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Hypothesis on the Cause of Serious Accidents Related to Salutes Charges

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ABSTRACT

First, we hypothesize that a serious accident related to the use of salutes may be caused by the simultaneous explosion of several salutes or salute components, resulting in an unexpected, abnormally strong shock wave. To prove our theory, we conducted three experiments. In Experiment 1, we examined the transfer of the explosion between salutes with one donor to shed light on the properties of the charges. Experiment 2, which we conducted to examine the transfer in the case of two donors, revealed a localized effect of the transfer. In Experiment 3, we measured the pressure during explosion using a pressure-sensing film, which was used to create pressure contour lines. Our experiments reveal that there is an area of abnormally high pressure, a finding which supports our hypothesis.

1. Introduction

Pyrotechnic salutes are generally very susceptible to mechanical stress. To prevent accidents when handling and storing them, two methods are commonly used: dividing a charge into as many small pieces as possible and isolating each partial charge using appropriate methods, such as placing parts at a distance from one another and separating them up or enclosing them. The reasoning behind this approach is that, even if one of the salute components were to explode somehow, no serious accident would result. Yet, in the past, the occasional accident has been encountered for which no clear cause could be determined, since it was always difficult to recreate any of the accidents under experimental conditions.

One hypothesis is that a serious accident can occur when just two salute components (or more) explode at the same time. This creates an unexpected, strong shock wave, as I will explain in an experimental context below. Due to a chain reaction occurring among the components, the shock wave will be transferred to all the charges.

2. Experiment 1

We used the following common Japanese salute formulations:

A:	potassium perchlorate	64%
	aluminum (300 mesh flakes)	23%
	sulfur	13%
B:	potassium chlorate	64%
	aluminum (300 mesh flakes)	23%
	sulfur	13%
C:	potassium chlorate	57%
	realgar (As_2S_2)	43%

The individual charges were represented by spherical or cylindrical salutes as shown in Figure 1. Each salute, with the exception of a few, contained an explosive charge of 25 g of either A, B or C, enclosed in a hard paper shell casing, with a charge density of 0.65 g/cm^3. Depending on the requirements, the thickness of the hard paper shell casing ranged from 0.7 to 4 mm. Occasionally, a piece of steel pipe with an inner diameter of 28 mm and a thickness of 1 mm was used for the cylindrical salute (Figure 1).

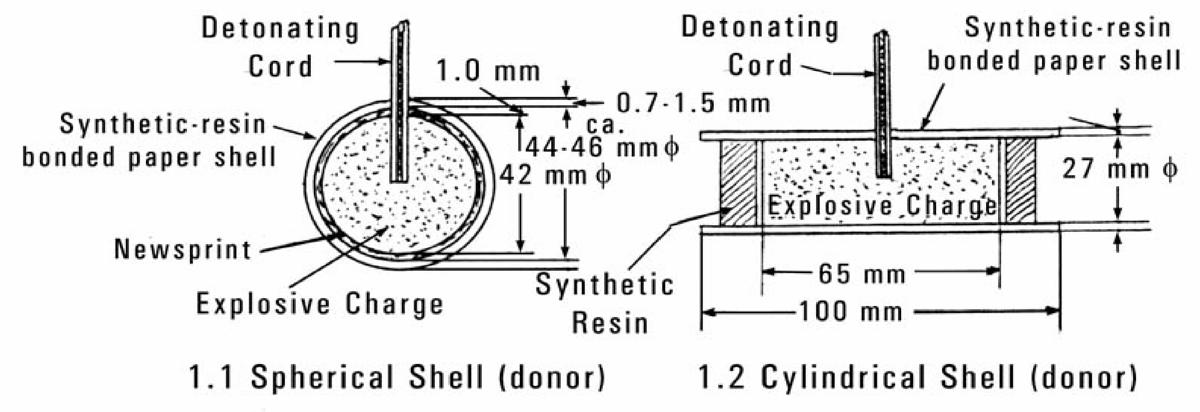


Figure 1. Samples used as partial charges.

Three identical salutes were each suspended 35 cm from a horizontal steel rod using 0.7 mm thick steel wire so as to hang in a horizontal line, about l m above the ground, at an equal distance of 0–4.4 D from each other, D being the diameter of the salute. The first salute, which was used as the donor, contained an igniter (detonating cord with an electric detonating cap, an electric igniting primer or quick match) (Figures 2.1 and 2.2). The donor was ignited and the transfer of the explosion from A to B and then to C was examined. The results are shown in Table 1.

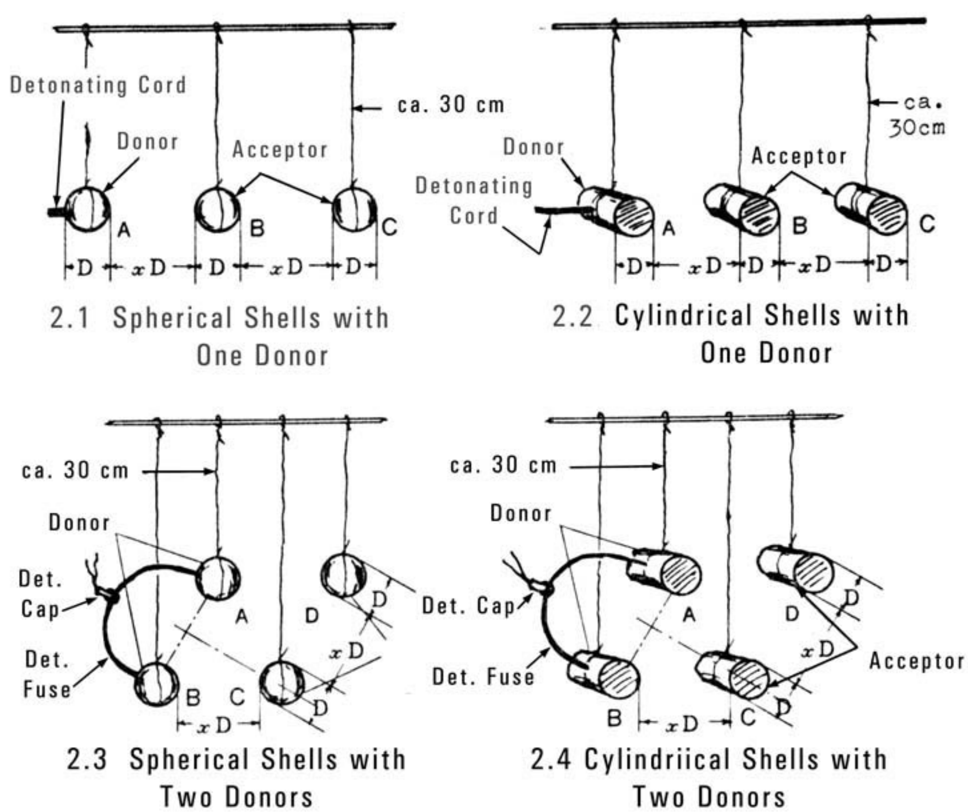


Figure 2. Assemblies for transfer experiments.

The results show that the transfer effect of the first salute (the donor) is much greater than that of the second, if detonating cord is used to ignite the donor. In reality, an accident would happen differently, since this type of igniter would not actually be used in practice. However, to make two salutes explode simultaneously, as done in the experiments described below, Detonating cord had to be used.

3. Experiment 2

Four identical salutes were suspended on 0.7 mm thick steel wire from a steel rod and arranged in the shape of a rectangular parallelogram (Figures 2.3 and 2.4). Salutes A and B were used as donors. They were attached to each other with a piece of detonating cord. A detonating cap was attached at the center of the detonating cord, so as to ensure that A and B would explode simultaneously.

The two donors were ignited and the transfer of the explosion from A and B to C and D was examined. The results are recorded in Table 2. They show that the effect of the shock wave is much stronger at location C than at location D, because each salute at location C (with the exception of sample 24, for which the spacings were very wide) exploded, while none (with the exception of sample 25) exploded at location D. We also provided a few additional results in Table 3.

Table 1. Results of Transfer Tests Using Three Identical Salutes with One Donor.

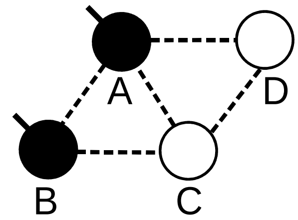
Charge per shell: 25 g —● A — ○ B — ○ C

No.	Charge	Shell: Shape	Shell: Material	Shell: Thickness (mm)	Space between (mm)	Igniter	A	B	C
1	A	Spherical	Hard paper	1.5	115 (2.5D)	cap and cord	—●	●	○
2	A	Spherical	Hard paper	1.5	92 (2D)	cap and cord	—●	●	○
3	A	Spherical	Hard paper	1.5	46 (1D)	cap and cord	—●	●	○
4	A	Spherical	Hard paper	1.5	0	cap and cord	—●	●	○
5	A	Spherical	Hard paper	1.5	92 (2D)	igniting primer	—●	○	○
6	A	Spherical	Hard paper	1.5	69 (1.5D)	igniting primer	—●	○	○
7	A	Spherical	Hard paper	1.5	46 (1D)	igniting primer	—●	○	○
8	A	Spherical	Hard paper	1.5	23 (0.5D)	igniting primer	—●	○	○
9	A	Spherical	Hard paper	1.5	0	igniting primer	—●	●	○
10	A	Spherical	Hard paper	1.5	0	quick match	—●	●	○
11	A	Spherical	Hard paper	0.7	50 (1.1D)	cap and cord	—●	●	○
12	B	Spherical	Hard paper	0.7	100 (2.2D)	cap and cord	—●	●	●
13	B	Spherical	Hard paper	1.5	200 (4.4D)	cap and cord	—●	○	○
14	C	Spherical	Hard paper	0.7	100 (2.2D)	cap and cord	—●	●	○
15	C	Spherical	Hard paper	1.5	100 (2.2D)	cap and cord	—●	○	○
16	A	cylindrical	Hard paper	0.5	29 (1D)	cap and cord	—●	●	●
17	A	cylindrical	Hard paper	1.0	29 (1D)	cap and cord	—●	●	●
18	A	cylindrical	Hard paper	2.0	29 (1D)	cap and cord	—●	●	◐
19	A	cylindrical	Hard paper	4.0	29 (1D)	cap and cord	—●	○	○
20	B	cylindrical	Hard paper	2.0	29 (1D)	cap and cord	—●	●	●
21	C	cylindrical	Hard paper	2.0	29 (1D)	cap and cord	—●	●	●
22	A	cylindrical	Iron	1.0	30 (1D)	cap and cord	—●	○	○

Notes:
—● = donor with igniter
● = acceptor which exploded
◐ = acceptor only half of which exploded
○ = acceptor which did not explode
D = outer diameter of shell

Table 2. Results of Transfer Tests Using Four Identical Salutes with Two Donors Ignited Simultaneously.

Explosive charge per shell: 25 g
Shell: Shape: Spherical
Material: Hard paper casing
Thickness: 1.5 mm
Igniter: Detonating cap and cord

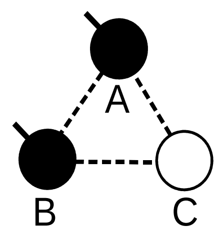


No.	Charge	Space between (mm)	Results A	B	C	D
23	A	74 (1.6D)	–●	–●	●	○
24	A	140 (3D)	–●	–●	○	○
25	A	74 (1.6D)	–●	–●	●	●
26	A	118 (2.5D)	–●	–●	●	○
27	A	118 (2.5D)	–●	–●	●	○

Note: The symbols are the same as in Table 1.

Table 3. Results of Transfer Tests Using Three Salutes with Different Explosive Charges and Two Donors Ignited Simultaneously.

Shell: Shape: Spherical
Material: Hard paper casing with thickness: 1.5 mm



No.	Charge	Space between (mm)	Igniter	Charge per Firecracker & Result A	B	C
S1	A	300 (6.5D)	cap and cord	25 g –●	25 g –●	15 g ○
S2	A	100 (1.8D)	cap and cord	25 g –●	25 g –●	15 g ●
S3	A	100 (1.8D)	cap and cord	15 g –●	15 g –●	15 g ●
S4	A	100 (1.8D)	cap and cord	10 g –●	10 g –●	10 g ○
S5	A	100 (1.8D)	igniting primer	25 g –●	25 g –●	15 g ○

Notes: The symbols are the same as in Table 1.
When the igniting primers were used, the two donors likely did not explode simultaneously.

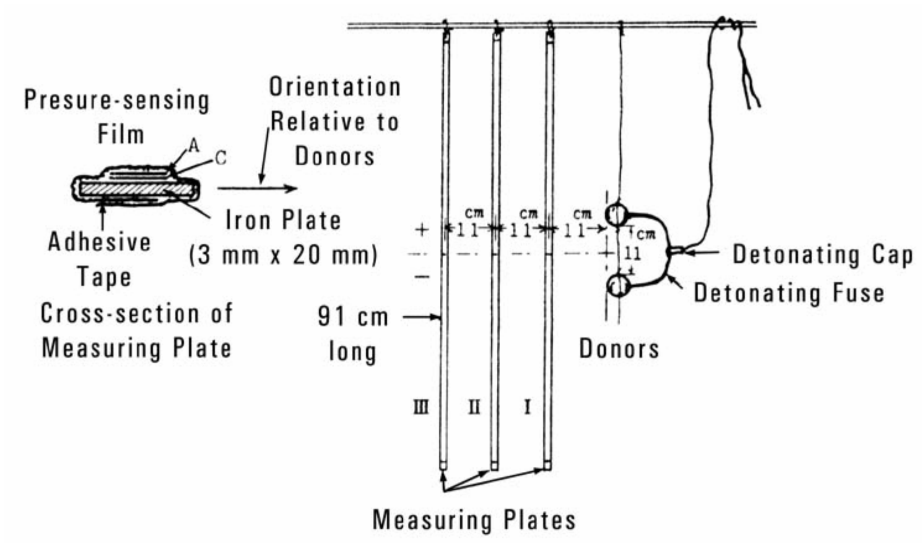


Figure 3. Pressure-measuring assembly.

4. Experiment 3

To explain the propagation of pressure from the two donors, we measured the pressure using a pressure-sensing film (Prescale) from Fuji Film Co. When pressure is exerted on the film, microcapsules burst and color the film red. The pressure is measured by measuring the density of the coloration. The film consists of two films, A and C. A is 0.105 mm thick and contains a layer of microcapsules. C is 0.095 mm thick and contains a color-producing layer. The films were cut into 10 mm-wide strips and both layers placed onto a 3 mm-thick, 20 mm-wide and 91 cm-long steel plate. This assembly was covered with cloth adhesive tape to prevent destruction by the explosion (Figure 3, left). The pressure-measuring assembly is shown in Figure 3.

Ignition of the donors resulted in the red coloration of the strips, as shown in Figure 4. The density of the coloration was measured using a Fuji FPD201 density-measuring device, the latter also indicating the pressure directly (Figure 7). Figures 5 and 6 show examples of pressure contour lines, which were drawn by the pressure, assuming that the pressure is continuous. This method does not explain how pressure develops in a given area; all it indicates is maximum pressure over time. Pressure in the shaded area is 50 kg/cm^2 and more.

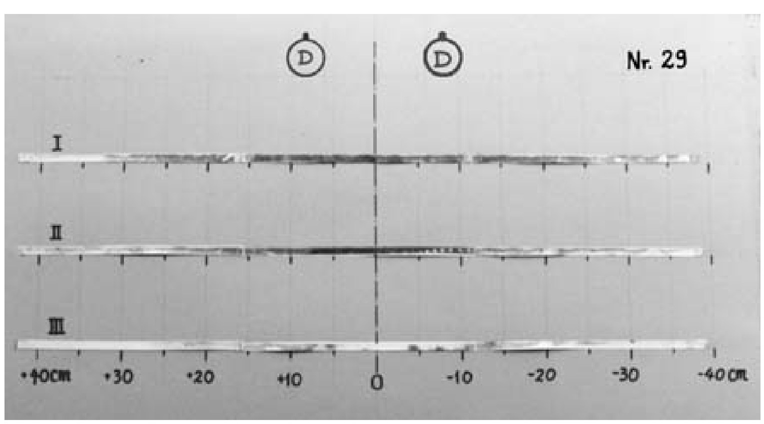
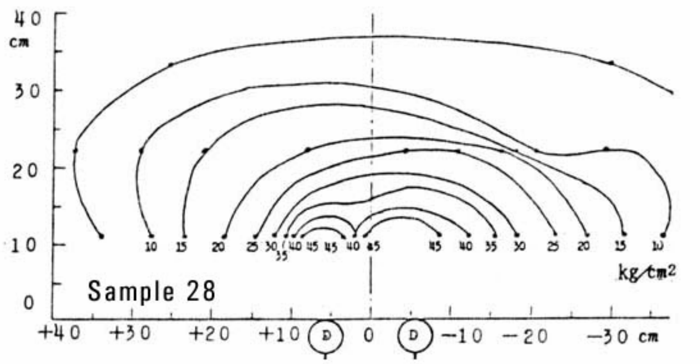
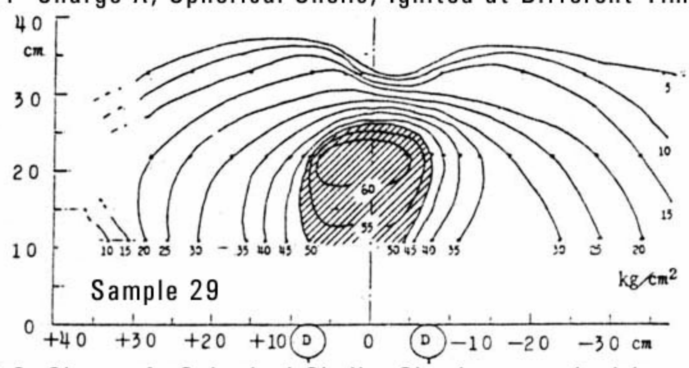


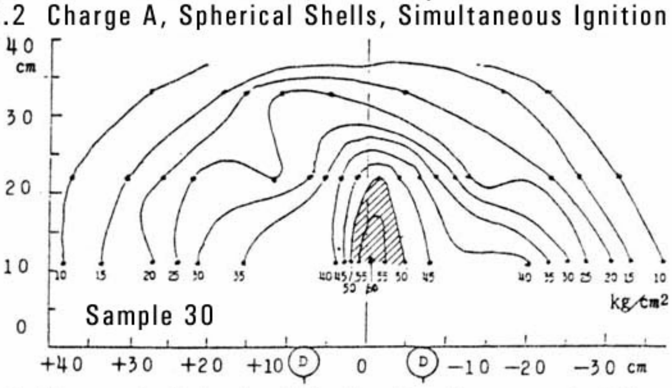
Figure 4. Coloration of pressure-sensing films (sample 29).



5.1 Charge A, Spherical Shells, Ignited at Different Times



5.2 Charge A, Spherical Shells, Simultaneous Ignition



5.3 Charge A, Spherical Shells, Simultaneous Ignition

Figure 5. Pressure propagation upon explosion of dual donors (I).

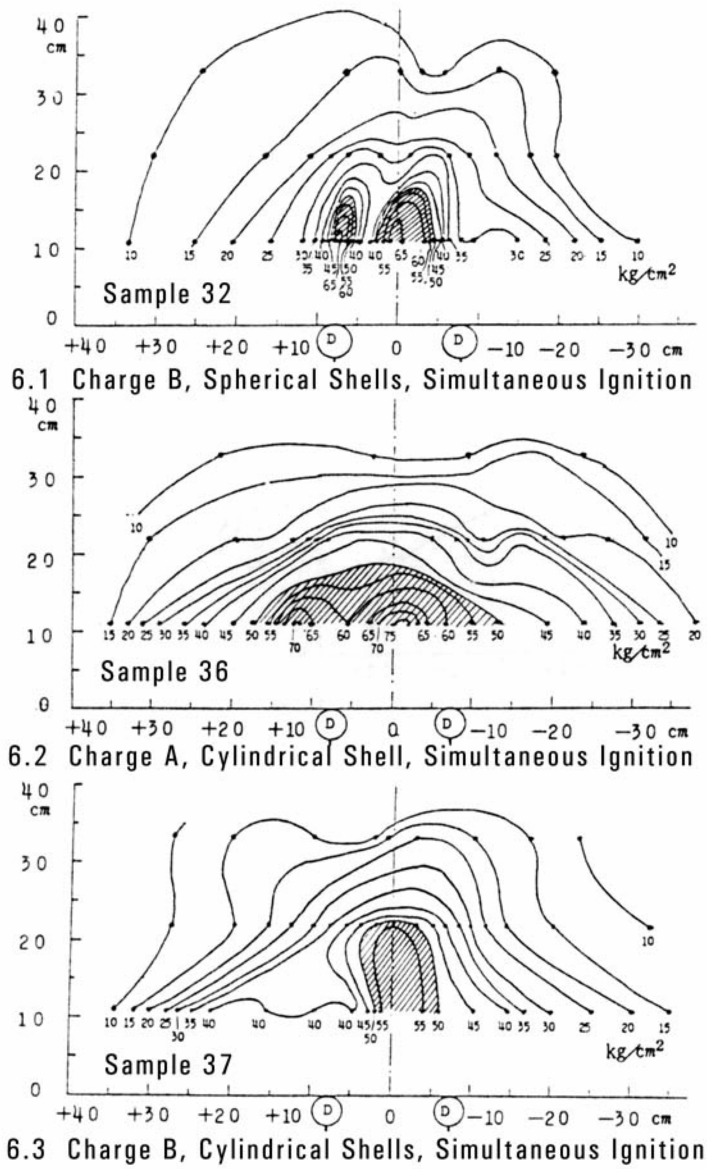


Figure 6. Pressure propagation upon explosion of dual donors (II).

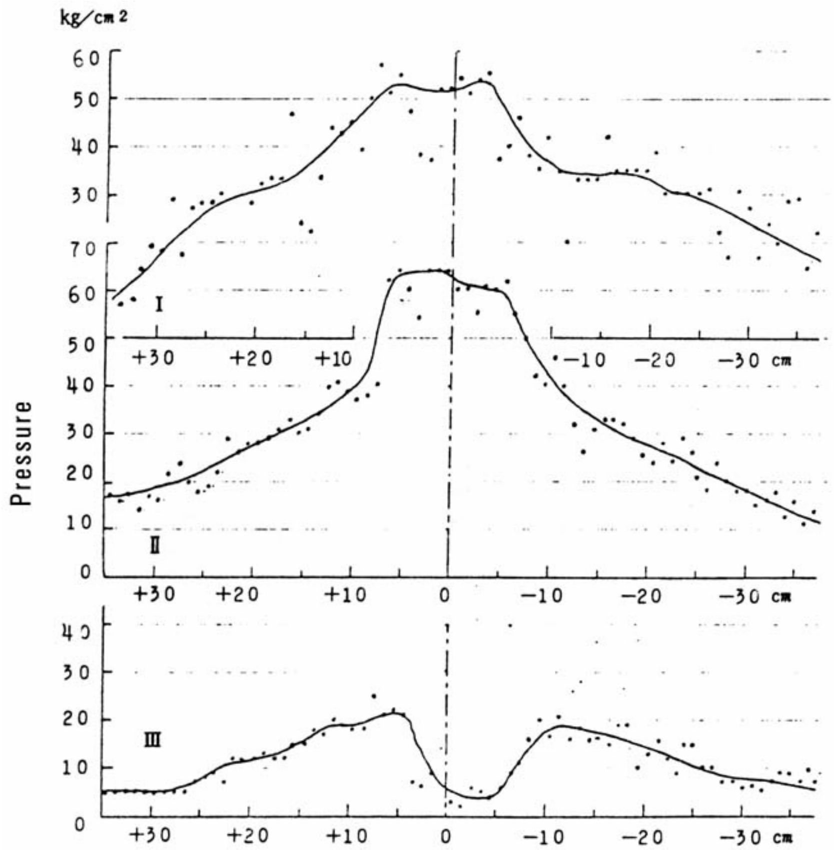


Figure 7. Reading of pressure as indicated by the coloration of the pressure-sensing films, using a Fuji FPD201 density-measuring device (sample 29).

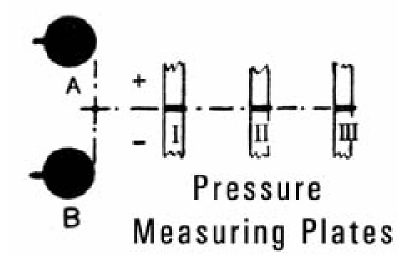
5. Discussion

It seems that the transfer effect of the donor having the detonating cord is not equally strong in all directions, but one-sided in the direction of the detonating cord (Figure 5.1). As previously mentioned, use of the detonating cord was necessary, in order to be able to explode the two donors simultaneously.

When the two donors were not ignited simultaneously, the maximum pressure in their vicinity was lower, and it soon weakened (Figure 5.1 and Table 4). However, when the two donors were ignited simultaneously, a very high pressure resulted along the axis (Figures 5.2 and 5.3; Table 4). This may be caused by the fact that the shock waves from the two donors collide with one another. We therefore think that the simultaneous explosion of two or more salutes or salute components of an explosive charge may cause a chain reaction, resulting in a serious accident. In terms of the shape of the salute, it seems that the transfer effect of the cylinder is greater than that of the sphere, since the maximum pressure of the former was generally higher than that of the latter (Tables 1 and 4). The thickness of the shell also influences the transfer effect (samples 16–19 and 22 in Table 1). The thicker the shell, the weaker the effect.

Table 4. Results of Tests Measuring Pressure in the Case of Dual Donors.

Explosive charge per shell: 25 g
Shell: Material: Hard paper casing
Thickness: Nos. 28–34: 0.7 mm
Nos. 35–39: 1.0 mm
Space between salutes:
No. 28: 66 mm (1.5D)
Nos. 29–30: 110 mm
D = 44 mm (outer diameter of shell)
Ignition: Detonating Cap and Cord



No.	Charge	Shell Shape	Ignition	Maximum Pressure I Press. kg/cm²	I Loc. cm	II Press. kg/cm²	II Loc. cm	III Press. kg/cm²	III Loc. cm
28	A	Spherical	Not Simultaneous	52	–6	30	–8	11	0
29	A	Spherical	Simultaneous	57	+8	64	0	25	+7
30	A	Spherical	Simultaneous	60	0	50	0	41	+5
31	A	Spherical	Simultaneous	65	+3	52	+2	18	+13
32	B	Spherical	Simultaneous	66	–2	44	+3	21	+2
33	B	Spherical	Simultaneous	57	–5	22	–8	8	+2
34	C	Spherical	Simultaneous	33	+7	22	–8	19	0
35	A	Cylinder	Simultaneous	76	+8	47	–7	29	+5
36	A	Cylinder	Simultaneous	76	–2	56	+7	15	+16
37	B	Cylinder	Simultaneous	68	–3	55	0	30	0
38	B	Cylinder	Simultaneous	68	0	48	–	35	–2
39	C	Cylinder	Simultaneous	19	+3	22	0	17	+6
40	for none of the detonators, except in the case of the detonating cap and cord			10	+2	—	—	—	—

6. Summary

By carefully testing salutes for their transfer effect and measuring the propagation of the pressure created during the simultaneous explosion of two donors, we determined that an area of abnormally high pressure is produced. This is likely due to the collision of the shock waves created by the two donors. However, in reality, this scenario is rather unlikely, since the possibility that several salutes or salute components will explode at the same time is rather low. Still, it must be ensured that salutes are handled, stored and safety-tested properly.