.0	3.9	17.0	0.6	13.0	0.6	535.0	104.3	0.261	2912
D21	59.6	4.6	303.0	46.1	115.7	6.9	15.5	0.9	13.6	0.1	518.5	60.8	0.285	1940
DV1	16.9	0.2	238.7	15.4	134.2	2.7	16.3	1.8	8.9	0.6	554.3	61.5	0.325	7925
EV1	18.2	2.0	229.0	26.4	149.7	9.2	16.6	1.1	9.8	0.3	566.4	18.2	0.310	8240
FV1	15.0	0.7	215.4	1.2	135.3	4.4	13.2	0.4	9.6	0.2	391.3	31.7	0.289	8997
DV2	25.5	1.9	222.2	16.2	119.0	7.9	16.1	0.6	9.1	0.4	554.4	39.5	0.272	4669
EV2	18.9	0.7	179.8	30.9	118.6	6.1	14.0	0.6	10.4	1.0	454.1	19.4	0.216	6257
FV2	20.3	2.1	191.3	27.9	128.1	8.9	13.2	0.8	9.8	0.5	375.6	23.5	0.236	6295

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