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DYNAMIC MODEL OF WATER DELUGE SYSTEM FOR PROPELLANT FIRES.(U)
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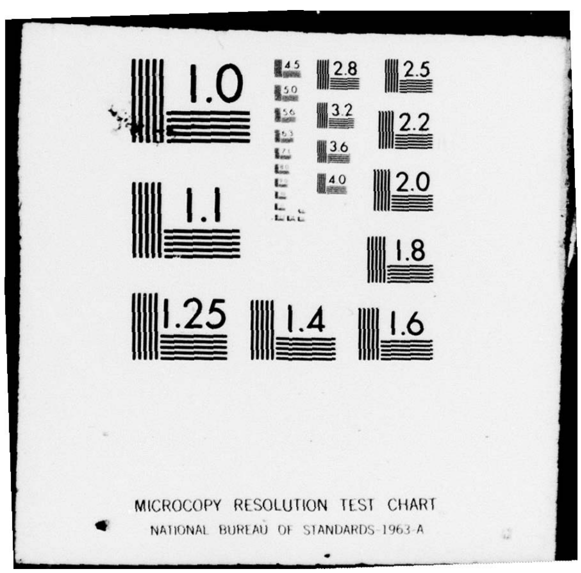
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MEMORANDUM REPORT ARLCD-MR-78008

DYNAMIC MODEL OF WATER DELUGE SYSTEM FOR PROPELLANT FIRES

JOSEPH P. CALTAGIRONE

MAY 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER
WEAPON SYSTEMS LABORATORY
DOVER, NEW JERSEY

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Since the conventional water deluge system is ineffective in extinguishing propellant/explosive fires, a program was undertaken to develop a deluge system able to withstand the pressures involved in a propellant or explosive fire and to extinguish it before a detonation or extreme hazard occurs. Testing a full-scale water deluge system is costly; therefore, a model law was developed in order to test scaled-down systems.

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INTRODUCTION

A conventional water deluge system is ineffective in extinguishing propellant/explosive fires, since it can be destroyed by an accidental detonation. A water deluge system which can withstand accidental detonation has been successfully deployed in extinguishing the resulting fires. However, testing and proving-out the effectiveness of the deluge system against a variety of propellants/explosives in different physical environments is expensive. The development of a model for testing will reduce this cost and make it possible to test for the various types of propellants/explosives and configurations present in manufacture and storage.

The scope of this memorandum is limited to the modeling of a propellant hopper set-up.

This model was initially developed as a project for a course, "Modeling in Engineering Dynamics," given by Southwest Research Institute at ARRADCOM, Dover, NJ. It has since been refined.

DEVELOPMENT OF THE MODEL

Parameters and Assumptions

Before a model can be developed, all pertinent parameters must be known. In modeling the water deluge system, the system's parameters (table 1) were taken into account, and the following assumptions were made:

1. Propellant being processed in hopper is bulk, single perforated.

2. Ignition of propellant is at bottom of hopper (worst case).

3. Water flow through pipe is neglected; response is taken as water leaves nozzle.

4. Nozzle spray is sufficient to cover hopper.

5. Constant line pressure.

In choosing the parameters, the characteristics of the pipe (that is, the flow characteristics) were neglected. This can be done since the only significant characteristics to be considered are the pressure and the pattern with which the water leaves the nozzle.

A hopper of single-perforated propellant was chosen to simplify the model, since multi-perforated propellant has more surface area and exhibits different characteristics.

Development of PI Terms

From table 1, there are three dimensionless parameters. These are the first three pi terms:

$$\pi_1 = d_n$$

$$\pi_2 = d_h$$

$$\pi_3 = d_g$$

Also, from the remaining parameters, we can create an equation of dimensional homogeneity:

$$F^\circ L^\circ T^\circ \Theta^\circ \stackrel{d}{=} \nu^{a_1} t_e^{a_2} t_o^{a_3} P_\omega^{a_4} P_r^{a_5} \Delta^{a_6} \rho^{a_7} V^{a_8} H^{a_9} \ell^{a_{10}} \Theta_o^{a_{11}}$$

or, substituting in each parameter's fundamental dimensions, we obtain:

$$F^\circ L^\circ T^\circ \Theta^\circ \stackrel{d}{=} (L^3/T)^{a_1} (T)^{a_2} (T)^{a_3} (F/L^2)^{a_4} \left(\frac{F}{L^2T}\right)^{a_5} (\Theta)^{a_6}$$

$$(FT^2/L^4)^{a_7} (L^3)^{a_8} (L^2/T^2)^{a_9} (L)^{a_{10}} (\Theta)^{a_{11}}$$

These terms are then placed into a matrix:

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
	ν	t_e	t_0	P_ω	$\dot{P}_r$	Δ	ρ	V	H	ℓ	Θ_0
F	0	0	0	1	1	0	1	0	0	0	0
L	3	0	0	-2	-2	0	-4	3	2	1	0
T	-1	1	1	0	-1	0	2	0	-2	0	0
Θ	0	0	0	0	0	1	0	0	0	0	1

Rearrange matrix:

	a_4	a_{10}	a_3	a_6	a_5	a_1	a_7	a_8	a_9	a_2	a_{11}
	P_ω	ℓ	t_0	Δ	$\dot{P}_r$	ν	ρ	V	H	t_e	Θ_0
F	1	0	0	0	1	0	1	0	0	0	0
L	-2	1	0	0	-2	3	-4	3	2	0	0
T	0	0	1	0	-1	-1	2	0	-2	1	0
Θ	0	0	0	1	0	0	0	0	0	0	1

Add two times row 1 to row 2 and the identity submatrix is obtained. This indicates that the rank of the matrix is 4 and thus 11-4 or 7 pi terms will result.

	a_4	a_{10}	a_3	a_6	a_5	a_1	a_7	a_8	a_9	a_2	a_{11}
	P_ω	ℓ	t_0	Δ	$\dot{P}_r$	ν	ρ	V	H	t_e	Θ_0
F	1	0	0	0	1	0	1	0	0	0	0
L	0	1	0	0	0	3	-2	3	2	0	0
T	0	0	1	0	-1	-1	2	0	-2	1	0
Θ	0	0	0	1	0	0	0	0	0	0	1

This matrix yields four simultaneous equations:

F: $a_4 = -a_5 - a_7$

L: $a_{10} = -3a_1 + 2a_7 - 3a_8 - 2a_9$

T: $a_3 = a_5 + a_1 - 2a_7 + 2a_9 - a_2$

Θ: $a_6 = -a_{11}$

Substituting back into the equation of dimensional homogeneity:

$$F^\circ L^\circ T^\circ \Theta^\circ \stackrel{d}{=} \nu^{a_1} t_e^{a_2} t_o^{a_5+a_1-2a_7+2a_9-a_2} P_\omega^{-a_5-a_7} \dot{P}_r^{a_5} \Delta^{-a_{11}}$$

$$V^{a_8} H^{a_9} \ell^{-3a_1+2a_7-3a_8-2a_9} \Theta_o^{a_{11}}$$

Collecting terms of like exponents yields the remaining terms:

a_1: $\pi_4 = \dfrac{\nu t_o}{\ell^3}$

a_2: $\pi_5 = t_e/t_o$

a_5: $\pi_6 = \dfrac{t_o \dot{P}_r}{P_\omega}$

a_7: $\pi_7 = \dfrac{\rho \ell^2}{P_\omega t_o^2}$

a_8: $\pi_8 = V/\ell^3$

a_9: $\pi_9 = \dfrac{t_o^2 H}{\ell^2}$

These pi terms can be expressed as a set of functions:

$$\left.\begin{array}{l} \dfrac{t_e}{t_o} \\[2ex] \dfrac{t_o^2\, H}{\ell^2} \\[2ex] \Delta/\Theta_o \end{array}\right\} \quad f_i\left(d_n, d_h, d_g, \frac{\nu t_o}{\ell^3}, \frac{t_o \dot{P}_r}{P_\omega}, \frac{\rho \ell^2}{P_\omega t_o^2}, \frac{V}{\ell^3}\right)$$

The Model

Referring to the list of pi terms in table 2, the model can be derived and the appropriate scale factors determined. These must be followed to fully satisfy the model criteria. The set of pi terms in table 2 constitutes the model law. For strict adherence to the law, all nine dimensionless groups should remain invariant between the model and prototype. Pi terms 1 to 3 denote geometric similarity; in other words, the geometry must be the same in the model and in the prototype. The other pi terms result in the following relationships between scale factors:

$$\pi_4: \quad \lambda_\nu \lambda_{t_o} = \lambda_\ell^3 \qquad (1)$$

$$\pi_5: \quad \lambda_{t_e} = \lambda_{t_o} \qquad (2)$$

$$\pi_6: \quad \lambda_{t_o} \lambda_{\dot{p}_r} = \lambda_{p_\omega} \qquad (3)$$

$$\pi_7: \quad \lambda_\rho \lambda_\ell^2 = \lambda_{p_\omega} \lambda_{t_o}^2 \qquad (4)$$

$$\pi_8: \quad \lambda_V = \lambda_\ell^3 \qquad (5)$$

$$\pi_9: \quad \lambda_{t_o}^2 \cdot \lambda_H = \lambda_\ell^2 \qquad (6)$$

$$\pi_{10}: \quad \lambda_\Delta = \lambda_{\theta_o} \qquad (7)$$

These relationships may be easier to satisfy if we set one scale factor arbitrarily, say $\lambda_\ell = \lambda$ (any scale factor). Using the same propellant in the model as is used in the prototype, $\lambda_\rho = \lambda_H = 1$. Also, if we keep the water pressure and the initial temperature the same, i.e., $\lambda_{p_w} = \lambda_{\Theta_o} = 1$, then:

from π_7 ; $\lambda_{t_o} = \lambda$

from π_5 : $\lambda_{t_e} = \lambda$

from π_{10} : $\lambda_\Delta = 1$

from π_4 : $\lambda_\nu = \lambda^2$

from π_6 : $\lambda_{\dot{p}_r} = 1/\lambda$

from π_8 : $\lambda_V = \lambda^3$

If a half-scale model is selected, then:

$\lambda_\ell = 1/2$	$\lambda_{p_w} = 1$
$\lambda_{t_o} = 1/2$	$\lambda_\rho = 1$
$\lambda_{t_e} = 1/2$	$\lambda_H = 1$
$\lambda_\Delta = 1$	$\lambda_V = 1$
$\lambda_\nu = 1/4$	
$\lambda_{\dot{p}_r} = 2$	

Substituting these scale factors back into the required relationships between scale factors (equations 1 through 7) serves as proof that the model law has been satisfied.

CONCLUSIONS AND RECOMMENDATIONS

The model law for the deluge system developed in this memorandum will permit scaled-down systems to be tested, reduce costs, and/or decrease the number of tests. This model may be fabricated for testing with relative ease.

It is recommended that this model and others for different types of deluge systems be adopted for use in developing scaled-down models.

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3. "Safety, Pollution Abatement, and Conservation of Energy Review", Special Publication ARLCD-SP-77001, ARRADCOM, Dover, NJ, May 1977

Table 1. Parameters for water deluge system model

Parameter	Symbol	Dimensions
Water flow rate	ν	L^3/T
Time to detection	t_o	T
Extinguishment time	t_e	T
Water pressure	P_w	F/L^2
Pressure rise rate of propellant	$\dot{P}_r$	$\frac{F}{L^2T}$
Change in temperature	Δ	Θ
Nozzle spray pattern	d_n	-
Hopper shape	d_h	-
Packing density of propellant	ρ	$\frac{FT^2}{L^4}$
Volume of propellant	V	L^3
Heat of combustion	H	$\frac{L^2}{T^2}$
Grain shape	d_g	-
Spray distance	ℓ	L
Initial temperature of propellant	Θ_o	Θ

Table 2. Pi terms for water deluge system model

$\pi_1 = d_n$		
$\pi_2 = d_h$	}	Geometric similarity
$\pi_3 = d_g$		
$\pi_4 = \dfrac{\nu t_o}{\ell^3}$		Water flow
$\pi_5 = t_e/t_o$		Extinguishment response
$\pi_6 = \dfrac{t_o \dot{P}_r}{P_w}$		
$\pi_7 = \dfrac{\rho \ell^2}{P_w t_o^2}$		
$\pi_8 = V/\ell^3$		
$\pi_9 = \dfrac{t_o^2 H}{\ell^2}$		Fire intensity response
$\pi_{10} = \dfrac{\Delta}{\Theta_o}$		Temperature ratio

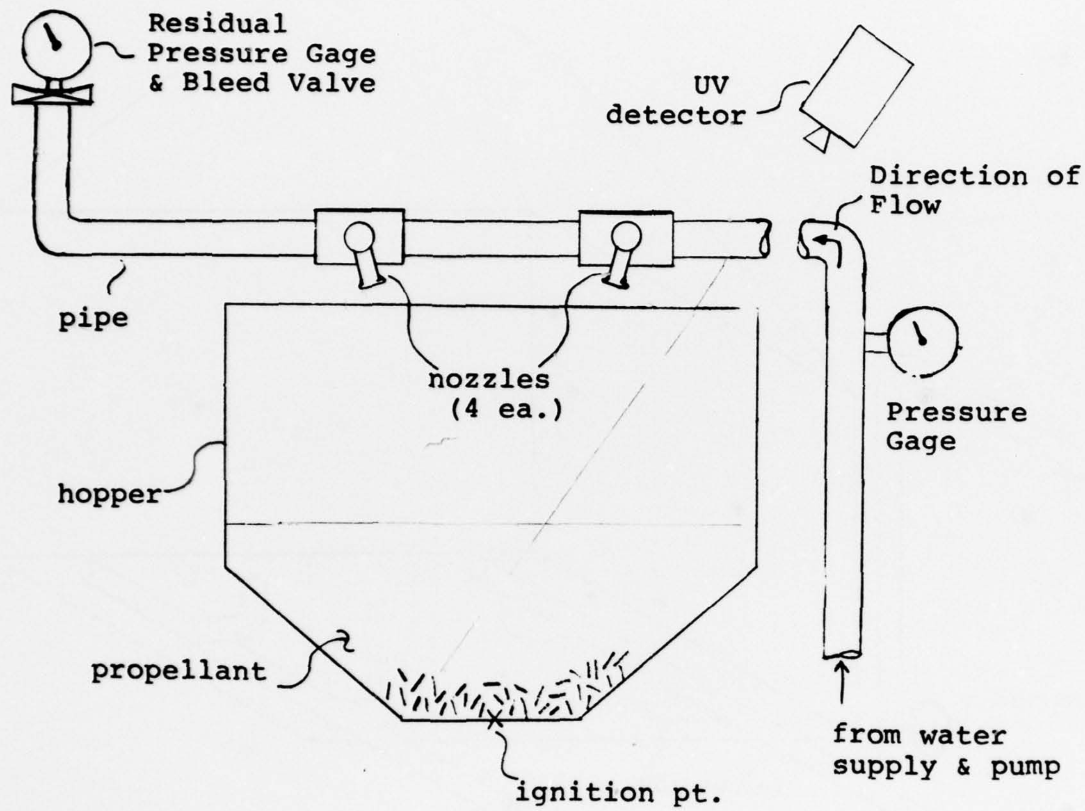

Figure 1.   Water deluge system for propellant hopper.

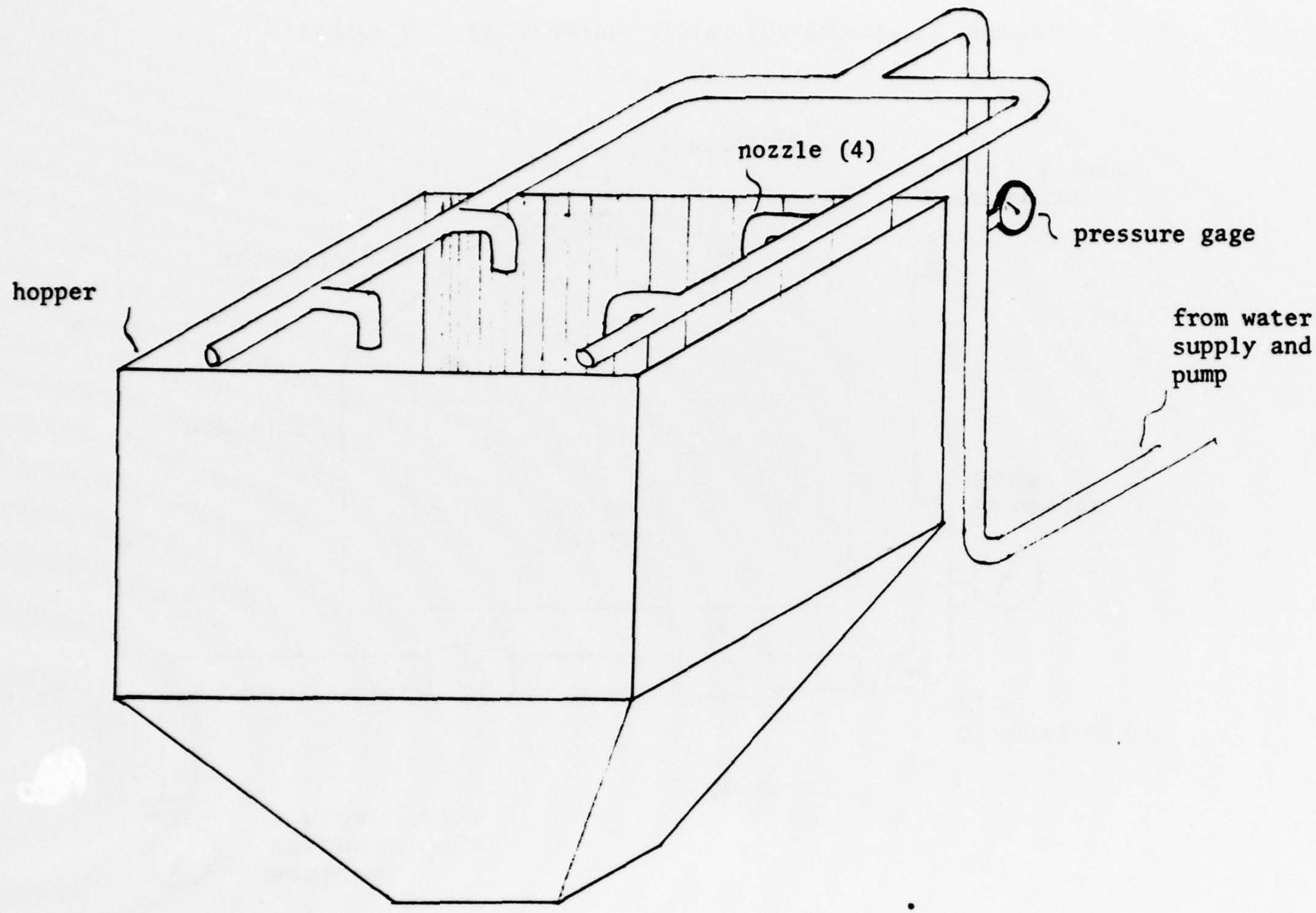

Figure 2. Schematic of hopper deluge system.

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