Development of IM Design Methodology against Liquid Fuel Fire Threat

Investigation of Boundary Conditions and Time to Reaction for the Thermal Analysis of fast-cook off test by means of Numerical and Experimental Approach

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Abstract:

The present paper is a part of an effort to describe a methodology for designing an insensitive munition of type V against fast cook-off threat. Experimental investigation of boundary conditions is carried out in order to simulate fuel fire tests numerically for thermal analysis. The aim is to describe the boundary conditions for thermal analysis of the test item being exposed during the fast cook-off test.

Thermal analyses are performed by the defined boundary condition (BC) in order to predict time to reaction. Comparison between the numerical results and experiments are also made. In addition, some information about the second part of the methodology is also provided.

1. Introduction:

Design phase of an insensitive warhead can be messy considering the number of tests which should be carried on. Considering the cost and environmental concerns, among all other Insensitive Munition (IM) sign tests fast cook-off will probably lead in a "number of tests to be decreased" list for most nations.

In IM design, one of the important parameters to be predicted is time to reaction. This is important for the precautions that are taken to work before reaction occurs. To be able to foresee the time to reaction, one should either model the liquid fuel fire or force a boundary condition which is eligible to mimic the fire itself. There are some calculation methods offered by Pakulak [1] and Victor [2] to predict time to reaction for munitions. Both methods proposing the use empirical equations to solve 1-D heat transfer equations. There is also a boundary condition definition proposed by Victor [2] where temperature is assumed to be constant throughout the test and is 1073°K with a convection coefficient of 6 W/m^2K and emissivity of 1. Applying heat flux as a boundary condition is another option. There are some studies going on by FFE Working Group [3] to measure heat flux rates and compare the data with the alternative fast cook-off test measurements. This is being done as to check if there is any alternative method eligible to mimic standard hydrocarbon fuel fire thermal load. Measurements within the hearth of fire shows that, heat flux values vary between 100-150 kW/m^2 [4].

The most time consuming but accurate way of predicting the time to reaction is probably modeling the fire itself instead of applying the thermal load as a boundary condition. There are some examples of fire modelling codes such as C-SAFE [5] and LES solver [6]. But as these codes are not available for commercial use it has been decided to go on with the effort of finding the least time consuming and “accurate enough way” of predicting the time to reaction.

2-D and 3-D thermal analysis were performed using commercial ANSYS Fluent software as it is commonly used in similar applications [7]. The aim was to conclude to a point of an improved BC definition and to see how accurate the predictions are from 2-D and 3-D analysis.

A generic test item has been designed and manufactured, aiming to visualize the time passes till the reaction occurs from the initiation of the test. To come up with an improved BC we have made surface temperature measurements over a single test item. These test items can also be used to characterize ventilation characteristic which is mentioned as a future work.

2. Description of the Test Items:

There are 2 different type of test items which differ on the length of explosive contacting cylinder casing. The length ratio over test specimens are about ¾ and designed to see if there is an effect of length on time to reaction. The short test item is shown in Figure 1. Two different liner types (HTPB based thermoset liner and a thermoplastic liner) and two different thicknesses (1 mm and 3.5 mm) are tested.

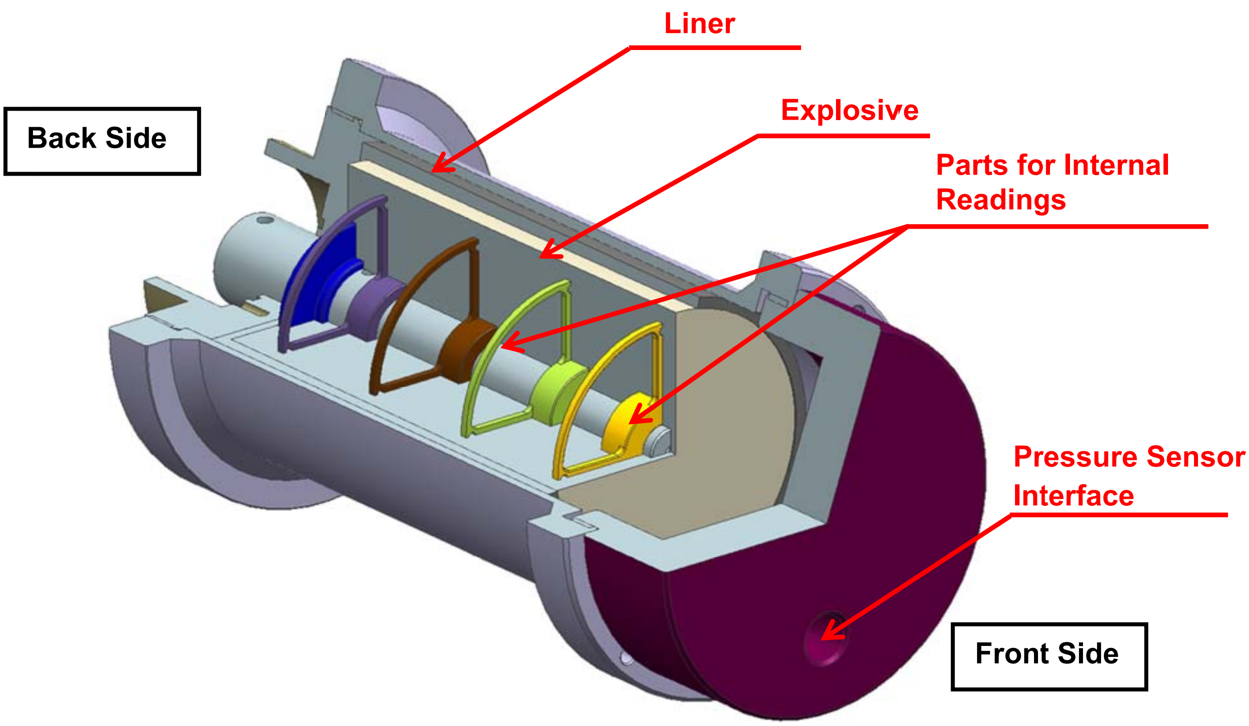

Figure 1. Generic Test Item (Short Version)

Test items were designed so that one can be able to take internal measurements such as temperature and burning rate from the internal parts shown in Figure 1.

Some pre-analysis are also made to ensure that the application of internal reading addition to test item do not affect the heating rate over explosive and hence do not change time to reaction. The only major change that the internal measurements effected on test was the back plate insulation. To protect cables that were coming out of the test item, insulation was applied to back plate of the test item along the test pool to data acquisition system.

3. Experimental Setup:

Tests have been performed with the mini fuel fire test setup as the test item dimensions are within the range of declaration of NATO standard 4240 [8].

Total of eight surface thermocouples (STC) is used to measure test item surface temperature. Measurements are made both in the front and rear side. Thermocouples are placed circumferentially with an angle of 90 degrees. To avoid contact dislocations and increase the heat transfer to STCs a thermal paste (Thermigrease TG 20033) was used which can withstand temperatures up to 1200°C and has relatively high thermal conductivity.

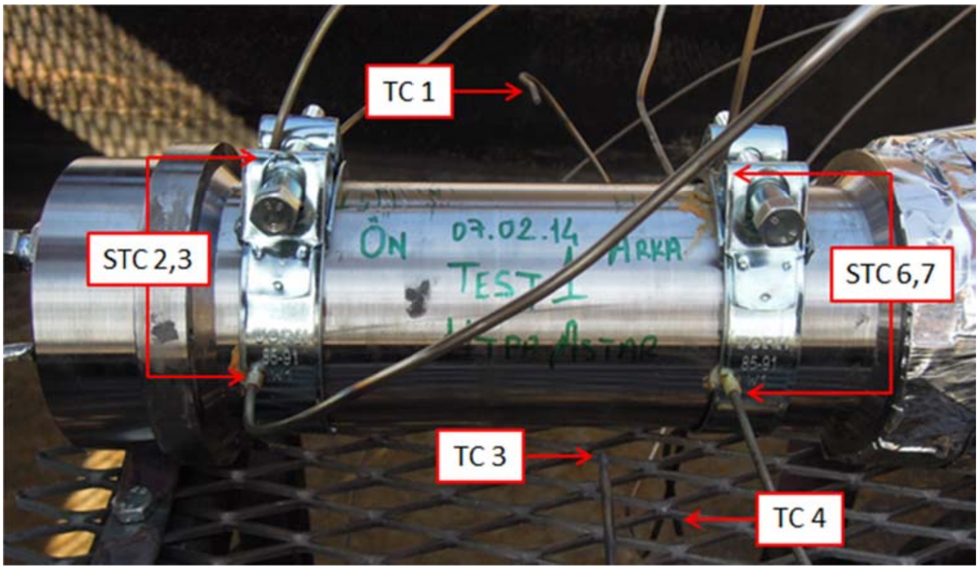

Figure 2. Thermocouple Placement on 1st Test Item

Total number of 8 tests has been made for the determination of TtR. Although there were no internal measurements taken from inside of test case in some tests, back side of those test items were still isolated to simulate the same conditions with previous tests.

4. Results:

Flame temperature measurements that have been made around the first test item are used to simulate BC of the test item model in ANSYS Fluent. This is done by averaging the flame temperature over the entire event. Afterwards, 6 piecewise high order polynomial curves are fitted (Figure 3) along different time ranges ($t \in [0,19s)$, $t \in [19s,51s)$, $t \in [51s,80s)$, $t \in [80s,98s)$, $t \in [98s,116s)$ and $t \geq 116$ s) and it is used as an input parameter of free stream and external radiation temperature.

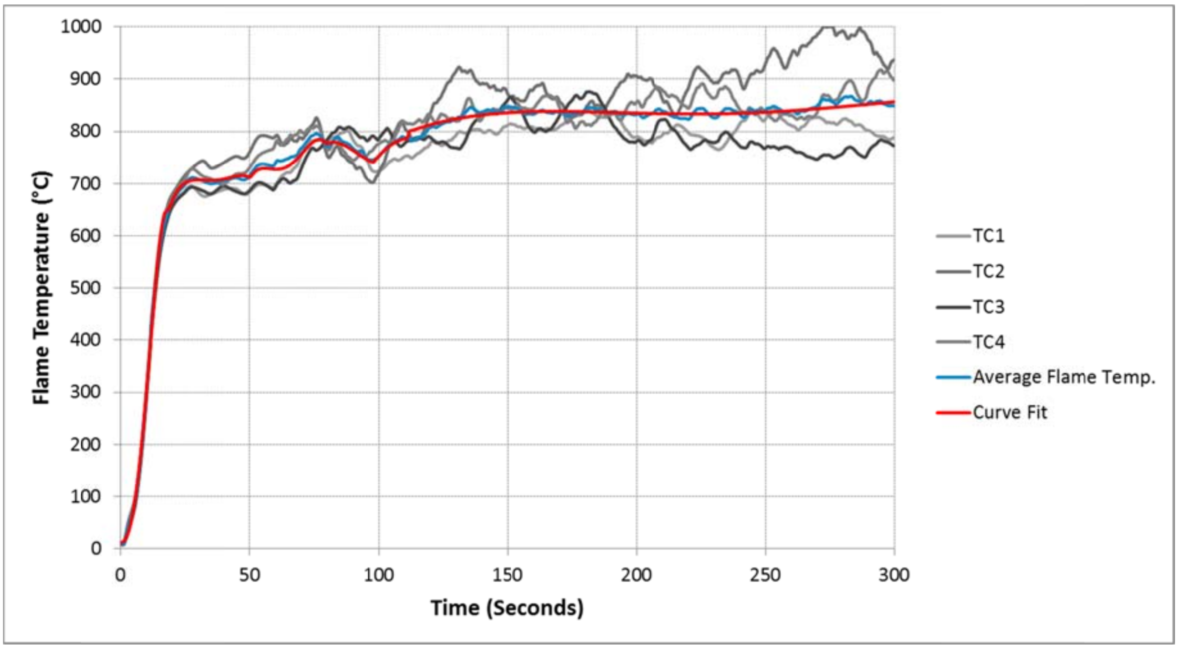

Figure 3. Flame Temperature Readings from the 1st Test

Temperature measurements that are taken from surface are also averaged to check if BC that is implemented to the analysis represents these measurements. Both measurements and averaged temperature are given in Figure 4.

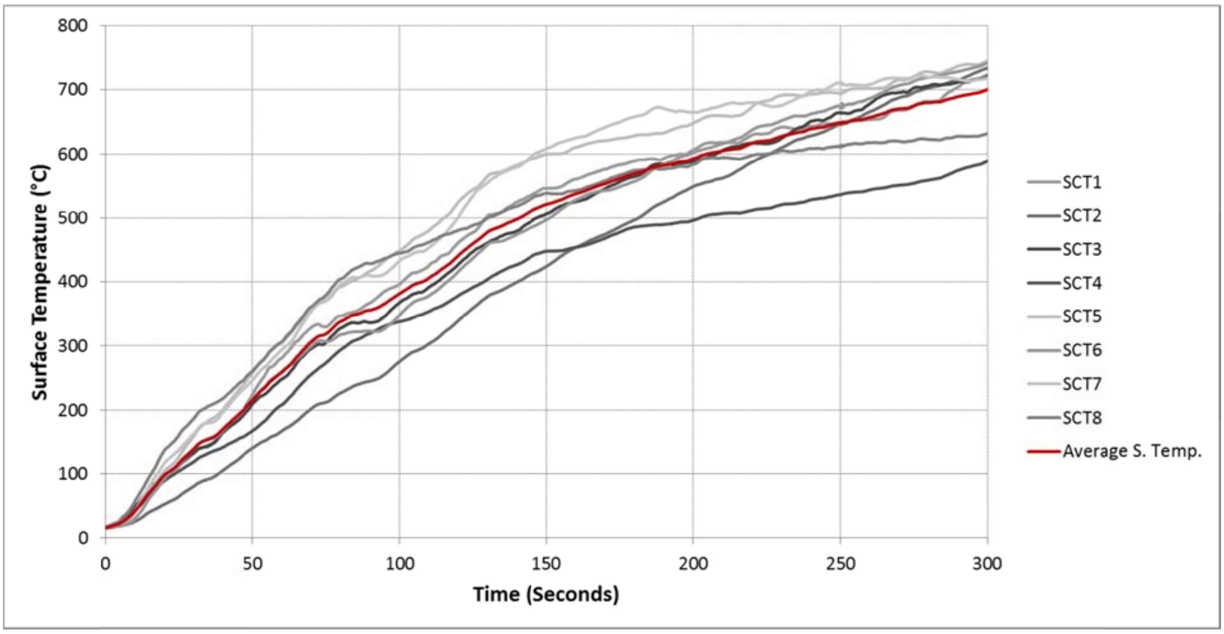

Figure 4. Surface Temperature Readings from the 1st Test Item

Temperature dependent heat generation term (1) and time dependent piece-wise boundary condition of PBXN-109 is implemented into Fluent with a user defined function (UDF). Heat generation constants of PBXN-109 are given in Table 1 where Q_{act} is the heat of reaction (Eq.1), Z is the collision number, E is the activation energy and A is the molar fraction.. The full reaction was modeled as an instantaneous one step exothermic chemical reaction thus, A is taken to be 1.

$$\text{Heat Generation} = \rho QZAe^{(-E/RT)} \tag{1}$$

Table 1. Heat Generation Constants [9]

ρ (kg/m^3)	Q_{act} (J/kg)	Z (1/s)	E (J/mol)	R (J/mol.K)
1680	2198070	1.023x10^{14}	152716	8.314

After the analyses of the first test item, surface temperature from the analysis is compared with the test measurements. According to the comparison, a time delay of 12 seconds between the solution and measurement along time is observed (Figure 5).

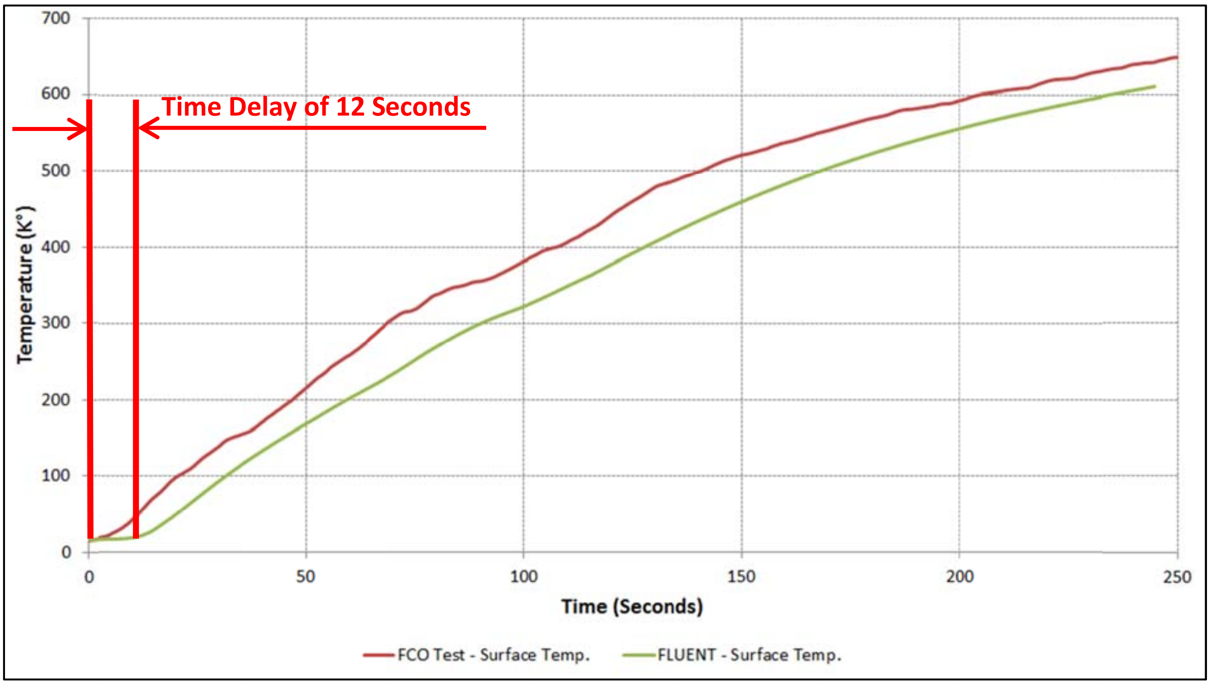

Figure 5. Surface Temperature Comparison of Test and Numerical Results - Test Case 1

The most common reason for this time delay is using of "thick" thermocouples which can withstand for a couple of tests. Knowing that, thick thermocouples have slower response, one can use faster response types of these thermocouples and minimize the time delay. To overcome mismatch of results, we have shifted the resultant predicted time of reaction from analyses by means of calculated amount of time delay.

Both 2-D axisymmetric and 3-D analyses are made to compare results between them. 3-D analyses were made in order to see the effect of buoyancy (trapped heated air within the test chamber). For 3D analysis, gravitational force of earth is activated to consider buoyancy effects. For 2-D analysis, the convection and radiation terms are applied as boundary condition, the energy equation is only left with the heat generation and conduction term.

After the first analyses, it was concluded that the effect of buoyancy is below %1 when TtR values are compared. Thus, further analyses are carried out with the 2-D axisymmetric approach. Internal parts are not modeled in axisymmetric simulations. Total of 12510 elements in 2-D were used whereas 469100 elements were used in 3-D version of the analyses. Both mesh construction and temperature gradients of test item containing 1 mm of HTPB liner (for test cases 7-8) are shown in Figure 6.

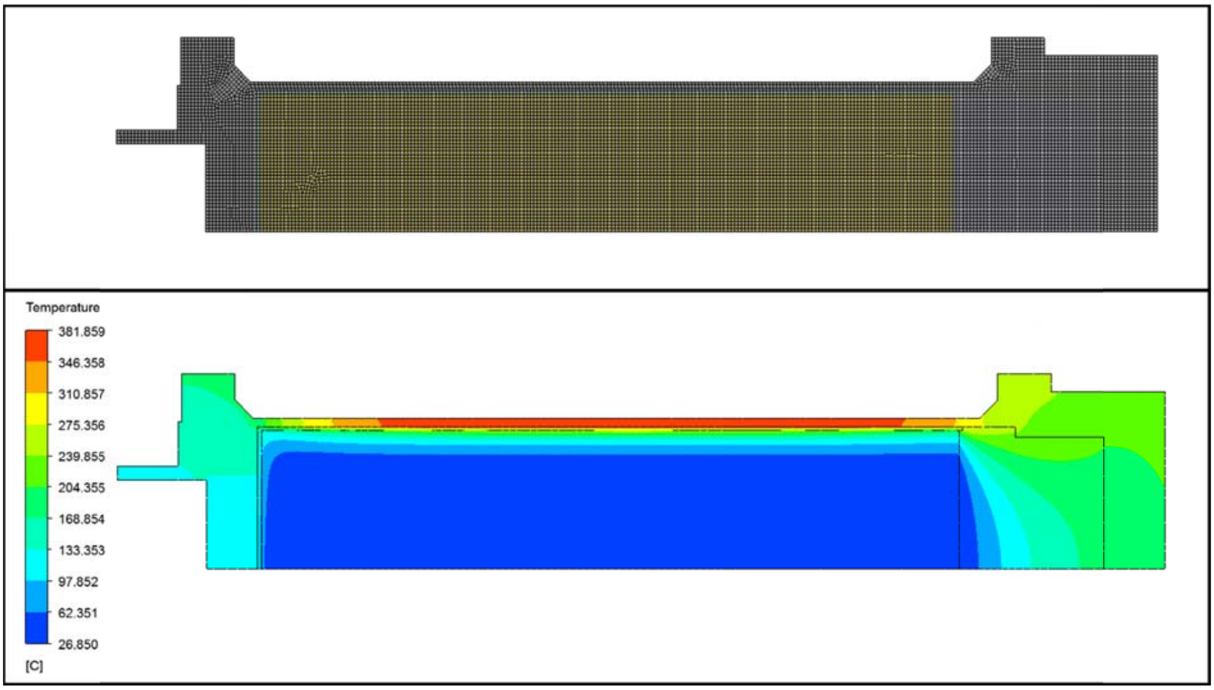

Figure 6. Mesh Construction (top) and Temperature Gradient (bottom) of Test Items 7-8

Table 2. Comparison of Calculated and Test Observed TtR

Test Item No	Explosive L/D	Liner Thickness	Liner Type	Predicted TtR (sec.)	Predicted TtR* (sec)	Observed TtR (sec.)	Difference (sec.)	Error %
1	2.67	3.50	HTPB Based Thermoset	238	226	200	26	13.1
2	1.71	3.50	Thermoplastic Liner	229	217	200	17	8.6
3	1.71	3.50	Thermoplastic Liner	229	217	186	31	16.7
4	1.60	1.00	Thermoplastic Liner	129	117	120	-3	-2.8
5	1.60	1.00	Thermoplastic Liner	129	117	108	9	8.0
6	1.60	1.00	Thermoplastic Liner	129	117	120	-3	-2.8
7	1.60	1.00	HTPB Based Thermoset	133	121	107	14	13.0
8	1.60	1.00	HTPB Based Thermoset	133	121	118	3	2.5

*: Predicted times to reactions are corrected according to the observed time delay

The largest difference between the predicted and observed ignition times occurred with a 16.7 percent difference for 8 tests. Addressing the 16.7% difference, the prediction does not take into account the decomposition/melting of the liner and decomposition of the explosive that occurs before ignition in the analyses. It is assumed that the liner thickness is constant along the solution. These phase shifting and/or chemical reactions are thought to effect heat transfer to explosive through the test item hence increasing the error.

Flame temperature may directionally vary within the hearth either caused by wind or the chaotic environment of its nature. as shown in figure 4 different thermocouples have different temperature readings. The temperature distribution between thermocouples is shown in Figure 4. As mentioned above, the average of all 4 thermocouples is used as a temperature boundary condition. On the other hand because of directionality of the flame, heat flux on one surface might be higher than the other three causing a hot spot along the circular direction. Thus, even if by small amounts we were already expecting to have different ignition times for the test item having the same geometry and liner type/thickness.

Even with these limitations, predicted ignition time can be accepted to be close to the experimental data.

5. Conclusion:

Total of 8 tests were examined in this study utilizing thermal modeling of liquid fuel fire. They were performed in order to observe ignition time of generic test items. From the first test, an improved temperature boundary condition is obtained. With the more realistic boundary condition, 4 different analyses are conducted with 2-D, axisymmetric approach. This is done since the 3-D model where the buoyancy terms are included does not change the predicted time by more than %1.

Predicted ignition times and test results shows a maximum difference of 16.7%. Possible reasons of this error are discussed above. An improvement on the methodology can be made upon implementing a melting and/or decomposition model into the ANSYS Fluent. By considering the current results methodology, using a 2-D axisymmetric thermal analysis for predicting the time to reaction seems to be applicable.

By this work, it will be possible for one to predict the ignition time of a munition containing an energetic material by knowing the heat generation characteristic of that energetic material. Using the ANSYS Fluent or any other software that is eligible to model the heat transfer one can also study possible critical thermal path of the energetic system and take necessary precautions to avoid any violent reactions.

As a future study, ventilation characteristics of the energetic system is planned to be considered. For this purpose, burn characteristics of PBXN-109 under relatively low pressures (0-10 MPa) will be studied. Knowing the burn characteristics of the energetic material, it will be possible to determine necessary ventilation area by means of self-developed 1-D conservation of mass equation solver or 2-D Fluent simulations including both energy and mass conservation. These critical ventilation area predictions shall be compared with the experimental observations.

Acknowledgement:

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References:

[1] Pakulak J. M., “Simple Techniques for Predicting Sympathetic Detonation and Fast and Slow Cookoff Reaction of Munitions,” Technical Report, Naval Weapons Center, June 1988

[2] Victor, A.C., "Simple Calculation Methods for Munitions Cook-off Times and Temperatures, "Propellants, Explosives, Pyrotechnics, Vol. 20, pp. 252-259, 1995

[3] Swierk T., Fuel Fire Experts Working Group IV Meeting Summary, September 2014

[4] Yagla J., Griffiths D., Hubble D., Ford K., Washburn E., “Experimental Development of Propane Burners for Fast Cook Off Testing”, in Minutes of the IMEMTS Symposium, October 2013

[5] Pershing D. W., Center for the Simulation of Accidental Fire and Explosion Annual Report , September 1999

[6] Rawat R., Pitsch H., and J. F. Ripoll, “Large-Eddy Simulation of Pool Fires with Detailed Chemistry Using an Unsteady Flamelet Model”, Center of Turbulence Research Proceeding of the Summer Program, 2002

[7] Ford K. P., Davis N. C., Farmer A. D., Washburn E. B., Atwood A. I., Wilson K. J., Abshire J. P., Shewmaker M. L., Goedert Z. P., Wheeler C. J., Curran P. O., Covino J., “Subscale Fast Cookoff Test Result”, in Minutes of the IMEMTS Symposium, 2010

[8] NATO standard 4240 (Edition 2), NATO Liquid Fuel / External Fire, Munition Test Procedures, April 2003

[9] Vetter, R.F., “Reduction of Fuel Fire Cook-off Hazard of Rocket Motors”, NWC-TP 5921, Naval Weapons Center, China LAKE, CA, USA, June 1977