Tests for Evaluating the Ignitability of Firework Stars and Compositions

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Abstract: *A shot test was examined for evaluating the ignitability of cylindrical bare and primed stars. The primed stars were more easily ignited than the bare stars. The ignition limit lift charge was defined and used for evaluating the ignitability. Though the ignition limit lift charges of the primed stars were widely scattered, the order of average ignitability of primed stars was: F > J > D > C > L > G > A > E > H > K > I > B The order of ignitability of bare stars was: blue star > yellow star > purple star > green star > red star. The hot plate and electric match tests were carried out for screening the ignitability of star, prime, lifting charge and bursting charge compositions. Both the test methods may be applied to screen the ignitability of bare star compositions from the other more ignitable compositions though there are rare exceptions.*

Keywords: *fireworks, ignitability, shot test, hot plate test, electric match test, prime, star, lifting charge, bursting charge*

Introduction

Fireworks give various effects by means of the combustion of the stars and compositions. The ignitability of the stars and compositions is important from the point of view of safety and performance of the fireworks. Too high an ignitability may cause a fire and explosion accident. Too low an ignitability may cause a misfire and a firework cannot work properly when one of the components is too insensitive to an igniter.

Ignitability tests of energetic materials including pyrotechnics were developed mainly for safety.[1,2] BAM in Germany developed several test methods for evaluating the ignitability of energetic materials. These methods include the cerium–iron spark, fuse, small gas flame, hot iron rod and hot bowl tests.[3] In Japan, the hot hole test has been used as a heat sensitivity test for energetic materials.[4]

Misfires of the fuse of a shell, the lifting and bursting charges, and stars have been suggested as causes of firework incidents. The misfires may be caused by the too low ignitability of those components of fireworks. In order to improve the ignitability of bare stars, the prime has been used. Kosanke and Kosanke have explained primes and priming.[5] We started to study the ignitability of these components using three tests: shot test, hot plate test and electric match test. Sashimura *et al.*[6] carried out a shot test for evaluating the ignitability of bare and primed stars of compositions cited in the literature.[7]

The shot test was referred to but details are not known except for Sashimura's work. The hot plate test used in this work is a similar method to the BAM hot bowl and Japanese hot hole tests. The electric match test is similar to the cerium–iron spark test in principle. In this article, those methods are applied to the compositions of prime, star, lifting and bursting charges.

Experimental

Materials

The sample compositions of stars and primes tested were prepared by the present authors and are listed in Tables 1 and 2, respectively. The lift and burst charges were supplied by Sunaga Fireworks Co. Ltd. The cylindrical bare and primed stars were

Table 1 *Compositions of bare stars.*

	Red star	Yellow star	Green star	Blue star	Purple star
$KClO_4$	53	48		62	53
$SrCO_3$	12				7
$K_2Cr_2O_7$		1	1		
$BaCO_3$		10			
$Ba(NO_3)_2$			54		
CuO				12	9
MgAl 180 mesh	15				
MgAl fine		15	20	1	8
Rice granules	5	5	5	4	5
Chlorinated gum	6		8	8	5
PVC	4	8		2	5
Phenol resin	3			10	8
Red gum	2	10	9		
Hemp charcoal			1	1	
Cryolite		3			

manufactured by Alps Fireworks Co. Ltd. Cross-section models of bare and primed stars are shown Figure 1. The bare star is 11 mm in diameter and about 10 mm long. The primed star is covered by a prime layer on the bare star.

The powdery compositions were wetted with 10% water and pressed into a square rod 1.5 × 5 mm in cross section by 30 mm in length, and then cut into 1.5 × 5 × 5 mm pieces. The pieces were dried in the open air.

Table 2. *Compositions of primes.*

Prime	A*	B	C	D	E	F	G	H	I	J	K	L
KNO_3	75	75	80	75	75	75	75	80	80	80	80	56
Hemp charcoal	15	15	20	15	15	15	15	20	20	20	20	9
S	10	10		10	10	10	10					5
Rice granules	5	5	5	5	5	5	5	5	5	5	5	7
MgAl 180 mesh				11				11				
MgAl fine												9
Al VA150					11				11			
Ti fine						11				11		
Si 200 mesh							11				11	
$K_2Cr_2O_7$				1				1				5
H_3BO_3					1				1			
Sb_2S_3												9

*Commercial black powder.

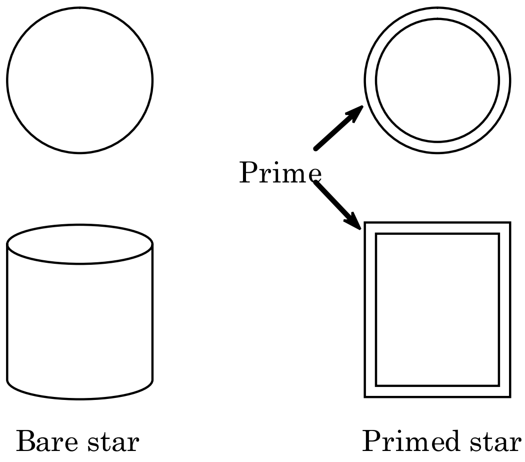

Figure 1. *Star samples.*

The electric match for the electric match test is a product of Nippon Kayaku Co. Ltd. The electric bridge wire of the electric match is made of a platinum–iridium alloy, about 0.03 mm in diameter and 300–400 Ω in electric resistance. The ignition charge is an equal mixture of lead thiocyanate and potassium perchlorate , and 12±3 mg in mass.

Apparatus

The setup of the shot test is shown in Figure 2. The mortar is a steel tube 270 mm long and 15 mm in inner diameter. The setup of the test apparatus

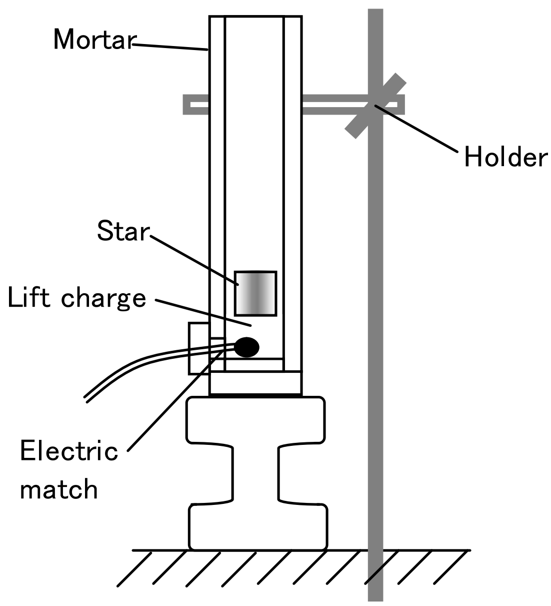

Figure 2. *Setup of shot test.*

for the ignitability test using a hot plate is shown in Figure 3. The apparatus consists of a 300 W electric Ni–Cr heater, 140 mm Ø × 1.0 mm steel plate, thermocouples, 140mm Ø × 40 mm heat insulating half-cut bricks. The heater was heated by an electric current through a transformer. The surface temperature of the hot plate was measured by a digital thermometer through the thermocouples attached on the plate. A high-speed video camera (Phantom VR-V4.2) was used for measuring the drop and ignition times of a sample piece.

The setup of the ignitability test using an electric match is shown in Figure 4.

Procedure for the shot test

An electric match is inserted into the bottom of mortar, which is fixed perpendicularly, the lift charge is poured into the mortar, and a star is dropped on the lift charge. The lift charge is ignited and the star is shot into the air, and the ignition or absence of ignition of the star is examined by observation by eye.

The star does not ignite when the lift charge is large, and the star does ignite when the lift charge is smaller. The mean of maximum lift charge for ignition and minimum lift charge for no ignition is defined as the ignition limit lift charge for an ignitability scale:

The ignition limit lift charge = (maximum lift charge for ignition + minimum lift charge for no ignition)/2

The test starts with a lift charge near the ignition limit lift charge, the lift charge is increased when there is ignition, and it is decreased when there is no ignition by 1 g increments above 1 g lift charge and 0.1 g increments below 1 g lift charge.

Procedure for the ignitability test using a hot plate

The steel plate was heated to 600 ºC, 650 ºC, 700 ºC, 750 ºC or 800 ºC, and the temperature maintained by adjusting the voltage of the transformer. A piece of sample was dropped on to the surface of the hot plate through a hole in the insulating brick. The experiment for each sample at the same temperature was repeated 5 times. The time of the drop and ignition of the sample was observed through an opening between the plate and the brick, and recorded by the high-speed

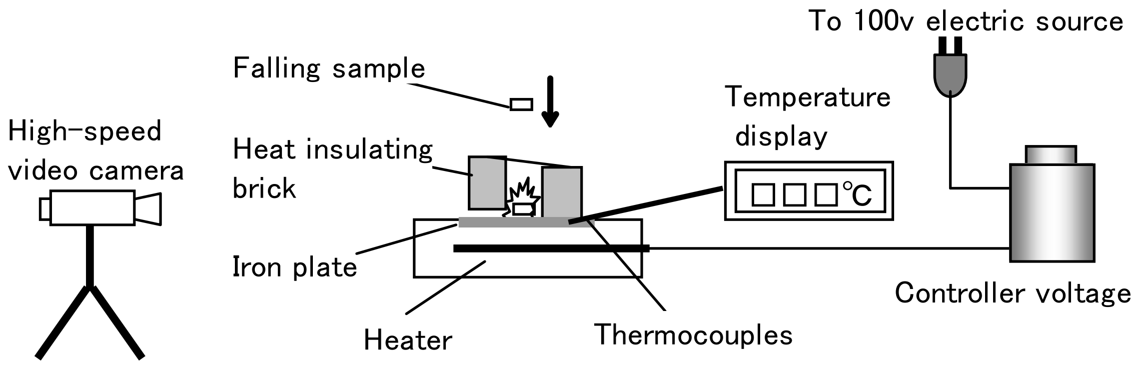

Figure 3. *Schematic diagram of ignitability test using a hot plate.*

video camera.

Procedure for the ignitability test using an electric match

A 1.5 × 5 × 5 mm sample and an electric match were wrapped together by a sheet of 3M Scotch green mending tape 10 mm wide and 30 mm long. The blue tape is not suitable because the confinement by the blue tape is weaker than that of the green tape. The wrapped sample was put on a heat resistant brick and covered with a transparent cup. A 12 V electric current was passed through the electric match and the match ignited. The tests were carried out 10 times and the number of ignitions was recorded.

Results and Discussion

Ignition limit lift charge of bare and primed stars

The results of the shot test of bare and primed stars are listed in Table 3. The order of the ignition limit lift charge of bare stars with (ignition limit lift charge) is as follows:

Yellow star (0.5 g) = purple star (0.5 g) > green star (0.3 g) = blue star (0.3 g) > red star (0.15 g)

The ignition limit lift charges of primed stars were scattered widely and therefore exact discussion is difficult. The mean values were in the following order:

Primed blue star (5.4 g) > primed yellow star (4.5 g) > primed purple star (4.3 g) > primed green star (4.0 g) > primed red star (3.1 g)

Figure 5 shows the plot of ignition limit lift charge of primed stars vs. that of bare stars. The ignition limit lift charges of primed stars were scattered widely but without exception were larger than those of bare stars. That is, the ignitability of primed stars was larger than that of bare stars, and the primers were all effective for promoting ignitability of bare stars. There is a relationship between the mean ignition limit lift charge of primed stars and the ignition limit lift charge of bare stars, and the ignitability of bare stars is

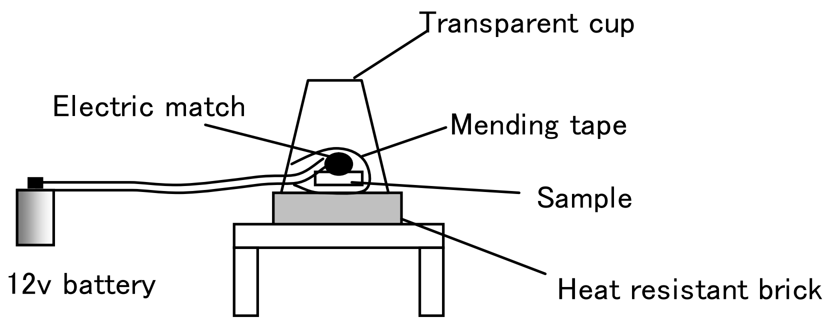

Figure 4. *Schematic diagram of ignitability test using an electric match.*

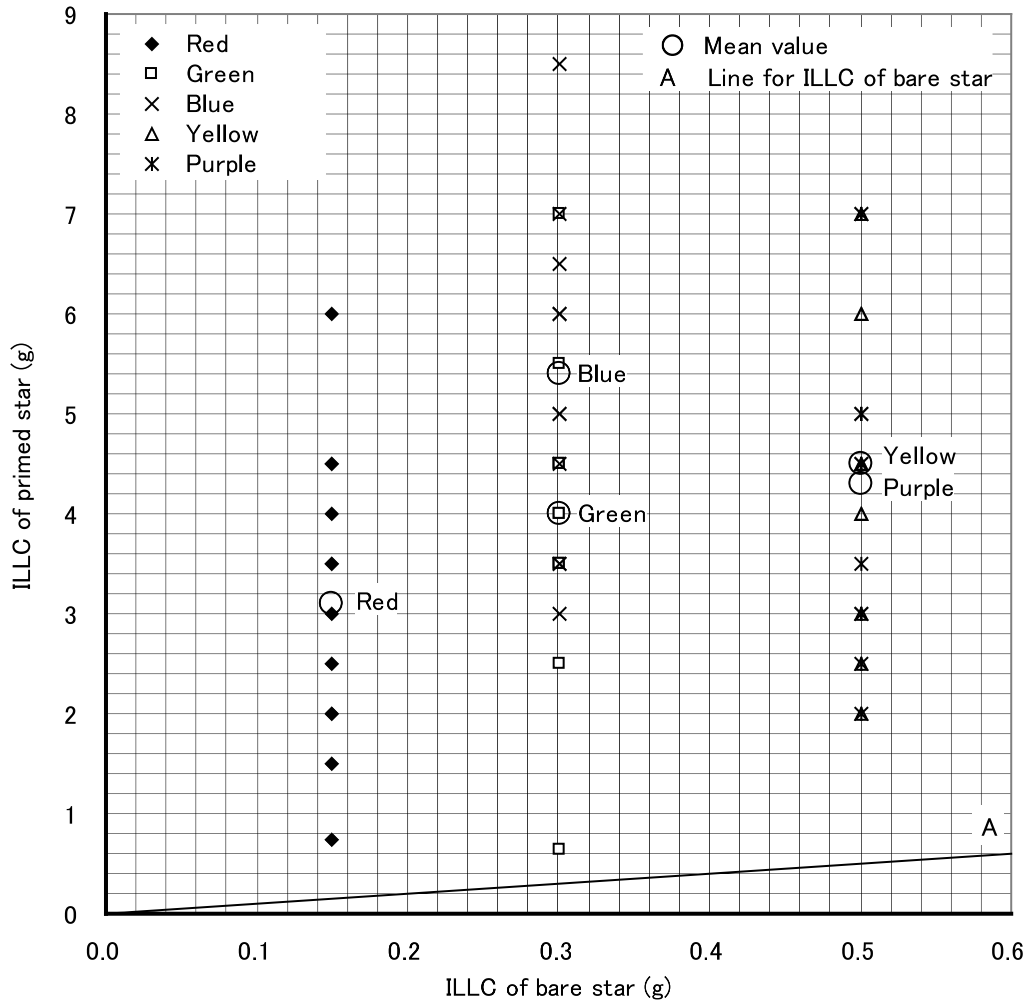

Figure 5. *Plot of ignition limit of lift charge (ILLC) of primed star vs. that of bare star.*

recognized to affect that of the primed star to a certain extent.

The order of ignitability of primers is difficult to judge because of the large scatter of the data. The order of mean ignition limit lift charge of primes was as follows:

F (5.5 g) > J (4.9 g) > D (4.8 g) > C (4.7 g) > L (4.6 g) > G (4.5 g) > A (4.4 g) > E (4.2 g) > H (3.8 g) > K (3.7 g) > I (3.5 g) > B (3.0 g)

Examples of recorded results by the hot plate test

The scatter of the ignition delay times was very large. The examples of original data are listed in Table 4. Large scatters in the test may come from the exceptional extremely short delay time, which in turn may come from the quick ignition of the small powdery fragments or a sharp edge of the sample. Smaller particles are easier to ignite than larger pieces. Because of the large scatter, log τ was used instead of ignition delay time τ for statistical treatment.

The standard deviation of log τ of the primer D was lowest among the tested samples, because there was no exceptionally short ignition delay time. That of the burst charge 3 was largest, because of the existence of exceptionally short and long τ. The piece of the burst charge was more easily fragmented than the pieces of the other samples. In the case of the yellow star, there was an exceptionally short τ, probably owing to the broken small fragments.

Table 3 *Ignition limit lift charge of bare and primed stars.*

	Ignition limit lift charge/g					
	Red	Green	Blue	Yellow	Purple	Mean
Bare star	0.15	0.30	0.30	0.50	0.50	0.35
Primed star						
Prime A	3.50	4.50	6.50	2.50	5.00	4.40
Prime B	2.00	0.65	5.00	4.50	3.00	3.00
Prime C	1.50	7.00	6.00	4.00	5.00	4.70
Prime D	4.50	5.50	6.00	3.00	5.00	4.80
Prime E	3.00	4.00	5.00	2.00	7.00	4.20
Prime F	2.00	3.50	8.50	6.00	7.00	5.50
Prime G	4.00	4.50	4.50	7.00	2.50	4.50
Prime H	3.50	4.00	3.00	4.00	3.00	3.80
Prime I	2.50	3.50	3.50	4.50	3.50	3.50
Prime J	4.50	3.50	6.00	6.00	4.50	4.90
Prime K	0.75	2.50	7.00	6.00	2.00	3.70
Prime L	6.00	4.50	3.50	4.50	4.50	4.60
Mean	3.10	4.00	5.40	4.50	4.30	4.30

Reproducibility of the hot plate test results

The mean and standard deviation (SD) of log τ of piece samples at 700 ºC and 600 ºC are listed in Table 5.

At first the experiments for the hot plate test were conducted at 700 ºC. Then the experiments were carried out at different temperatures from 600 ºC to 800 ºC and the lowest standard deviations of log τ were obtained at 600 ºC. But at 600 ºC, values of log τ for star compositions were not necessarily larger than those for other compositions.

The mean and SD of log τ at different temperatures are listed in Table 6, and the plot of SD against the reciprocal is temperature shown in Figure 6.

Results of the electric match test

The electric match test was applied to the pieces of prime A–D, lift and burst charges, and star compositions. The results are listed in Table 7. The probability of ignition in this test was lowest for green star composition and highest for prime C and D compositions. This method may be used for differentiating the ignitability of star and prime compositions.

Correlation of the hot plate and electric match tests results

The plot of log τ at 700 ºC in the hot plate test against the ignition probability in the electric match test is shown in Figure 7. The primes C and D have the highest ignitability by this test among primes A–G. However, these results do not necessarily agree with those of the shot test results, probably because there is some scatter of the data in the results of the electric match test.

Correlation of the hot plate and electric match tests results with the shot test results

The plots of log τ at 700 ºC in the hot plate test and the ignition probability in the electric match test against the ignition limit lift charge in the shot test are shown in Figure 8. It is found from Figure 7 that there is a large difference between the ignition limit lift charges of bare stars and primed stars tested. There are positive and negative correlations between the ignition limit lift charge, and the

Table 4. *Examples of observed results at 700 ºC.*

Sample	Drop time/ms	Ignition time/ms	Delay time τ/ms	log τ
Primed D	3120	3700	580	2.76
	3230	3955	725	2.86
	2777	3537	760	2.88
	2455	3044	589	2.77
	2705	3387	682	2.83
Mean			667	2.82
SD[a]			81	0.05
RSD[b]			0.12	
Lift charge	10870	10970	100	2.00
	10985	11725	740	2.87
	10880	11532	652	2.81
	10617	10912	295	2.47
	10437	10652	215	2.33
Mean			400	2.50
SD[a]			280	0.36
RSD[b]			0.70	
Burst charge 3	11172	11192	20	1.30
	10720	10952	232	2.37
	10687	10742	55	1.74
	10610	12452	1842	3.27
	11005	11147	142	2.15
Mean			458	2.16
SD[a]			778	0.74
RSD[b]			1.70	
Yellow bare star	11507	13940	2433	3.39
	10445	12957	2512	3.40
	10607	11057	450	2.65
	10417	12252	1835	3.26
	10732	13202	2465	3.39
Mean			1939	3.22
SD[a]			877	0.32
RSD[b]			0.45	

[a] Standard deviation. [b] Relative standard deviation (SD/mean).

ignition probability in the electric match test and log τ at 700 ºC in the hot plate test, respectively. It seems that the shot test is the best ignitability test among the three test methods, and the other two methods may be used as screening methods.

Conclusion

Table 5. *Mean and standard deviation (SD) of log τ.*

Sample	T/ºC	Mean of log τ	SD of log τ
Prime A	700	2.57	0.13
	600	3.55	0.08
Prime B	700	2.31	0.45
	600	3.35	0.24
Prime C	700	2.75	0.21
	600	3.64	0.28
Prime D	700	2.82	0.05
	600	3.31	0.15
Prime E	700	3.02	0.08
	600	3.56	0.09
Prime F	700	2.73	0.27
	600	3.46	0.12
Prime G	700	2.89	0.21
	600	3.56	0.08
Prime H	700	3.19	0.18
Prime I	700	2.71	0.46
Prime J	700	2.45	0.54
Prime K	700	2.54	0.52
Prime L	700	2.62	0.36
Lift charge	700	2.50	0.36
	600	3.40	0.08
Burst charge 3A[a]	700	2.16	0.74
	600	3.44	0.42
Burst charge 3B[a]	700	2.61	0.25
Burst charge 5A[a]	700	2.58	0.41
Burst charge 5B[a]	700	2.53	0.41
Burst charge SA[a]	700	2.55	0.41
Burst charge SB[a]	700	3.01	0.22
Yellow star	700	3.22	0.32
	600	3.78	0.08
Red star	700	3.35	0.32
	600	3.72	0.08
Green star	700	3.32	0.10
	600	3.91	0.14
Blue star	700	3.00	0.26
	600	3.36	0.12
Purple star	700	3.27	0.16
	600	3.03	0.06

[a] Burst charge 3A and 3B are the piece and original grain burst charges, respectively, for no. 3 shell. S stands for special shells.

Table 6. *Temperature, reciprocal temperature, and mean and SD of log τ of samples.*

Sample	T/ºC	$1000/T$ (K^{-1})	Mean of log (τ/ms)	SD of log τ
	600	1.145	3.31	0.15
	650	1.083	3.31	0.14
Prime D	700	1.028	2.82	0.05
	750	0.978	2.63	0.40
	800	0.932	2.63	0.40
	600	1.145	3.40	0.08
	650	1.083	3.24	0.19
Lift charge	700	1.028	2.50	0.36
	750	0.978	2.28	0.15
	800	0.932	2.54	0.32
	600	1.145	3.78	0.08
	650	1.083	3.75	0.11
Yellow star	700	1.028	3.22	0.32
	750	0.978	3.00	0.19
	800	0.932	3.08	0.28

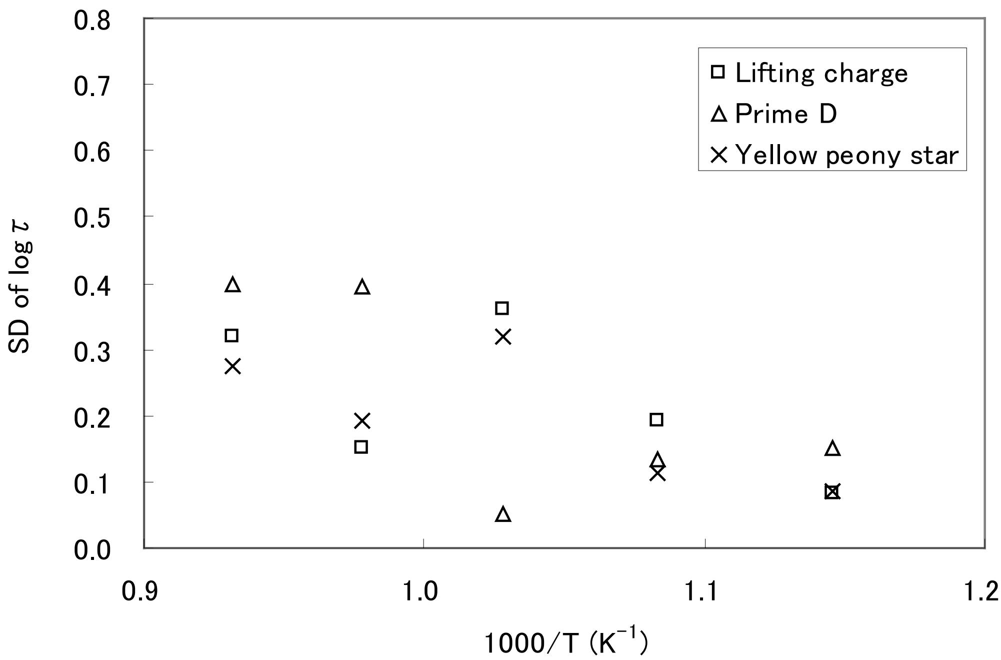

Figure 6. *Plot of SD of log τ vs. 1000/T.*

Table 7. *Results of electric match test.*

Sample	Ignitions/Trials
Prime A	8/10
Prime B	7/10
Prime C	10/10
Prime D	10/10
Prime E	9/10
Prime F	8/10
Prime G	8/10
Lift charge	8/10
Burst charge	9/10
Star red	4/10
Star green	0/10
Star yellow	7/10
Star blue	6/10
Star purple	5/10

The shot test was applied to the ignitability of bare and primed stars, and was found to be a useful method for evaluating the ignitability of the stars though there was some scatter in the observed data. The hot plate and electric match tests were applied to the ignitability of prime, star, lift and burst charge compositions. The hot plate and electric match tests may be used for screening the ignitability of the firework compositions.

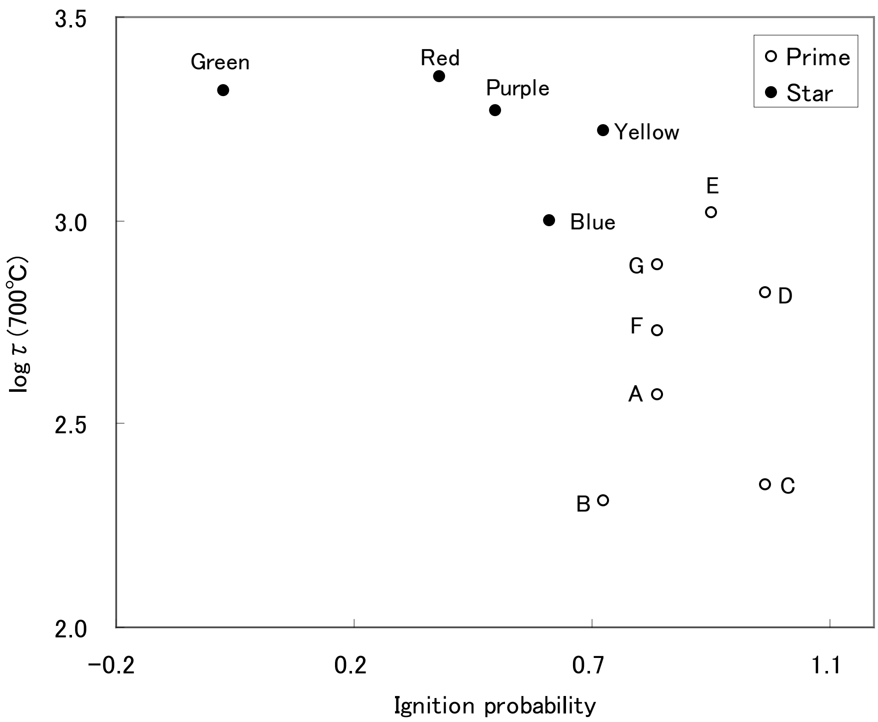

Figure 7. *Plot of log τ (at 700 ℃) in hot plate test vs. ignition probability in electric match test.*

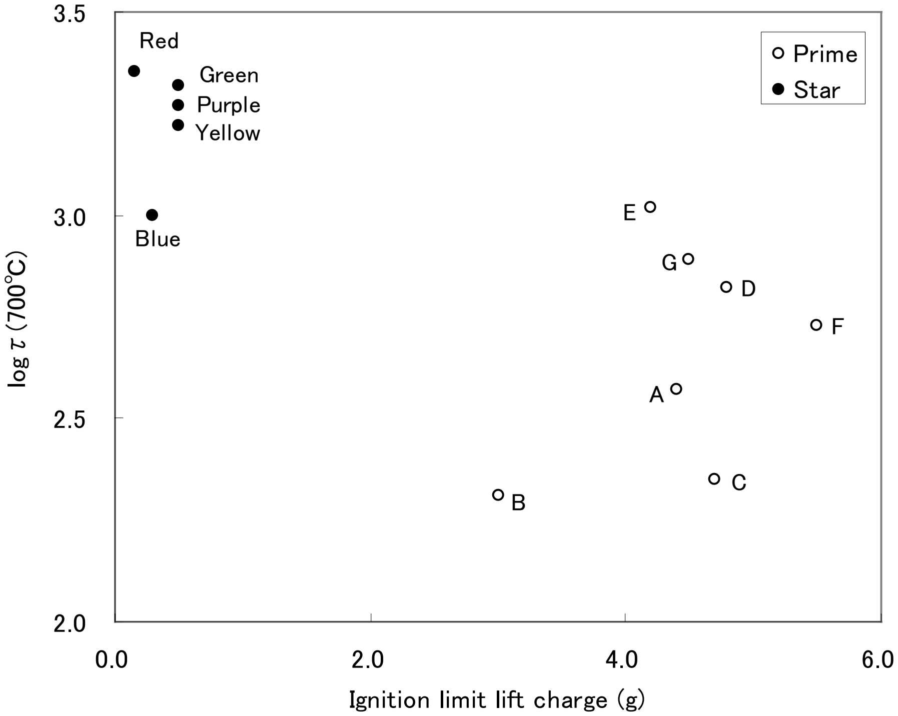

Figure 8. *Plots of log τ (at 700 ºC) and ignition probability vs. ignition limit lift charge for bare and primed stars.*

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