Optimization of a Smoke Producer Composition by Experiment Design

M. Vaullerin*, P. Morand, and A. Espagnacq

Giat Industries, DSAM/DT/PYRO, 7 route de Guerry, F-18023 Bourges Cedex (France)

Summary

This paper deals with the work carried out to define new formulations used to increase the infrared effectiveness of a reference smoke producer composition. This pyrotechnic mixture is constituted by a combination of oxidizing agents and fuels generating mainly carbon but also chlorinated metallic salts which are essential for camouflage by combustion. First, for several compositions, the 3–5 μ m and $8\!\!-\!\!12\,\mu m$ extinction coefficients are correlated to the proportions of Magnesium and (Mg+MgCl), respectively (determined by thermochemical computations with the Bagheera code). Then, to widen the investigations on smoke producing compositions, this correlation was studied by associating two experiment designs, an equiradial matrix and a Scheffe mixing matrix. We would point out that using this experimental strategy makes both possible, the minimization of the number of experiments - and therefore the cost factor - and the modelling of the results which allows to gain the properties of potential formulations on the whole experimental field.

1. Introduction

In the military field, some tactical operations need obscurant materials to protect sites, vehicles and troop movements against enemy observations.

Until the end of the 70s, the aim of these screening materials was only the camouflage in the visible window. Nowadays, they must also be effective against observation means operating in the infrared window. Generally, these materials are fogs (droplet clouds), smokes (particle clouds) or solid particles dispersed as aerosols by explosion.

Their effectiveness depends on several criteria:

- Type and concentration of the screening material
- Application process
- Usage concept

These three aspects are interdependent and directly associated with scenarios (definition of the tactical operation, type of threat), but also with the local atmospheric conditions. Today, on the international market there is a smoke generator dispersion system developed by the companies Giat Industries and Lacroix which has the capability of dispersing visual and IR screening materials. The objective of the study was to demonstrate if it is possible to increase the effectiveness of this munition in the infrared range.

2. Definition of the Parameters

We have to define new formulations able to increase the IR effectiveness of the reference smoke producer composition⁽³⁾. This mixture is constituted by a combination of an oxidizing and a reducing agent generating mainly carbon but also chlorinated metallic salts which are essential for camouflage by combustion.

To widen the range of the new compositions, we studied the influence of:

- The magnesium ratio
- The carbon generator by the addition of a new carbon generator up to 50% and
- The binder up to the complete replacement of the reference composition's binder

3. Experimental Field of Interest

Ultimate values of each component ratio were defined (Table 1):

Magnesium was studied between 15% and 30%, the binder between 5% and 10% and the carbon generator between 60% and 80%.

In addition, we studied how the effectiveness is affected by the:

- Addition of a new carbon generator up to 50%, and the
- Use of a new binder up to the complete replacement of the present one.

4. Matrices of Experiments

To take into account this experimental domain of interest we used a design methodology specially built to treat five parameters, the concentration of magnesium, two binders and two carbon generators. In fact, these five parameters are the formulation components and the appropriate experimental methodology could make use of a Scheffe matrix.

However, we prefered a two-stage approach because we had also to take into account the relative ratios of carbon generators and binders. First, relative ratios of binders and carbon generators were optimized by using an equiradial matrix^(2,4). Then, the component ratios of the composition

^{*} Corresponding author; e-mail: m.vaullerin@giat-industries.fr

Table 1. Parameters Studied and Experimental Field

	Experimental field		
	Minimum	Maximum	
Magnesium	15%	30%	
Binder (Binder $1 + Binder 2$)	5%	10%	
Carbon generator ($GeC1 + GeC2$)	60%	80%	
GeC1/GeC2	0	1	
Binder1/Binder	0	1	

were optimized by using a specific Scheffe matrix^(2,5) taking into account the definition of the experimental domain.

4.1 Equiradial Matrix

The equiradial matrix (Figure 1) chosen to optimize the relative proportions of the binder and the carbon generator makes it possible to study the ratios of these components on several levels (5 for the binder ratios and 4 for the carbon generator ratio). It requires six experiments including one in the center of the experimental domain.

4.2 Mixing Matrix

The Scheffe matrix (Figure 2) makes it possible to take into account all variations of the components. It requires five experiments.

4.3 Resulting Matrix

The resulting matrix is obtained by the application of the Scheffe matrix to every point of the equiradial matrix. So we



O Experimental points

Figure 1. Diagram of the equiradial matrix.



O Experimental points

Figure 2. Diagram of the Scheffe mixing matrix.

need $6 \cdot 5 = 30$ experiments. A grey parallelogram showing the continuous variation field of the Scheffe matrix is combined with every experimental point of the equiradial matrix. These 30 experiments are represented by white points in Figure 3.

4.4 Postulated Mathematical Models

The postulated model for the equiradial matrix is described by the following quadratic Eq. (1).

$$Y_{i} = b_{i0} + b_{i1} X_{i1} + b_{i2} X_{i}^{2} + b_{i11} X_{i1}^{2} + b_{i22} X_{i2}^{2} + b_{i12} (X_{i1} X_{i2})$$
(1)

where:

$$X_{i1} = \text{GeC1/GeC2}$$
 ratio between the two
carbon generators

 X_{i2} = Binder 1/Binder ratio between the binders

The mathematical model chosen with the mixing matrix is a special polynomial equation. It is represented by the following Eq. (2):

$$Y_{j} = b_{j1} X_{j1} + b_{j2} X_{j2} + b_{j3} X_{j3} + b_{j123} (X_{j1} X_{j2} X_{j3})$$
(2)

where:

 X_{j1} : Magnesium ratio X_{j2} : binder ratio X_{j3} : carbon generator ratio

5. Experiment Design

Details of the experiment design as a result of the product of the equiradial matrix with the Scheffe matrix are given in Table 2. To make things easier, identification numbers are used. The first digit is the experiment's number in the equiradial matrix and the second one the experiment's number in the mixing matrix.



Figure 3. Representation of the experimental points (Equiradial matrix and Scheffe matrices).

Identification	Experiment	GeC1	GeC2	Binder 1	Binder 2	Mg
number	number	(%)	(%)	(%)	(%)	(%)
1.1	1	0.000	80.000	2.500	2.500	15.000
1.2	2	0.000	75.000	5.000	5.000	15.000
1.3	3	0.000	65.000	2.500	2.500	30.000
1.4	4	0.000	60.000	5.000	5.000	30.000
1.5	5	0.000	70.000	3.750	3.750	22.500
2.1	6	20.544	59.456	0.000	5.000	15.000
2.2	7	19.260	55.740	0.000	10.000	15.000
2.3	8	16.692	48.308	0.000	5.000	30.000
2.4	9	15.408	44.592	0.000	10.000	30.000
2.5	10	17.976	52.024	0.000	7.500	22.500
3.1	11	37.994	42.006	0.955	4.045	15.000
3.2	12	35.620	39.380	1.910	8.090	15.000
3.3	13	30.870	34.130	0.955	4.045	30.000
3.4	14	28.496	31.504	1.910	8.090	30.000
3.5	15	33.245	36.755	1.432	6.068	22.500
4.1	16	37.994	42.006	4.045	0.955	15.000
4.2	17	35.620	39.380	8.090	1.910	15.000
4.3	18	30.870	34.130	4.045	0.955	30.000
4.4	19	28.496	31.504	8.090	1.910	30.000
4.5	20	33.245	36.755	6.068	1.432	22.500
5.1	21	20.544	59.456	5.000	0.000	15.000
5.2	22	19.260	55.740	10.000	0.000	15.000
5.3	23	16.692	48.308	5.000	0.000	30.000
5.4	24	15.408	44.592	10.000	0.000	30.000
5.5	25	17.976	52.024	7.500	0.000	22.500
6.1	26	26.668	53.332	2.500	2.500	15.000
6.2	27	25.001	49.999	5.000	5.000	15.000
6.3	28	21.668	43.332	2.500	2.500	30.000
6.4	29	20.001	39.999	5.000	5.000	30.000
6.5	30	23.335	46.665	3.750	3.750	22.500

Table 2. Experiment Design (Equiradial Matrix and Mixing Matrices)

6. Results and Analysis

The Bagheera computations⁽¹⁾ and the relationship between the ratio of the combustion products and the mass extinction coefficients of some mixtures already tested enabled to define the correlation to the mass extinction coefficients measured by experiment.

A comparison between the two diagrams in Figures 2 and 3 shows that the mole numbers of Mg and MgCl in relation to the mole numbers of carbon (Bagheera computations) are correlated with the $3-5 \,\mu m$ range extinction coefficient: in fact, the lower these ratios (that is, a maximum carbon product), the better the extinction coefficient.

We have a similar analysis for the correlation of the $8-12 \,\mu\text{m}$ extinction coefficient with the mole numbers of Mg in relation to the mole numbers of carbon (Figures 4 and 5).

Results of the experiment design (Table 3) presented in Figures 6 and 7 show that it is possible to improve the effectiveness of the smoke producer compositions in the $8-12 \,\mu\text{m}$ and $3-5 \,\mu\text{m}$ infrared window with formulations defined at the points 1 and 5 on the equiradial (the lowest [Mg/Cgr] and [(Mg+MgCl)/Cgr] ratios, Cgr = carbon generator). We would point out that the [Mg/Cgr] ratio correlates with the $8-12 \,\mu\text{m}$ range extinction coefficient.

Black areas on graphs of Figures 8 and 9 show that the most interesting points (Table 4) to maximize the extinction coefficients in 8–12 μ m and 3–5 μ m are placed at the bottom of the experimental domain on the Scheffe matrix, when the magnesium ratio is 15%.



Figure 4. Extinction coefficients of the reference compositions in 3-5 and $8-12 \,\mu\text{m}$.

Table 3.	Experimental	Results	for the	Equiradial	Matrix
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Figure 5. Correlation of the 3-5 and $8-12 \,\mu\text{m}$ extinction coefficients with the (Mg + MgCl)/Cgr and Mg/Cgr ratios.



Figure 6. Isoresponse curves $n_{Mg+MgCl}/n_{Cgr}$ for the equiradial matrix.



Figure 7. Isoresponse curves n_{Mg}/n_{Cgr} for the equiradial matrix.

Identification number	Experiment number	GeC1 (%)	GeC2 (%)	Binder 1 (%)	Binder 2 (%)	Mg (%)	$n_{\rm Mg}/n_{\rm Cgr}$	$n_{Mg+MgCl}/n_{Cgr}$
1.5	5	0.000	70.000	3.750	3.750	22.500	0.0903	0.1002
2.5	10	17.976	52.024	0.000	7.500	22.500	0.1129	0.1160
3.5	15	33.245	36.755	1.432	6.068	22.500	0.1235	0.1243
4.5	20	33.245	36.755	6.068	1.432	22.500	0.1191	0.1211
5.5	25	17.976	52.024	7.500	0.000	22.500	0.1051	0.1096
6.5	30	23.335	46.665	3.750	3.750	22.500	0.1142	0.1166



Figure 8. Isoresponse curves $n_{Mg+MgCl}/n_{Cgr}$.



Figure 9. Isoresponse curves $n_{\rm Mg}/n_{\rm Cgr}$

Therefore, as far as the proportions of Mg and (Mg+MgCl) relative to the carbon ratio are concerned, we note that the influence of the addition of the new carbon generator is very significant in relation to the influence of the nature of the binder (Figures 6 and 7). Certainly, when the portion of the binder in the mixture increases (Figures 8 and 9) these effects are highly lowered but are negligible when compared to the effect of the different carbon generators.

7. Conclusion

The application of an experimental methodology coupled with Bagheera thermochemical computations enabled to optimize a reference screening formulation. The result is a better compromise between the ratios of Mg/Cgr and (Mg+MgCl)/Cgr. An experimental validation confirmed the predicted results. In fact, the most promising composi-

Table 4. Experimental Results for the Scheffe Matrices at Points 1, 5 and 6 of the Equiradial Matrix

Identification number	Experiment number	GeC1 (%)	GeC2 (%)	Binder 1 (%)	Binder 2 (%)	Mg (%)	$n_{\rm Mg}/n_{\rm Cgr}$	$n_{\rm Mg+MgCl}/n_{\rm Cgr}$
1.1	1	0.000	80.000	2.500	2.500	15.000	0.0110	0.0158
1.2	2	0.000	75.000	5.000	5.000	15.000	0.0092	0.0134
1.3	3	0.000	65.000	2.500	2.500	30.000	0.2484	0.2554
1.4	4	0.000	60.000	5.000	5.000	30.000	0.2290	0.2394
1.5	5	0.000	70.000	3.750	3.750	22.500	0.0903	0.1002
5.1	21	20.544	59.456	5.000	0.000	15.000	0.0199	0.0229
5.2	22	19.260	55.740	10.000	0.000	15.000	0.0116	0.0139
5.3	23	16.692	48.308	5.000	0.000	30.000	0.2364	0.2379
5.4	24	15.408	44.592	10.000	0.000	30.000	0.2212	0.2258
5.5	25	17.976	52.024	7.500	0.000	22.500	0.1051	0.1096
6.1	26	26.668	53.332	2.500	2.500	15.000	0.0295	0.0315
6.2	27	25.001	49.999	5.000	5.000	15.000	0.0186	0.0208
6.3	28	21.668	43.332	2.500	2.500	30.000	0.2349	0.2356
6.4	29	20.001	39.999	5.000	5.000	30.000	0.2237	0.2259
6.5	30	23.335	46.665	3.750	3.750	22.500	0.1142	0.1166

tions have been produced and the extinction coefficients measured in the $3-5 \,\mu\text{m}$ and $8-12 \,\mu\text{m}$ infrared range. They were essentially higher than those of the reference composition. The improvement of the screening effectiveness in the $8-12 \,\mu\text{m}$ range goes up to 23%.

8. References

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