ENERGETIC MATERIAL RESPONSE IN A COOKOFF MODEL VALIDATION EXPERIMENT

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The cookoff experiments described in this paper belong to the small-scale experimental portion of a three-year phased study of the slow cookoff problem. This paper presents the response of three energetic materials in a small-scale cookoff experiment. The experimental effort is being used to validate the cookoff models currently under development by the Department of Energy (DOE).[1-2] In this phase of the project, a relatively simple geometry was used to evaluate the cookoff response of the energetic material with respect to both time to reaction and the level of reaction violence. Careful control of the experiment has been made with the selection of sample size (L/D ratio), containment (steel), sealing and thermal heating profile. Currently, the energetic materials under investigation include the RDX based explosive PBXN-109, an AP based propellant PS-1, and the HMX based explosive, LX-10. The focus of the current cookoff study is to provide experimental data for DOE model validation that span the levels of reaction violence from mild reactions to detonation events and to identify the contributing factors which influence these responses. Diagnostics include the use of thermocouples, strain gages, high-speed digital imaging (Cordin), and postmortem evaluation of fragments.

INTRODUCTION

Cookoff is a serious and costly hazard that has an impact over a broad range of disciplines, impacting the munitions design, testing, transportation, and storage, as well as fire fighting tactics. Shipboard fires are a major concern in the Navy, especially for the large aircraft carriers where the potential for fire is extremely high and the potential for weapons to be caught in fire is also high. There are many cookoff hazards situations to be considered, but the focus has been on the two ends of the spectrum: fast cookoff, where the item is subjected to direct fire such as a fuel fire; and slow cookoff, where thermal exposure of the item is indirect. In reality, the cookoff hazards threat spans the two extremes, where little data exist. With the advent of the Threat Hazards Assessment (THA), as allowed in MIL-STD 2105B, a cookoff testing regime can be selected that reflects the potential hazards environments that a weapons system is likely to experience, the stimulus levels, event probability, and likely outcome. Unfortunately, these kinds of data are rare, often difficult to obtain, and costly to generate for each specific weapons system.

The development of the THA will be streamlined with the use of fully validated modeling tools, thereby reducing cost and increasing efficiency.

It is neither practical nor affordable to generate the data describing ordnance response with respect to the shipboard fire threat for every ordnance item loaded. Ship commanders require accurate answers to a number of fire-related questions: (1) How long do their sailors have to fight a fire? (2) What are the most vulnerable munitions in a shipboard fire? (3) Can the munitions be loaded in the magazine in such a manner as to reduce their vulnerability? (4) What are the consequences of a cookoff reaction? These questions should be answered with the design of more sophisticated fire protection systems that incorporate part or all of the cookoff model concepts.

EXPERIMENT

In devising an experiment that could be used for model validation, a number of factors had to be considered, including the complexity and cost of the apparatus. Continuous communication between experimentalist and modeler was required for maximum success. The calculations for a cylindrical design indicated that as sample length was increased, temperature uniformity also increased, with the optimum being reached at about a sample length to diameter ratio (L/D) of 4. The current small scale experiments were performed in a cylindrical geometry with a sample L/D of 4.

The experiments described in this paper were sealed with a commercially available, high pressure tube plug (Torq N'Seal) Sealing of the experiment remains a concern to the DOE cookoff modeling community as the current mathematical descriptions being employed for energetic material decomposition assume that the energetic is confined and sealed. When the experiment vents, the models are no longer valid.

Seamless cold drawn type 1018 steel tubing of 6.75-mm (1.25-inch) outer diameter and a wall thickness of 4.78 mm (0.188 inch) was used as the confining medium. The tubing was machined as shown in Figure 1. With this arrangement, the desired wall thickness could be machined in the central portion of the tube. The samples were cartridge loaded into the tube and if desired ullage or free space remained on each end. The cookoff tests performed for this study were made with a 2.54-mm (0.1-inch) wall thickness.

The cookoff tube was instrumented with as many as 10 externally mounted type K thermocouples. Four thermocouples were placed around the center of the tube with the remaining thermocouples being placed along the top of the tube. High elongation precision strain gages were mounted in the hoop orientation at three locations along the cookoff tube. These gages were used to gain information on the early stages of wall motion during the cookoff event. As many as nine gage packages have been used in the experiments, however, six gages appear to provide adequate data for analysis.

A 110-volt flexible electric heating cord was used to heat the experiment. The heating cable was wrapped over the entire length of the tube. This approach to heater application was made in an effort to maximize the amount of material involved in the cookoff reaction; however, this apparently simple change in heater application adds considerable complexity to the cookoff experiment, as the tube failure cannot be guaranteed to occur in the center of the tube. A layer of Siltemp thermal barrier material was placed around the heater wrapped tube to reduce the amount of heat loss to the environment.

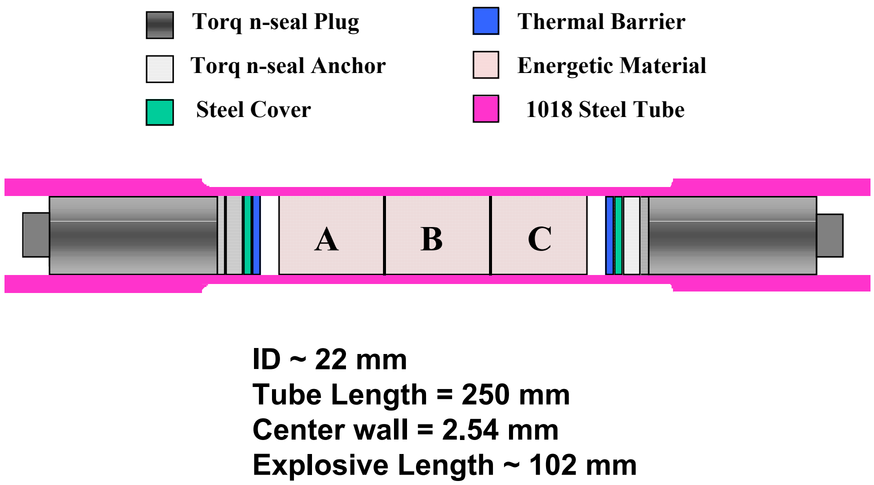


FIGURE 1. SCHEMATIC OF SMALL-SCALE COOKOFF EXPERIMENT.

A ramped heating profile was employed in the small-scale validation experiments. The profiles began with a heating rate of 10°C per minute to a soak temperature. The soak temperature was 155°C with a dwell time of 20 minutes, followed by a heating rate of 0.05°C per minute to cookoff with the exception of the propellant sample, which was ramped to a soak temperature of 180°C with a dwell time of 45 minutes. The soak temperature was modified in order to keep the test length approximately constant. Standard video and a Cordin digital CCD camera were used to monitor the cookoff reaction.

The thermocouple and strain gage data were recorded on a Nicolet Multipro transient analyzer. The data were collected at two digitization rates. A slow sampling rate (4 Hz) was used to obtain data over the entire test (up to 20 hours) and a fast rate (up to 10 MHz) was also recorded to obtain detailed data at the time of the cookoff event.

SAMPLE

Three energetic materials were selected for this study in order to obtain a range of cookoff reaction violence in the small-scale experiment. An experimental AP based propellant, PS-1, the RDX based explosive PBXN-109 and the HMX based explosive LX-10 have been investigated.

The AP based experimental propellant PS-1 contained 90 percent solids by weight. It contained 20 percent aluminum and 70 percent of a bimodal blend of AP in an HTPB binder system. The 86 percent solids loaded PBXN-109 contained about 65 weight percent RDX and 21 percent aluminum and an HTPB binder. The cookoff samples for these two materials were 22 mm in diameter and 102 mm in total length.

LX-10 is an HMX based explosive containing 95 weight percent HMX and 5 percent Viton A as binder. The cookoff samples were pressed to 98-99 percent of theoretical density and were 25.4 mm in diameter with a total length of 102 mm.

RESULTS

Cookoff results for the three energetic materials tested under the same conditions are summarized in Table 1. Explosive residue (8 grams) was recovered from the PBXN-109. The PS-1 and LX-10 were completely consumed in the cookoff reaction.

TABLE 1. COOKOFF RESULTS FOR PBXN-109, PS-1, AND LX-10.

Sample	ID	Time to reaction after soak, hr	Maximum external temperature, °C	Ullage	Fragments
PBXN-109	010419	5.12	169.8	10%	1
PS-1	010620	19.49	238.1	10%	3
LX-10	011023	15.82	205.3	10%	9
LX-10	011102	13.23	197.1	0%	7

A mild cookoff reaction was observed with the PBXN-109 explosive. This has been the case for all of the tests using PBXN-109.[3] The recovered fragments are shown in Figure 2 and strain rate versus time data are plotted in Figure 3. Previous tests with the explosive PBXN-109 showed no effect of ullage or free space on the time and at reaction.[4]

FIGURE 2. RECOVERED FRAGMENTS FROM THE PBXN-109 COOKOFF TEST.

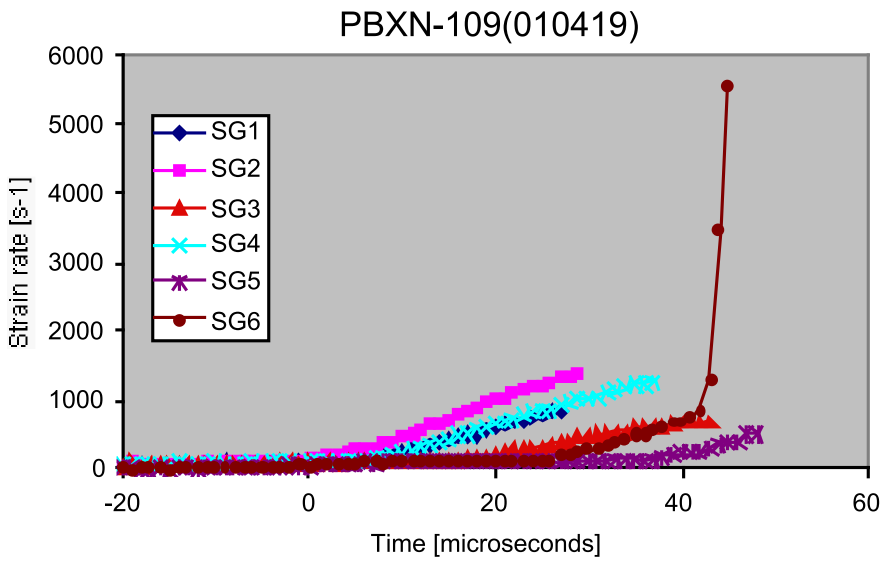


FIGURE 3. STRAIN RATE VERSUS TIME DATA.

No unreacted PS-1 was recovered from the cookoff reaction. The highest measured temperature at time of cookoff was 238°C, which would suggest that the propellant cookoff reaction occurred near the AP phase transition. The recovered fragments are shown in Figure 4 and would suggest a mild reaction similar to the PBXN-109. The strain rate versus time data are plotted in Figure 5. Tube failure occurred about 150 microseconds after zero time recorded on the strain gage data as shown in the Cordin images of Figure 6.

FIGURE 4. RECOVERED FRAGMENTS FROM PS-1 FIRING.

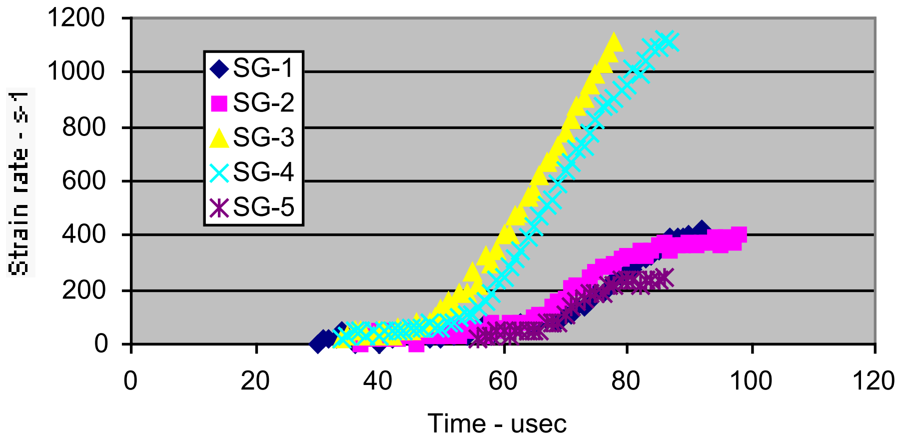


FIGURE 5. STRAIN RATE VERSUS TIME DATA FOR PS-1.

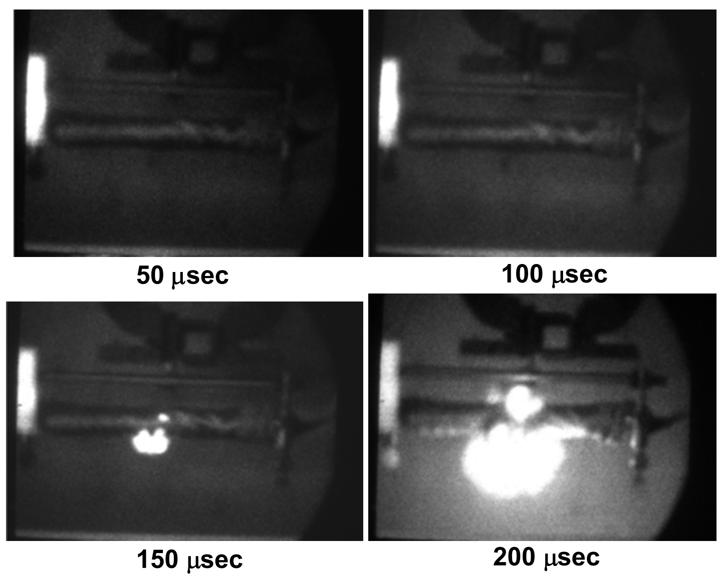
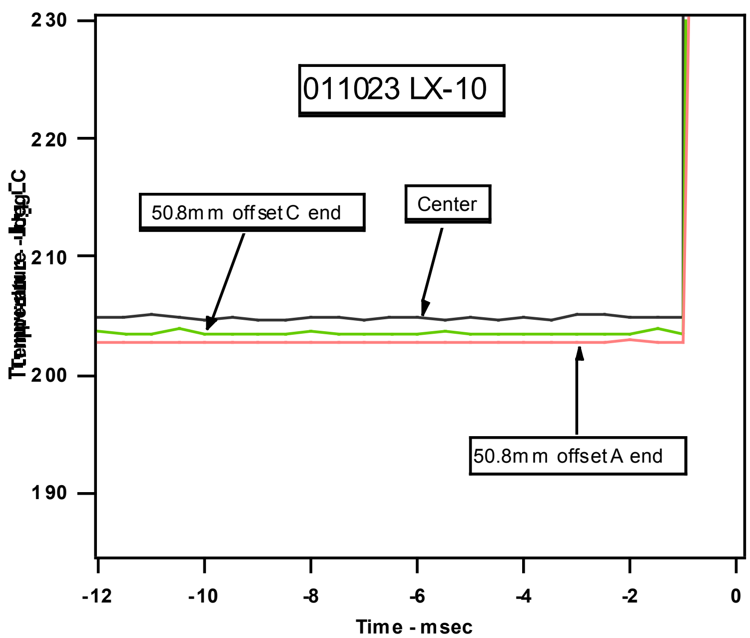
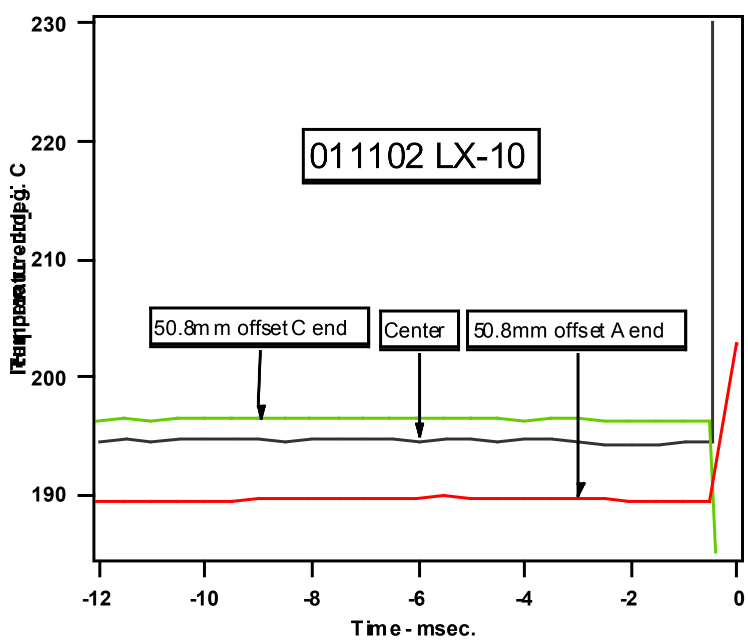


FIGURE 6. CORDIN IMAGES OF TUBE FAILURE FOR PS-1.

Cookoff tests were made with LX-10 with and without ullage. Unlike, the PBXN-109, the addition of ullage to LX-10 appears to change the cookoff temperature. The sample with about 10 percent free space had a cookoff temperature about eight degrees higher than that tested without ullage. (Test to test variation in this apparatus is about 2°C). Temperature versus time plotted in Figure 7a and b for the two LX-10 firings indicate about a 7-degree difference between the center of the tube and a location 50.8 mm from the center at one end for the test made with no additional ullage. The recovered fragments from these two tests are shown in Figure 8a and b. The size of the recovered metal strips and degree of peel back observed in the recovered end pieces would indicate a higher level of reaction violence in the LX-10 firing with ullage. Strain rate versus time data for the two firings are plotted in Figure 9a and b. Cordin images of the two tests indicate tube failure at about 100 microseconds after strain gage response in the test with no ullage and at 50 microseconds in the test with 10 percent additional ullage.



(a) With additional ullage.



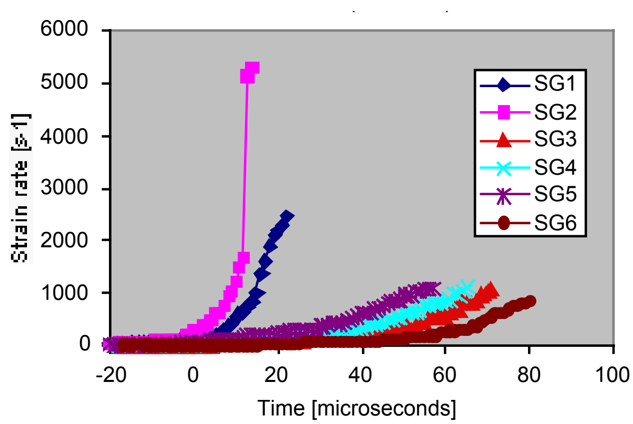
(a) Without additional ullage.

FIGURE 7. TEMPERATURE VERSUS TIME AT COOKOFF FROM LX-10 COOKOFF TESTS.

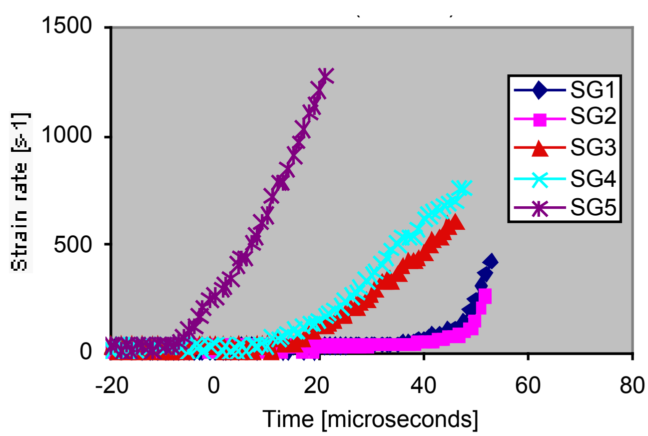
(a) With additional ullage.

(b) Without additional ullage.

FIGURE 8. RECOVERED FRAGMENTS FROM LX-10 COOKOFF TESTS.



(a) With additional ullage.



(b) Without additional ullage.

FIGURE 9. STRAIN RATE VERSUS TIME DATA FOR TWO LX-10 COOKOFF TESTS.

REACTION VIOLENCE

The ability to quantify the level of reaction violence has remained a particular challenge to the cookoff experiment. Fragment size and number offer qualitative information on the violence level, but do not provide a quantitative value for simulation. Fragment velocity measurements, collection, and analysis have not been emphasized in this work, as fragmentation has not yet been a focus in the DOE cookoff models. One means to quantify reaction violence is to determine the Maximum Initial Strain (MIS) rate from the strain gage response in each test. If we consider the strain rate as a velocity at which the tube ruptures, it would become a measure for determining reaction violence. That is, the more violent the reaction, the more the strain rate increases. The MIS rate values for the four cookoff tests described in this paper are listed in Table 2 and plotted in Figure 10. The LX-10 firing with no additional ullage and PBXN-109 gave the mildest reactions with the LX-10 firing with 10 percent ullage being the most violent. Judging from the recovered fragments, this appears to be a viable measure of reaction violence. A shortcoming to this approach is the location of the strain gages relative to tube rupture. If the tube does not fail at a strain gage location, their response is reduced. It is recommended that the heater application be adjusted in future tests to guarantee failure in the center of the cookoff tube.

TABLE 2. MIS RATE VALUES FOR TESTS WITH PBXN-109, PS-1 AND LX-10.

Test #	Explosives	Ullage	Reaction temp (‘C)	MIS* (strain/s)
011023	LX-10	10%	205.3	5255
011102	LX-10	NO	197.1	1276
010419	PBXN-109	10%	169.8	1345
010620	PS-1	10%	238.1	1106

*The maximum initial strain rate in the first appeared strain curve

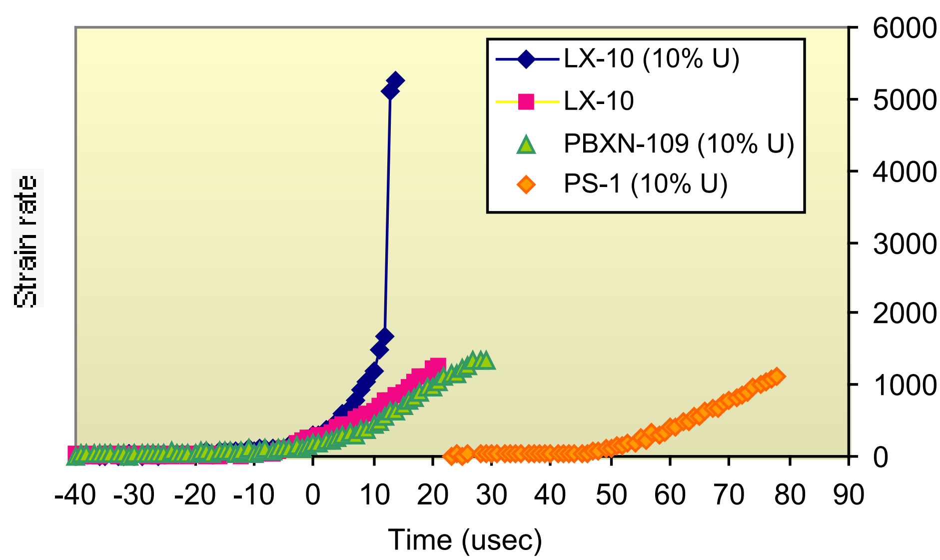


FIGURE 10. A COMPARISON OF MIS FOR THREE ENERGETIC MATERIALS.

SUMMARY/CONCLUSIONS

A small-scale cookoff test has been described which is being used for validation of the DOE cookoff models currently under development. A range of reaction violence has been demonstrated ranging from mild tube rupture and quenching as indicated by recovered PBXN-109 explosive to an apparent explosion in the HMX based explosive LX-10. The higher level of reaction violence may be due to the higher percentage of nitramine in this explosive as well as a slightly larger amount of explosive tested. The level of reaction violence can be quantified using the maximum initial strain rate measured in the initial tube failure. It appears that the presence of ullage or free space not only changes the time/temperature of reaction, but also the level of reaction violence. The test with ullage is more violent than the test without additional ullage.

FUTURE PLANS

Future plans call for a more thorough study of porosity and ullage on the LX-10 cookoff reaction. Tests are planned using samples at 75 and 85 percent initial density with and without ullage. These tests will be useful in gaining a complete understanding of porosity and free volume effects on cookoff reaction violence.

Cookoff tests are also planned using the HMX explosive PBX-9501 and heating profiles common to the tests made with PBXN-109, PS-1, and LX-10.

The final phase of the experimental cookoff project has been initiated with plans for testing the cookoff response of PBXN-109 in a generic heavy walled penetrator. Calculations on the appropriate heating cycle relative to ignition location and reaction violence have been made and two heating profiles have been selected for study.

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