Progress on "Possible instability removal in LRSAM class systems"

- Summary of progress reported in April 2012
- Some crucial analysis of instability data.
- T-burner data relevant? Useful?
- Understanding depressurization in this context.
- Aspects of steady burn behavior not recognized
- Can we simulate the instability
- Suggested way forward

DRDL, February 10, 2013

Varun Sivakumar, H. S. Mukunda,

IISc, Bangalore

Analysis of DRDL-HEMRL tests made till now - 1

- A total of 32 tests (brought to our attention)
- Data for 27 tests made available
- 16 steady runs over 7 propellant compositions at conditioned temperatures (-30, +25, +58, +70 °C) and three throat diameters (nominal, +5%, +10%)
- 11 instability-ridden runs (3C1, C2, 2C4, C6, 2C7, C8, C1b)
- **The instability behavior is statistically too significant to be ignored.**

Questions we posed then –

1. Is the steady behavior experimentally reproducible?
2. Is the steady behavior computationally captured (initial temp effects, etc)
3. Are there patterns of instability beyond propellant variations?
4. Can we solve the instability problem without driving the *propellant designers* crazy?

P1 Composition history (from DRDL presentation)

Composition	% Al	% RDX	% $ZrSiO_4$	Avg. size of Coarse AP	% ZrC	Remarks
C1	1	2.6	0.5	Std. 300 µm of HEMRL	---	Original composition
C2	1	6	1	250 µm	---	RDX increased to reduce burn rate. $ZrSiO_4$ increased to provide greater damping. Coarse AP size reduced to reduce the pressure coupled response.
C3	4	6	---	250 µm	---	Al increased to improve energetics and was expected to provide particle damping. Hence $ZrSiO_4$ was removed.
C4	4	6	0.5	250 µm	---	$ZrSiO_4$ was added back as low amplitude pressure oscillations were observed with composition 3 test.
C5	4	10	---	250 µm	1	Proposed but based on Prof. Mukunda committee recommendations not implemented due to increased RDX
C6	4	6	---	>300µm removed	1	$ZrSiO_4$ replaced by ZrC. RDX as in C4
C7	4	2.6	---	>300µm removed	0.5	$ZrSiO_4$ replaced by ZrC. RDX as in C1
C-1b	4	2.6	---	Std. 300 µm of HEMRL	0.5	RDX percentage and AP particle size same as in C1
C8	8	2.6	---	Std. 300 µm of HEMRL	0.5	Al increased to 8%

LRSAM propellant Composition and burn rate data

CH. NO.	FIRING Ref	n-value (strand)	n-value n-BEM	$ZrSiO_4$%, $SrCO_3$%	AP, C µm, %	AP, F, µm, %	Al %	RDX %	Type of BEM
2283	15460	0.29	---	0.5 ,0.5	300 µ -47.7,	80 µ -31.8	1	2.6	
2365	15705	0.25	---	0.5 ,0.6	300 µ -50.0	80 µ -29.4	1	2.6	C1, Bare
2453	16069	0.27	---	0.5 ,0.6	300 µ -63	80 µ -37	1	2.6	C1, Bare
2453	16068	0.27	---	0.5 ,0.6	same				C1, Bare
2483	16163	0.27	---	0.5 ,0.6	same				C1, Bare
2504	16218	0.27	0.243	0.5 ,0.6	same				C1, Case bonded
2504	16214	0.27	0.243	0.5 ,0.6	same				C1, Case bonded
2504	16239	0.27	0.243	0.5 ,0.6	same				C1, Bare
2504	16224	0.27	0.243	0.5 ,0.6	same				C1, Case bonded
2532	16286	0.27	0.27	1.0 ,0.6	300 µ M -55	80 µ -21	1	6	C2, Bare
2532	16287	0.27	0.27	1.0 ,0.6	300 µ M -55	80 µ -20.6	1	6	C2, Case bonded
2532	16284	0.27	0.27	1.0 ,0.6	same				C2, Case bonded
2532	16283	0.27	0.27	1.0 ,0.6	same				C2, Case bonded

RDX is always an ingredient - 2.6 – 6 %

LRSAM propellant Composition and burn rate data

Ch. no	Firing ref	n(strand)	n - BEM	ZiSul, ZrSiCor	AP coarse	AP fine	Al	RDX	
2538	16366	0.215	0.218	Nil, 0.6	Mod -300 µ -55.5%	80 µ , 18.1%	4%	6%	C3, Bare
2538	16364	0.215	0.218	Nil, 0.6	mod-300 µ -55.5%,	80 µ , 18.1%	4%	6%	C3, Case bonded
2538	16365	0.215	0.218	Nil, 0.6	same				C3, Case bonded
2538	16363	0.215	0.218	Nil, 0.6	same				C3, Case bonded
2541	16405	0.178	0.126	1.0,0.6	mod-300 µ -55.5%,	80 µ , 20.6%	4%	6%	C3, Case bonded
2541	16404	0.178	0.126	1.0,0.6	same				C3, Case bonded
2541	16403	0.178	0.126	same	mod-300 µ -55%,	80 µ , 20.6%	4%	6%	C3, Case bonded
2541	16394	0.178	0.126	same	same				C3, bare
2541	16402	0.178	0.126	same	same				C3, bare
2557	16447	0.308	0.297	0.5 ,0.6	mod-300 µ -55%,	80 µ , 17.6%	4%	6%	C4, Case bonded
2557	16448	0.308	0.297	same	same				C4, Case bonded
2557	16449	0.308	0.297	same	same				C4, Case bonded
2557	16443	0.308	0.297	same	same				C4, bare
2571	16488	0.239	0.236	same	same				C4, bare
2571	16489	0.239	0.236	same	same				C4, bare
2571	16486	0.239	0.236	same	same				C4, Case bonded
2571	16487	0.239	0.236	same	same				C4, Case bonded
2571	16485	0.239	0.236	same	same				C4, Case bonded

RDX is always an ingredient at 6 %

The composition when used without RDX

1.	**AP (coarse)**	**53.28**
2.	**AP (fine)**	**23.20**
3.	**Al**	**4.00**
4.	**HTPB**	**12.00**
5.	**DOA**	**3.80**
6.	**Silicon carbonate**	**2.00**
7.	**TMLLLL (?)**	**0.87**
8.	**Zirconium silicate**	**0.50**
9.	**Ambiluk (?)**	**0.15**
10.	**Ti tanium dioxide**	**0.10**
11.	**Phenyl-β-naphthyl amine**	**0.10**

Commercial grade AP: > 500 µm -- 5% (maximum); 500 - 355 µm -- 28 ± 5%, 355 - 300 µm -- 32 ±5% , 300 - 45 µm -- 37 ± 5%, < 45 µm -- 1% (maximium)

The range 300 to 45 microns looks very wide. Can this be detailed?

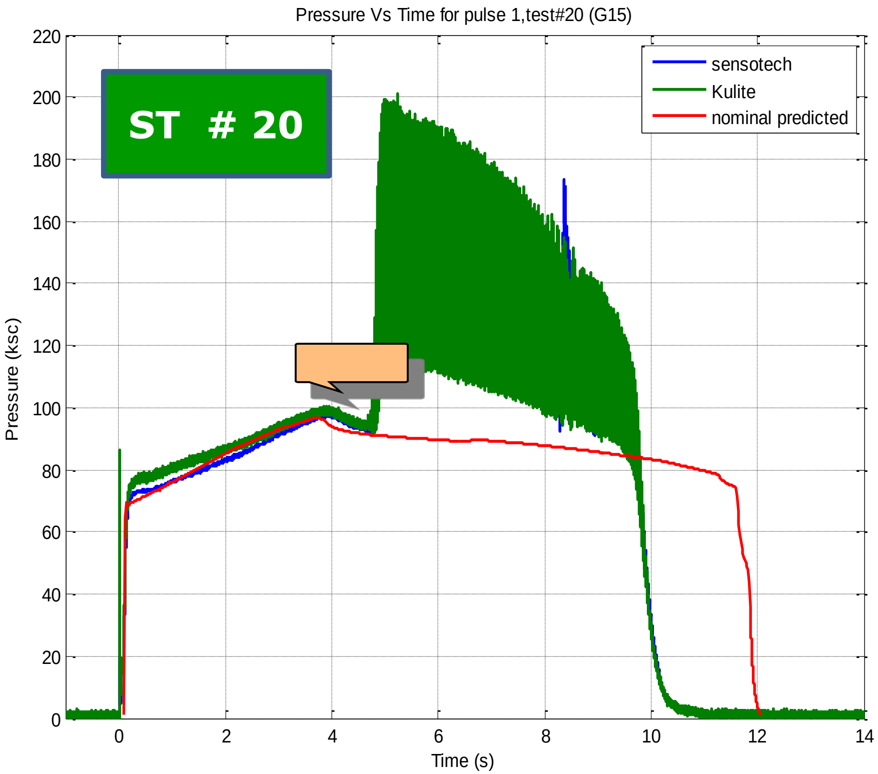
Analysis of stable mode DRDL-HEMRL tests

Prop	Test	Temp, °C, Throat dia	Burn time, s	Mean p_c, ksc	Temp sens, /K	Remarks
C1	ST2	+25	9.8	112	0.0012	
C1	ST3	+25	9.5	112	0.0017	Is -0.3 in tb OK?
C1	ST5	-30	11.0	90		
C1	ST8	+58,+10%	10.3	80		
C1	ST9	+58, +10%	10.4	80		
C1	ST10	+25, +10%	10.7	80		Pred: 10.6/10.3
C2	ST11	+58	10.0	105		
C2	ST13	+71	9.8	97		
C1	ST14	+25, +10%	10.8	75		Pred: 10.6/10.3
C3	ST15	+71	10.5	95		
C4	ST18	+71,	10.3	102		
C4	ST22	+71	10.8	75		
C7	ST25	+71	10.5	102		
C1	ST28	+25,+10%	10.5	85		Pred: 10.6/10.3
C1b	ST29	+71, 10%	10.8	85		
C6	ST31	-30,+10%	12.5	75		

Burn time ~ p_c^{-n} is used in simple estimates. What is required is rigorous matching with steady pressure – time data with true burning area representation.

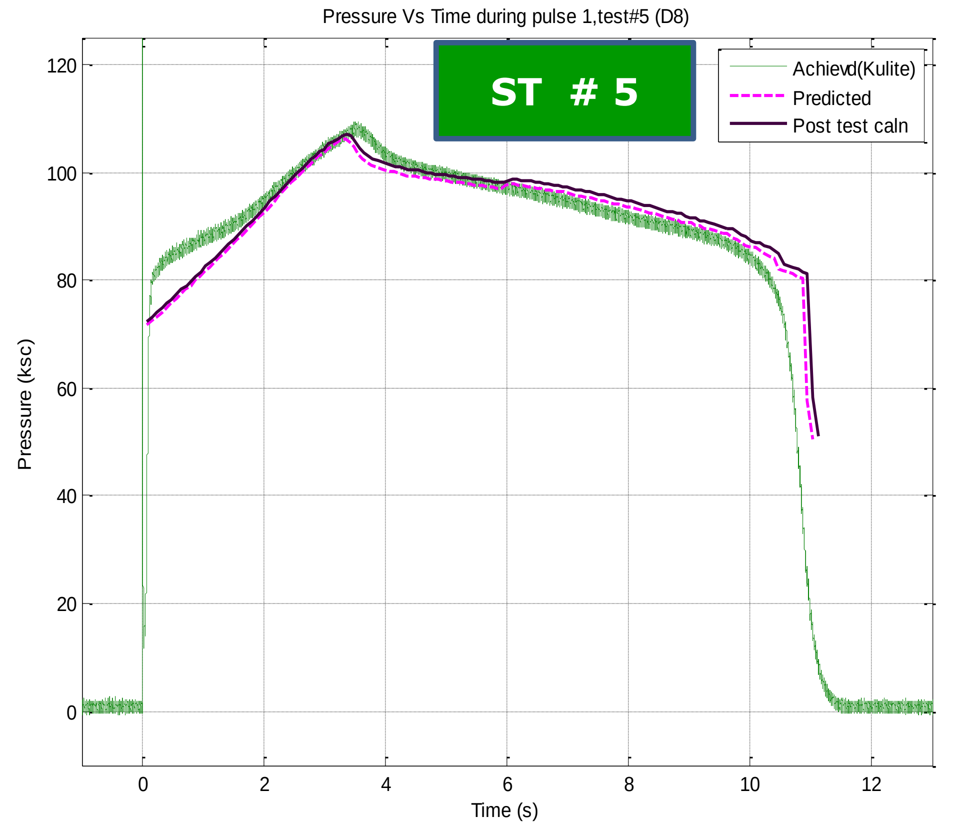
Instability mode DRDL-HEMRL results- 2

Test	Prop	Tempr °C	$P_{start,inst}$, ksc	$P_{mean.\ inst}$ ksc	Burn time, s	Burn rate enhancement
ST 06	C1	+58	115	140	8.5	1.04
ST 07	C1	+58	115	150	8.0	1.04
ST 17	C2	-30	104			Strange
ST 20	C4	-30	95	130	10.0	
ST 21	C4	+20	100	120	9.3	
ST 23	C1	+70	110	130	9.1	
ST 24	C6	-30	92	120	10.5	
ST 26	C7	-30	95	120	10.0	
ST 27	C7	-30	100	120	9.7	
ST 30	C8	+70	110	125	9.5	
ST 32	C1b	-30	75	90	11.5	



Intolerable instability
Composition, C4; T = -30C,
1 to 25 atm/ms

Tolerable instability,
Composition: C1; -20C, 1.3 atm/ms



Analysis of DRDL-HEMRL tests made till now

Propellant	AP, Prt size	Al	RDX	$ZrSiO_4$	ZrC	**Is there instability at T (C), Std = throat, +5 %, 10 % = +5%, +10% throat dia**							
						-25/-30C Std	-30C, +10%	+ 25C Std	+30, + 10	+58C Std	+58, +10%	+70C Std	+70C, +10, 5%
C1	300 µm	1	2.6	0.5	0	N*		N, N	N	**Y, Y, 3,4s**	N, N		**Y, 5, 5%**
C2	250 µm	1	6	1	0	**Y, 3.8s**				N		N	
C3	250 µm	4	6	0	0							N*	
C4	250 µm	4	6	0.5	0	**Y, 4.8 s**		Y,4.2s				N, N	
C5	250 µm	4	10	0	1	Tests not done							
C6	<300 µm	4	6	0	1	**Y, 5.8s**	N					N	
C7	<300 µm	4	2.6	0	0.5	**Y,6.5 , YR, 6s**						N*	
C1b	300 µm	4	2.6	0	0.5		**Y,7s**						N, 10%
C8	300 µm	8	2.6	0	0.5	**Y, 4.8 s**						**Y, 5.8s**	

- * Mild instability (tolerable).
- It appears low temperature triggers instability nearly always. **Why this is so needs study**. **Further, any tests and attempts to remove instability should concentrate on low temperature conditions first**.
- Aluminum, $ZrSiO_4$ or ZrC do not seem to offer any help. Literature indicates to such a possibility at these (low) frequencies ~ 250 Hz (see later). Add Al only to increase energy such that smoke problems do not occur. It cannot be depended on for instability removal.
- Perhaps, depending on the propellant to remove instability may not lead to any solution ….?
- **RDX seems to be responsible largely for low temperature instability! Avoid RDX?**

SUMMARY (from DRDL presentation)

Test no	Test condition (deg C)	Start time (s)	Pr. at CI start (ksc)	Dominant frequency (Hz)	DC shift	Amplitude	Web burnt at start of CI (mm)
S)T # 6 (C1)	+58	4.19	117	242	152	50	34
ST # 7 (C1)	+58	3	121.5	234	165	40	24.2
ST # 17 (C2)	-30	3.65	104	234	192	40	--
ST # 20 (C4)	-30	4.68	93	234	142	45	28.7

Comp	Al	RDX	$ZrSiO_4$	Coarse AP
C1	1	2.6	0.5	300
C2	1	6	1	250
C3	4	6	---	250
C4	4	6	0.5	250

Comment: DC –shift is an important inescapable feature. This is much unlike in liquid rocket or solid rocket with tangential instability

Critical questions to be answered

- Is the T-burner class characterization satisfactory? adequate?
- Is it indeed generally true to say the system is more prone to instability at lower temperatures? If so, why so?
- Why is there DC shift? It is not usually found in other forms of instability including liquid rocket engines.
- Is RDX responsible for instability? If so, any possible reasons?
- Can propellant be tailored to remove instability? Role of ZrC, Zr-Silicate, etc
- .....Really, what is really responsible for instability? (an important question after getting frustrated with earlier issues) or what is the connection between propellant steady burn behavior and instability?

On T-burners and their relevance – from Blomshield and others

- It is very important to remember that combustion stability in a rocket motor is a system dependent phenomenon – depends on factors such as pressure, geometry, structure, nozzle type.
- Normally linear stability evaluation is considered very valuable to make decisions. Pressure coupled response is a standard quantity (T-burner based largely).
- It is claimed that can be used to compare propellants destined for the same application. Once expected frequencies are known for a solid motor, the propellant with the lowest response will be less likely to drive instabilities, other factors remaining constant.
- *Another reason for obtaining the* response is that it is used by motor stability prediction program to compute the net driving by propellant combustion in a rocket motor.

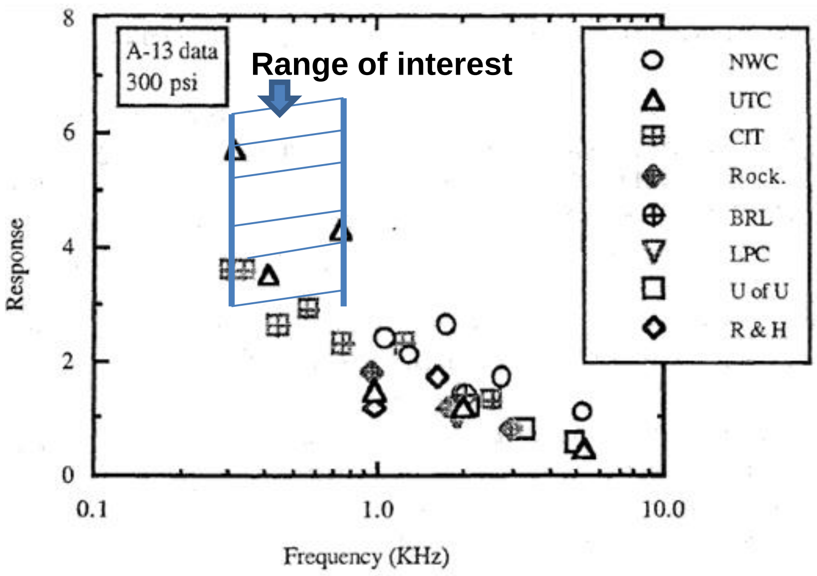
From Blomfied, Lessons learned and others

- At zero frequency R_{pc} is the exponent, n ($\dot{r} = a\, p_c^{\,n}$) and as frequency goes up so does the response to a maximum value of around 1.25 to 2.5 depending upon the propellant. The maximum value is attained at frequencies between 1 to 1.5 kHz

Most measurements of response factor are over a wide range of frequencies – up to 5 kHz.

The accuracy is understood to be not Too high - ± 25 % is considered OK.

The actual frequencies of interest to Longitudinal instability is between 200 to 800 Hz, because motor length in tactical motors used are L = a/(2 freq) = 1000/(400 to 1600) ~ between 0.6 and 2.5 m



Round Robin motor test results

No shorter length motor seems to have suffered longitudinal instability

From Blomfield and others – Response function

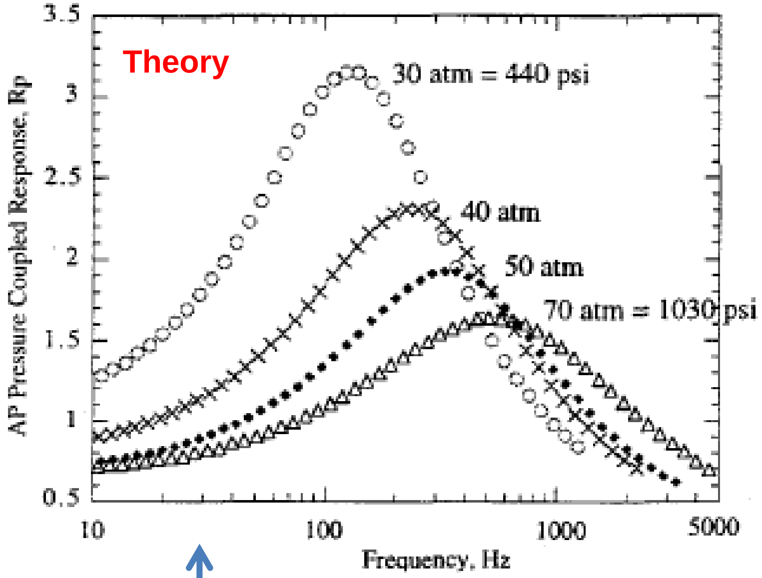
1. AP (84%)-HTPB, at 15 atm, R_p = 0.6 to 0.9 ± 0.2 pressure index, *n= 0.45*
2. AP (88%)-HTPB, at 34 atm, R_p = 0.4 to 0.7 ± 0.2 *n= 0.45*

1. AP pellets, at 34 atm, R_p = 2.0 to 1.5 ± 0.5 (decrease with frequency)
2. AP pellets, at 70 atm, R_p = 1.5 to 2.4 ± 0.5, *n = 0.77*
3. AP pellets, at 120 atm, R_p = 0.6 to 0.7 ± 0.5 (increase with frequency)

1. RDX pellets, at 34 atm, R_p = 0.8 to 1.2 ± 0.3 *n = 0.82*
2. RDX pellets, at 70 atm, R_p = 0.2 to 0.5 ± 0.1

1. HMX pellets, 10 to 70 atm, R_p = 1.2 to 1.5 ± 0.3 *n = 0.85*

Comment: The response function is expected to vary with pressure index.
This is not always true as at increased pressures, the results
do not show the appropriate trend. What more……..



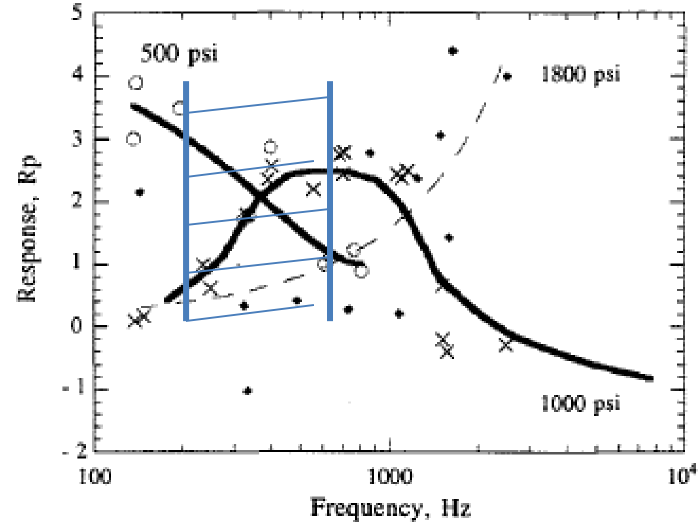
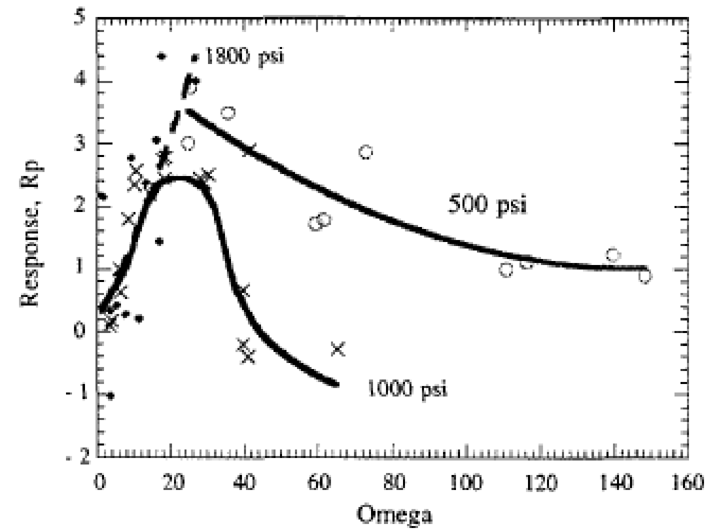


Figure 14. Pressure Coupled Response plot for UPAP pellets at 500, 1000, and 1800 psi.

Beckstead's predictions (AP) show that increased pressure implies reduced response.

In actual systems the behavior is contrary.

Many composite propellants (and double base propellants) have a pressure-coupled response evaluated by the T-burner have a response peak of 2 – 3 with an omega at around 7 (if you divide it by 2 π, this is about 1)



Omega = 2 pi (freq) α)/ṙ²

Figure 15. Pressure Coupled Response plot for AP pellets at 500, 1000, and 1800 psi plotted vs. Omega.

From Finlenson, Stalnaker and Blomshield, Ultra pure AP T-burner pressure coupled Response at 500, 1000 and 1800 psi AIAA 1998 – 3545, 34th AIAA Joint Prop conf.

Other statements of Blomfield

- If one increases burning rate with catalysts, propellant combustion response will tend to go down. (……every catalyst? not clear)
- Higher pressure exponents imply larger instability. Desirable to seek low *n* propellants.
- If one increases burning rate with fine AP, propellant combustion response will tend to go up.
- Very fine or very coarse AP is not good from a combustion instability point of view. These effects can be explained by the following -

  for very fine AP crystals burning in a fuel binder, chemical reaction processes are kinetically controlled and have a relatively high reaction order.

  for very large AP crystals, combustion is controlled by an AP mono-propellant flame which also has a high reaction order.

  in-between the extremes of particle size, combustion processes are believed to be controlled by more diffusional effects which are not as sensitive to pressure oscillations

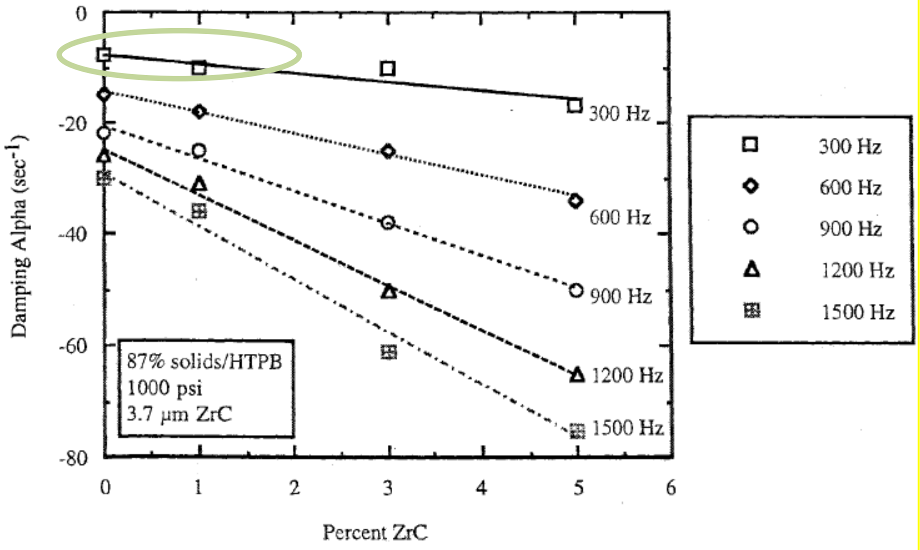
Comment: Many of these statements could be correct, but experience suggests that following them without considering other basic features does not help.

From the thesis of Perry, Cal Tech, 1971

Propellant	A-13	T-17	540-A	A-35
Binder/Oxidizer	PBAN[1]/AP[2]	PS[3]/AP	PPG[4]/AP	PU[5]/AP
Specific Heats Ratio, γ	1.28	1.25	1.22	1.25
Density (gm/cm^3)	1.56	1.58	1.63	1.58
Burning Rate at 300 psig (cm/s)	0.48	0.78	0.50	0.46
Burning Rate Exponent at 300 psig	0.42	0.38	0.15	0.0
Flame Temperature at 300 psig (°K)	2100	2050	2900	2160

……….The fact that the present T-burner investigations found 540 – A to be far from stable In this pressure range indicates again the lack of a thorough understanding of combustion instability in solid propellants………. The situation is not very from this even now!

Some additive effects



igure 10. Measured damping showing the linear effect of ZrC concentration.

From: Stability of full scale testing of tactical motors, Bloomshield, Crump , Mathes, and Beckstead, AIAA paper 1991-1954

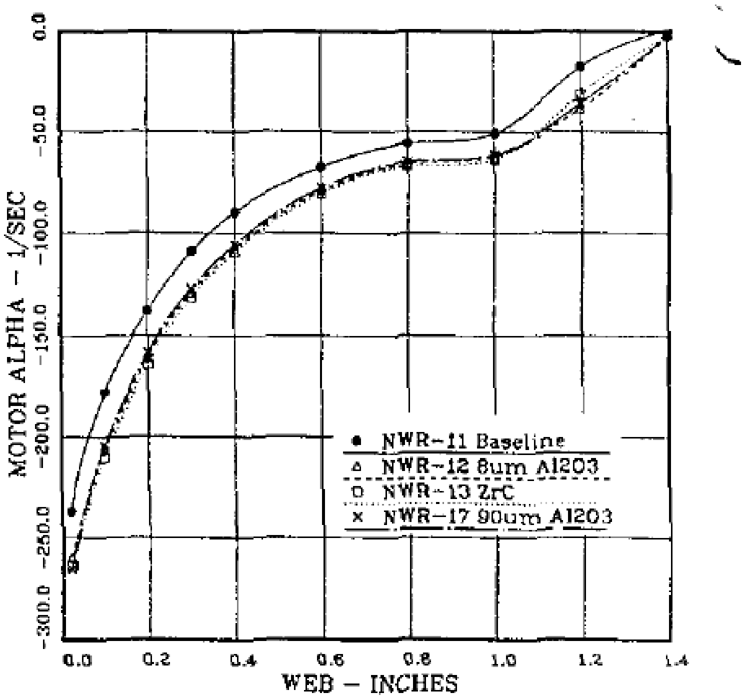


Figure 13. Stability Predictions for Star Aft 300 Hz Motors with Additives at 1000 psi

Note that inclusion of ZrC or Al_2O_3 makes little impact on instability at these frquencies.

For 250 Hz, depending on the particle density, 12 to 25 μm size is predicted. One has performance loss with this size of particles. Smaller particles do not provide damping at the required frequencies

$$D = \sqrt{\frac{18\mu}{\omega\rho_p}}$$

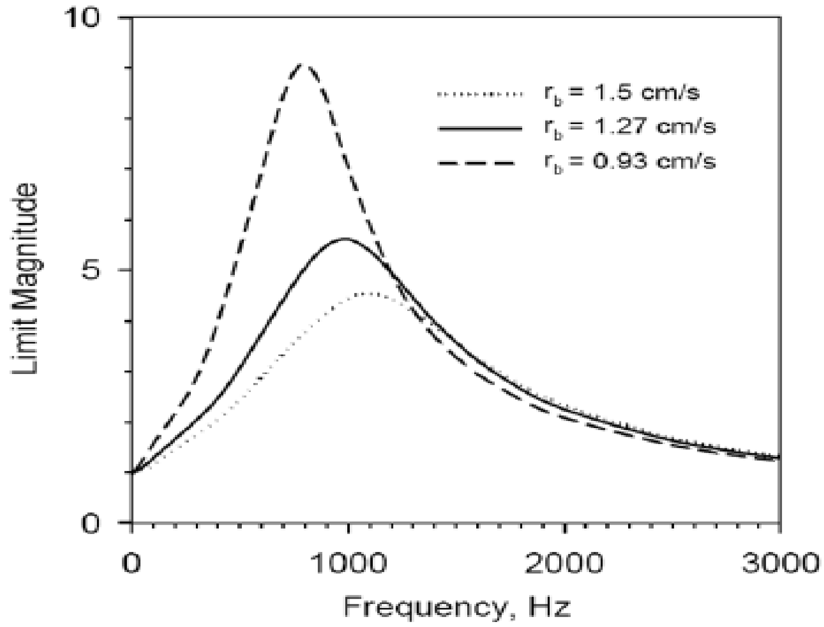
Low temperature sensitivity

Lower temperatures like – 30ºC as different from + 25ºC or + 70ºC imply higher heat absorption by the c-phase. More importantly, the c-phase thickness is larger. Larger the amount stored in the c-phase greater – does it imply larger (but not fast) responsiveness of the c-phase and tendency towards instability?

Lower temperature implies lower burn rate. Modeling studies indicate greater tendency towards instability

Figure illustrates the effect of changing the base burning rate, whereby a lower base rate increases the propellant's transient response, and lowers the resonant frequency thereof. **The burn rate range is large, though.**

From Greatrix: Scale effects of combustion instability behavior. open access Journal www.mdpi.com/journal/energies, ***energies,*** **ISSN 1996-1073**



On DC shift…from Flandro+

Flandro has been very concerned about DC shift and written several papers on the subject. In AIAA 2005 – 3998 (with French)….The main purpose of this exercise was not to match the pressure trace exactly, but to demonstrate that the main features of the DC shift and the limit cycle amplitude have the same general shape….

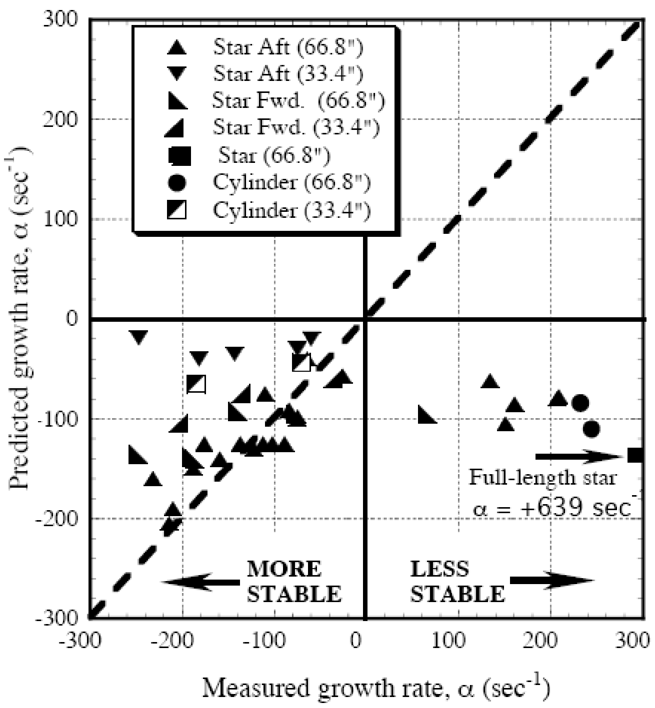


Fig. 4 Measured vs. theoretical growth rates.[36]

[36]Blomshield, F. S., "Stability Testing and Pulsing of Full Scale Tactical Motors, Parts I and II," Naval Air Warfare Center, NAWCWPNS TP 8060, February 1996.

From Flandro, Fischbach abd Majdalani, AIAA 2004 – 4054

…..A pivotal missing element is the ability to predict the mean pressure shift; clearly, the designer requires information regarding the maximum chamber pressure that might be experienced during motor operation. In this paper, a comprehensive nonlinear combustion instability model is described that supplies vital information. The central role played by steep-fronted waves is emphasized. The resulting algorithm provides both detailed physical models of nonlinear instability phenomena and the critically needed predictive capability. In particular, the true origin of the DC shift is revealed…….

Further…. From Flandro, J. Phys. Fluids, 2007

Since a central concern is the handling of steep fronted waves, it is necessary to carefully lay out a solution technique that will lead to a practical predictive algorithm.

To make the mathematical problem tractable, we choose to avoid fashionable numerical strategies such as the method of characteristics or a full computational fluid dynamics CFD treatment of the problem. Either of these techniques would likely fail in the problem we are attempting to solve here.

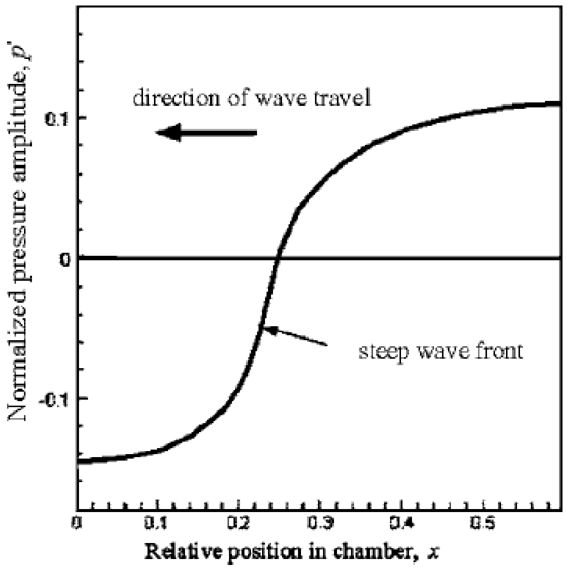


FIG. 5. Culick's fully steepened wave.

What is required is an approach that bridges the gap between the earlier perturbation techniques that limit the solutions to linear gas motions and other *ad hoc methods such* as those introduced by Culick to study nonlinear features of combustion instability.[17,24] Figure 5 displays a frame from an animation of the development of the wave system with time predicted by Culick's model…. Energy from the lower order modes has cascaded to the higher modes until the stationary state shown in the figure has been reached.

Comment: **The ideas of steep fronted waves demands that the pressure wave at both ends of the spatial domain should have a difference of 25 atm (± 0.25 of *p'*).**

In the case of LRSAM where the difference in pressures between the head end and the aft end is no more than ~ 2 atm.

Hence this direction of thinking to explain DC shift appears to us incorrect. *We need to have a very different explanation* . The solution lies in unsteady dynamics to which US science has also contributed – but less fashionable ones – earlier Princeton group and others.

Experience drawn from actual rocket motor development

Project	**Propellant**	**f, Hz**	**Solution**
Manpads	88 SL (18Al) – bi-modal AP, HTPB	700	Al to 16 %, **tri-modal AP**, 86 SL, Stable -40 ºC to +45 ºC, exact mechanism of instability unclear
AALM	AP-HTPB	370	Higher ZrC improved the linearly stable motor; **acceptable**
SLUFAE	AP-HTPB – 12 μm $A1_2O_3$	1500	A softball sized Helmholtz resonator was added to the forward end of the motor
MK-36 Side-winder	AP-HTPB	330	Change - the ratio of the burning area upstream of axial pressure node to that on the aft-end remains relatively constant and near unity throughout the motor operation. Also some AP to RDX
AGM-88	AP-HTPB	250	Minor oscillations present throughout **and tolerated**
EX-70	AP-HTPB		Used finer AP to increase ṙ and increased nozzle throat size to maintain the thrust time trace. This reduced pr-coupled response. Increased nozzle throat size implied increased port flow speed reducing the velocity-coupled response and increased nozzle damping. SSP code combined with ballistic analysis helped this.
ASROC	AP-HTPB	270	All test motors exhibited small oscillatory pressures between 1.5 and 3.0 seconds. **Accepted as it were**.

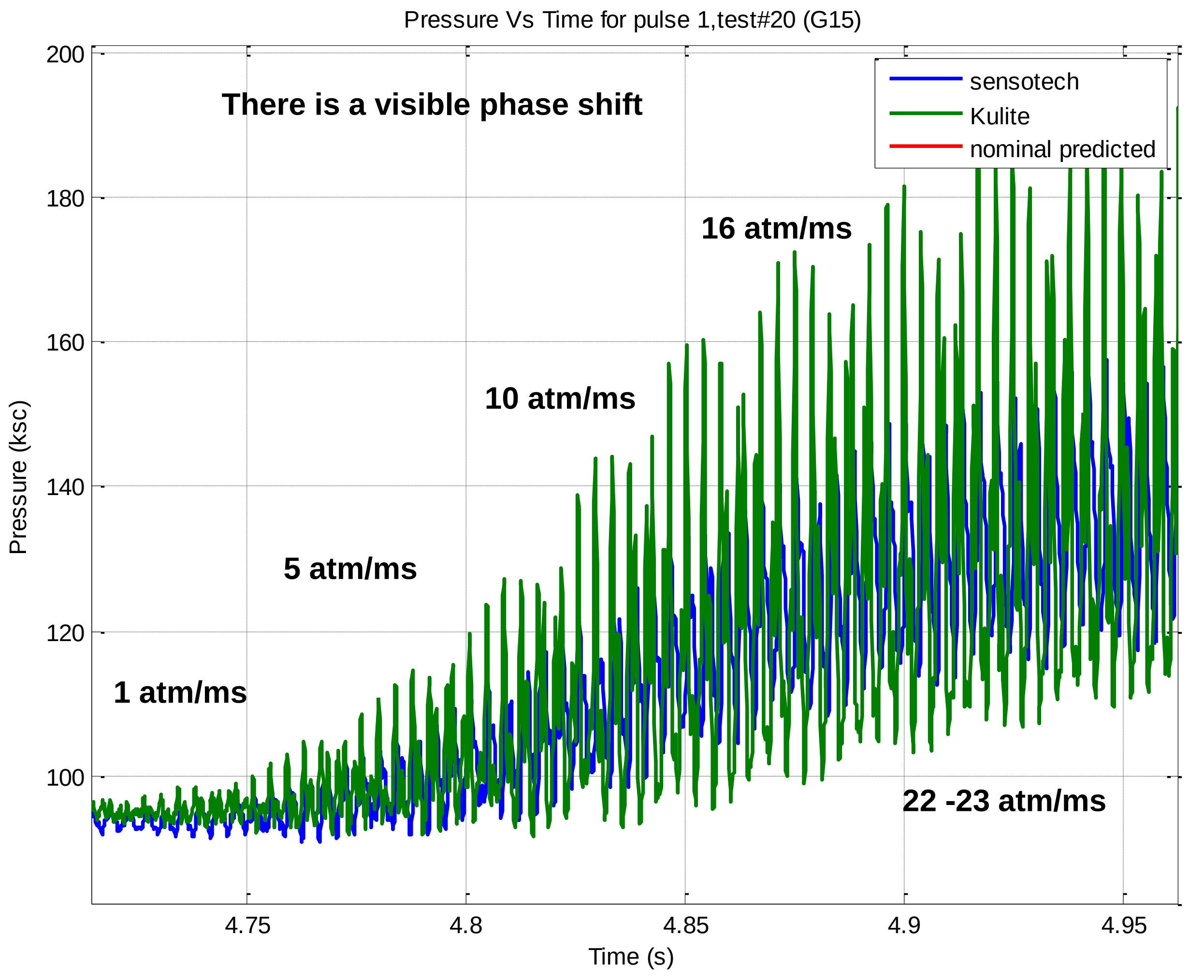
From Blomshield, AIAA – 2001-3875, historical perspective of combustion instability in solid motors – case studies

A different approach to instability study

1. We pose a question as to what can be learnt or extracted from the pressure time curve with full instability.
2. Classical arguments about things being non-linear sometimes draw away the thinking to areas like multi-mode coupling and other aspects that have been pursued (perhaps somewhat obsessively).
3. We ask using a simple minded argument to start with: treat the unsteady 1-d mass flow equation for the rocket and flip the equation to determine the burn rate that satisfies the unsteady mass balance. Examine if this burn rate dependence goes beyond the steady Vielle's law – if so in what direction and how much?

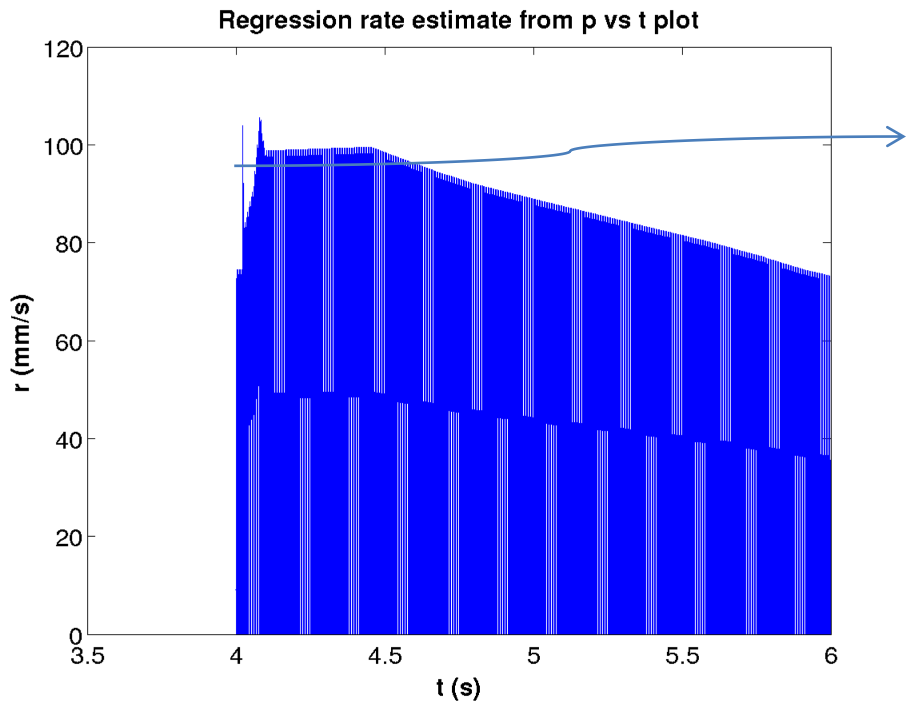
$$\frac{\mathcal{V}_c}{RT_c}\frac{dp_c}{dt} = \rho_p A_b a p_c^n - \frac{p_c A_t}{c^*}$$

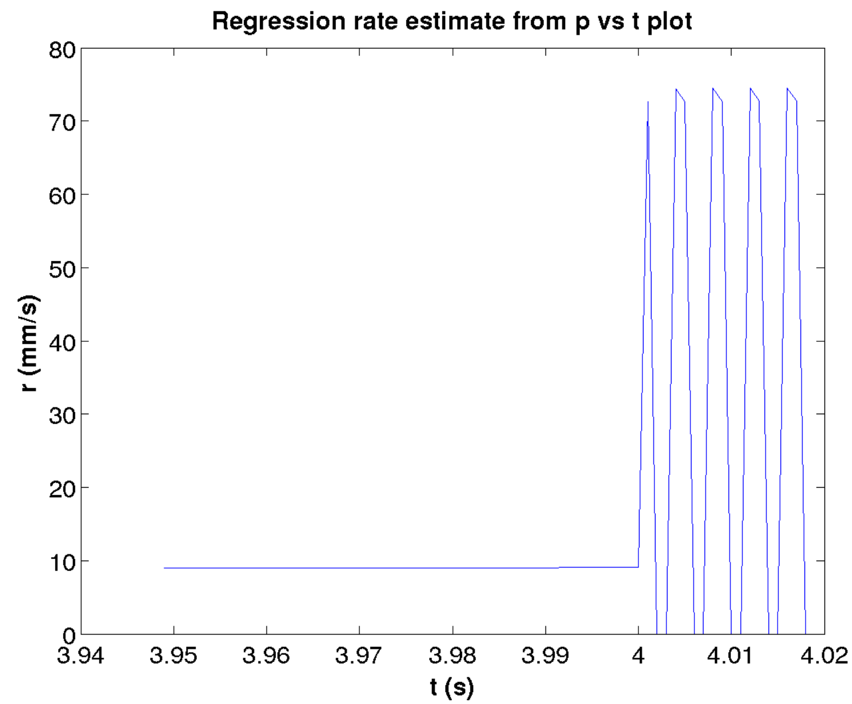
4. In the above mass balance equation, we need to rethink the burn rate expression $\dot{r} = ap_c^n$ as will be seen later.



p_c moves from 95 to 200 atm in about 16 ms implying a mean pressurization rate of 6.5 atm/ms. However, pressurization and depressurization rates change from 6 atm/ms to as high as 25 atm/ms. We should note that when depressurization rates exceed 3 to 10 atm/ms, extinction of propellant burn occurs for most composite propellants as data from other work shows….

Max depressurization rate = 2π (atm/ms) ~ 120 atm/ms for about 100 micro seconds
This is because of sinusoidal pressure variation that has the max. slope near the pressure node





ρ_p = 1680 kg/m^3 , c* = 1590 m/s, d_t = 45.5 to 47.3 mm (A_t = 16.2 to 17.6 cm^2)

$\dot{m} = p_c A_t/c^*$ gives at 4.0 s (p_c = 95 atm, $\dot{r}$ = 7.2 mm/s), $\dot{m}$ = 9.85 kg/s.

At peak p_c = 200 atm, $\dot{m}$ = 20.7 kg/s.

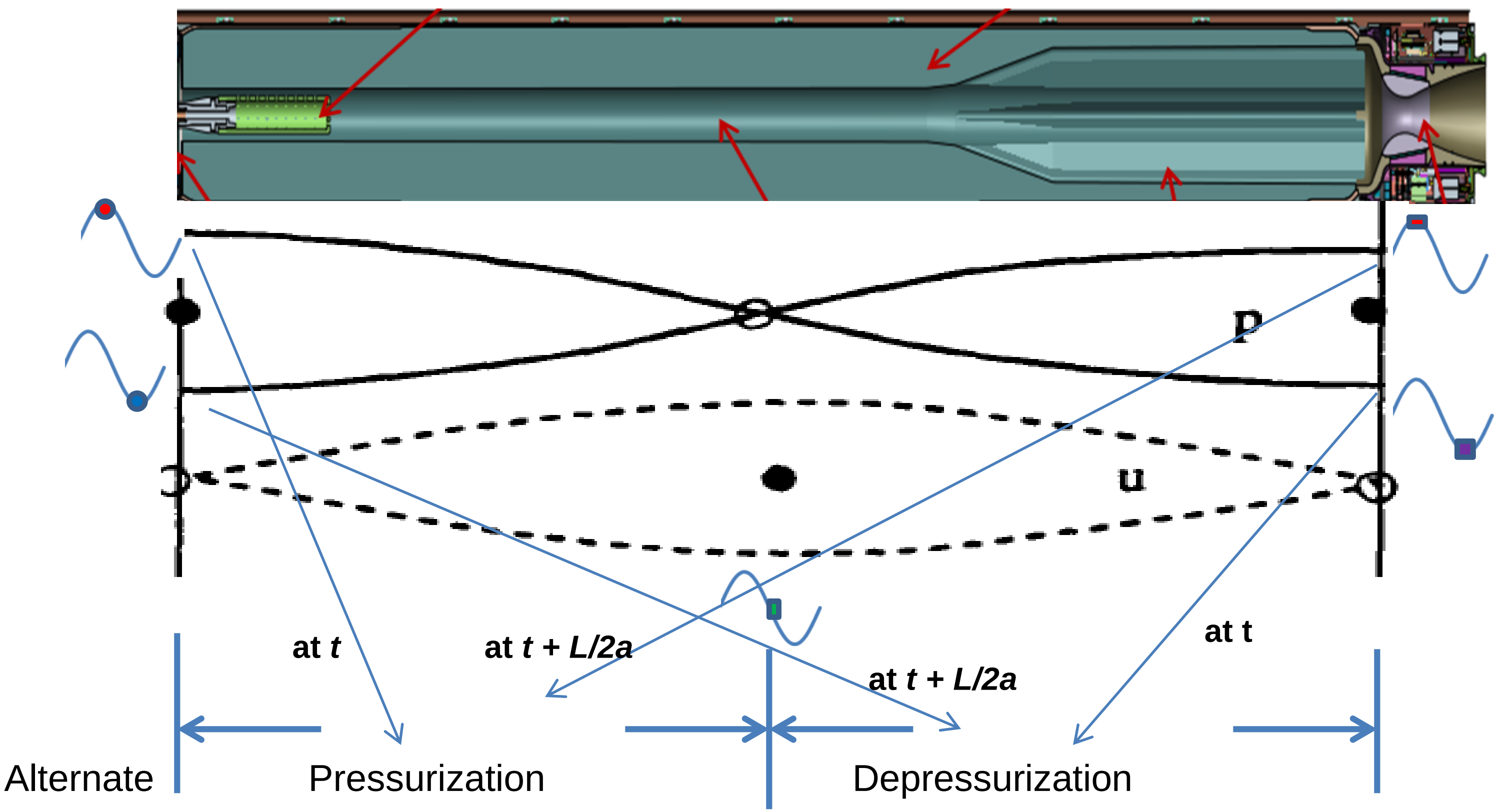
This change that occurs in in 60 ms requires for the same burning area, the burn rate changes from of 7.2 mm/s to 20.7/(1680*0.81) = 0.015 m/s or 15 mm/s.

$$\frac{V_c}{RT_c}\frac{dp_c}{dt} = \rho_p A_b \dot{r} - \frac{p_c A_t}{c^*}$$

$$\dot{r} = [\frac{V_c}{RT_c}\frac{dp_c}{dt} + \frac{p_c A_t}{c^*}]/\rho_p A_b$$

= [2 to120 + 9 to 20] / 1380 = 0.008 to 0.101 m/s = 8 to 101 mm/s !

How does combustion process occur in a radial burning grain during instability?



Reminds of

The role of acoustics is essentially limited to set the pressurization and depressurization cycles. The pressure variations affect the gas phase flux and control the burn behavior of the propellant. The sharp pressurization and depressurization aspects cause the high burn rates much beyond steady burn rates.

This is the crucial new finding. **Further…..**

So, What is our thinking?

- It is known that there are always acoustic fluctuations modulated by turbulence in the fluid flow damped by the nozzle.
- It is known that the burn rate of every propellant is amplified when subject to oscillatory acoustic flow field.
- It is known that gas phase fluctuations adjust themselves to acoustics nearly instantaneously, but solid phase processes are slow.
- Processes like depressurization have been modeled with the above thinking successfully.
- Pressurization after depressurization leads to high burn rates (~100 mm/s)
- Pressurization-depressurization behavior is coupled to acoustics that happens to be simply a driver of the pressure waves with little difference in pressures between head and aft ends.
- That the issue lies in propellant combustion more seriously than casually alluded to is a feature that seems to have bypassed all thinkers till now.
- This is the basis of our thinking. New thinking has adversaries and needs firm back-up of various kinds – earlier thinking, new modeling, etc…..

On depressurization data and binder effects

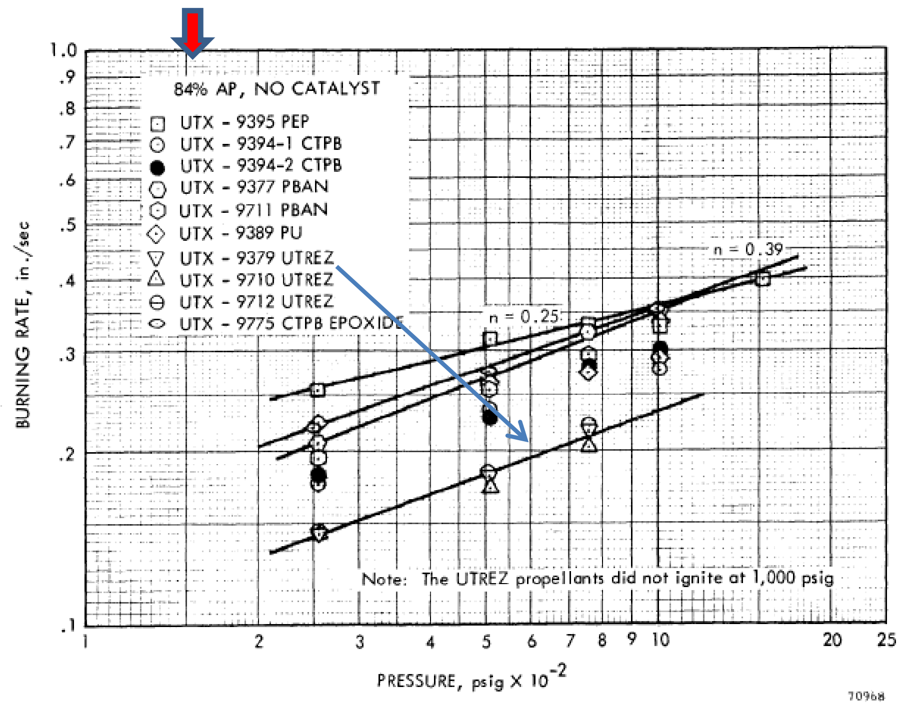


Figure 6. Strand Burning Rates of Nonaluminized Propellants

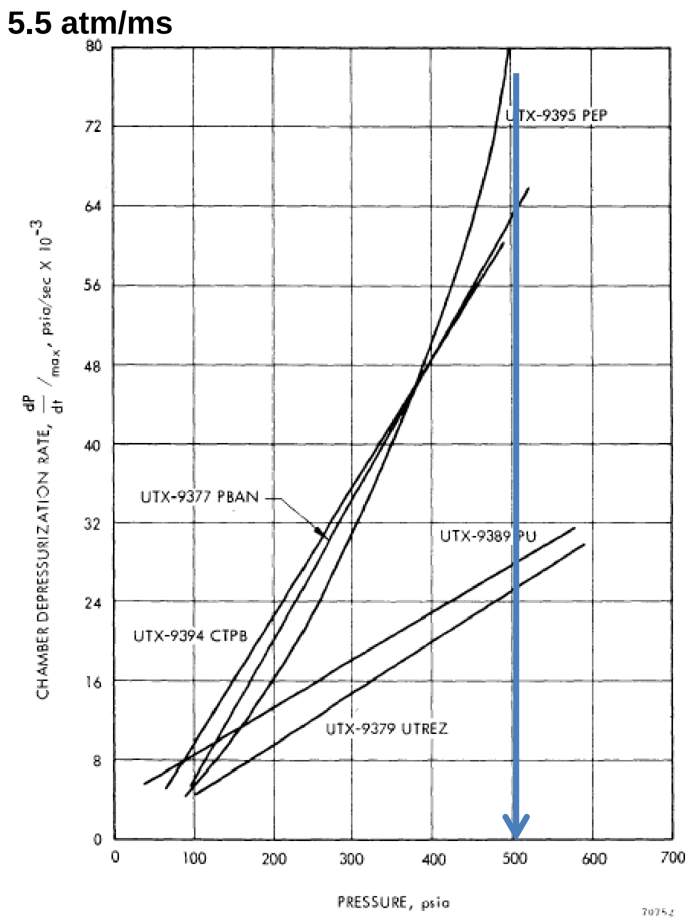


Figure 13. Comparison of Critical Depressurization Limit Lines as a Function of Binder System — 84% AP

Propellants containing CTPB, PBAN, and PEP binders were the most difficult to terminate and had similar termination characteristics (-60 *000 psi/sec at 500 psia – 4 atm/ms at 34 atm).*

PIB were found to be much easier to terminate (-26 *000 psi/sec at 500 psia – 1.8 atm/ms at 34 atm).*

The critical depressurization rate for termination was found to be related to the thermal and oxidative degradation features of the binder polymer. Those propellants exhibiting greater susceptibility to oxidative degradation of the binder (CTPB and PBAN) were more difficult to terminate than the more easily thermally-degraded propellants (PIB and PU).

Comment: HTPB which is not different from CTPB in these aspects behaves similarly. However, the introduction of other ingredients can affect this behavior. Is the liquid layer extensively found in PU propellants a cause for lowering the extinction pressure decay rate?

Results on de-pressurization by UTC for a range of propellants

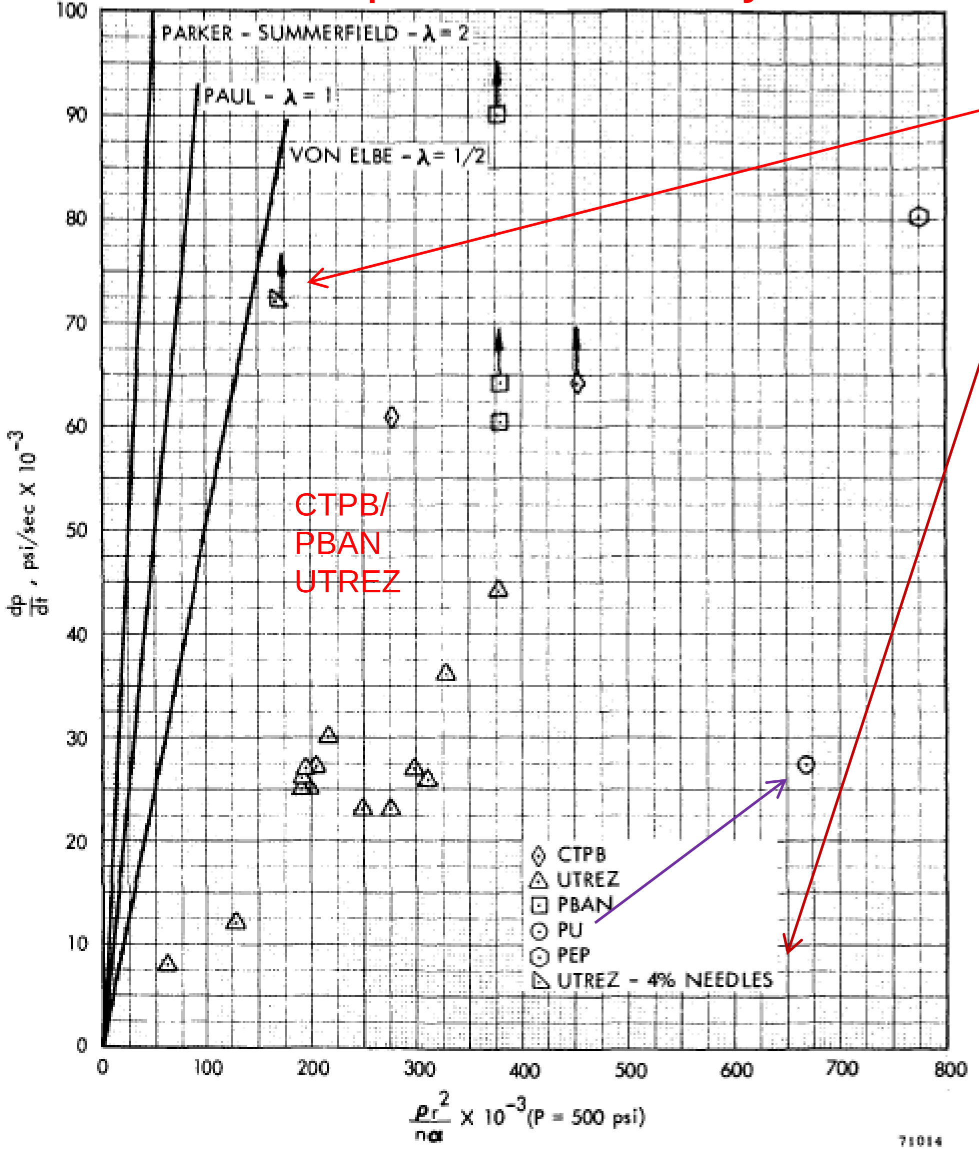


Figure 46. Predicted Termination Requirement vs Experimental Results (500 psi)

Increased thermal diffusivity seems to increase the $dp/dt]_{crit}$ substantially.

Support in fragments from earlier work - 1

From Williams, Barrere, Huang – Fundamentals of Solid Propellant Rockets, AGARDograph 117

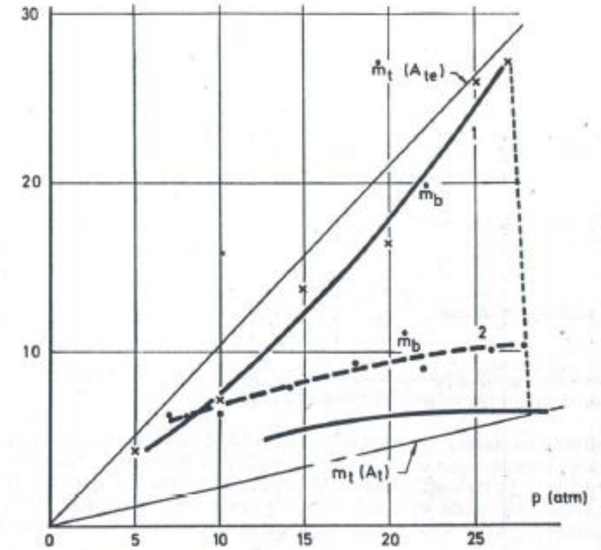


Fig. 8-48 Mass-flow-rate variation during the transient phase.

100 mm/s

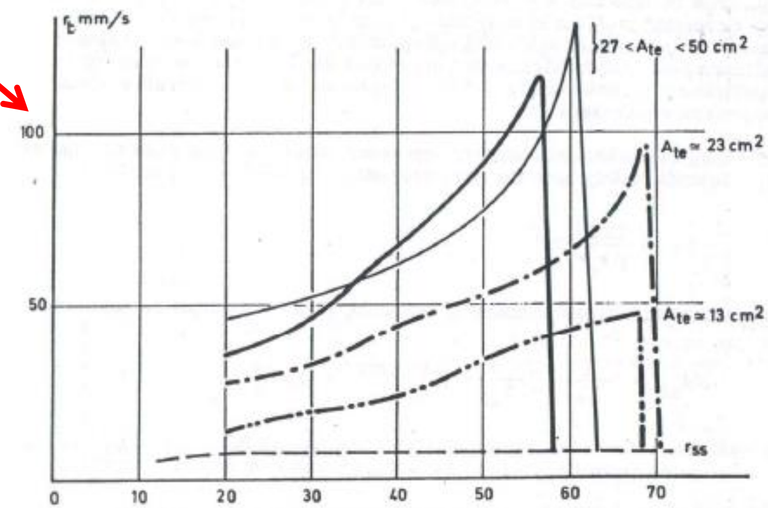


Fig. 8-49 Variation of burning rate with pressure during rapid depressurisation.

Note the kind of burn rates deduced during depressurization. We must have seen this diagram and left it aside…

Part support from earlier work - 2

$$\Theta_\tau + R\Theta_\eta - \Theta_{\eta\eta} = 0 \qquad (-\infty < \eta \leqslant 0) \qquad (1)$$

initial condition $\Theta(\eta, 0) =$ (1a)

boundary conditions $\begin{cases} \Theta(-\infty, \tau) = 0 & (1b) \\ \Theta_\eta(0, \tau) = & (1c) \end{cases}$

with $R = R(\Theta_s)$ (1d)

The gradient boundary condition in the Krier, et al., model is given by

$$\Theta_\eta(0,\tau) = RH + [P^{2n}\,(P^{n/m} - H)]/R \qquad (2)$$

where

$$R = \Theta_s{}^m \qquad (3)$$

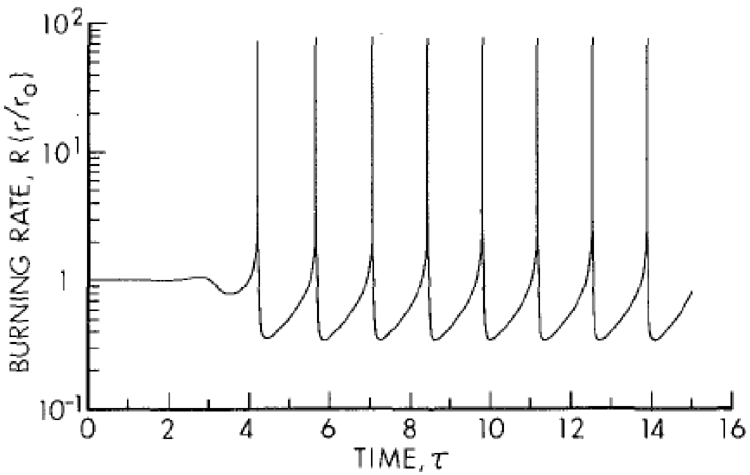


Fig. 5 **Response of Krier, et al.'s model to $P(\tau) \equiv 1$ when intrinsically unstable ($H = 0.88$, $n = 0.5$, $m = 6.0$)**

$$\tau = t(r_o{}^2/\alpha)$$

$$H = \overline{Q}_s/c_s\,(T_{s0} - T_\infty),\ [n - d]$$

From: Kooker and Nelson, Numerical solution of solid propellant transient conduction, Journal of Heat transfer, May 1979, v. 101, p 359

Thus, it appears that the result of very high unsteady burn rates can be captured by treating unsteady conduction

Relevant aspects of steady combustion yet to be recognized

- The role of binder melt and its effects on burn rate are discussed and not accounted for in the models. The role of the melt layer on unsteady combustion is discussed more sporadically in the literature. We need to understand the role of binder melt effects carefully beginning with steady burn behavior. Literature study is therefore important in many ways.

- The work of Fredrick (1988) on the steady combustion of widely separated particle size (400 and 25 μm, 400, 25 and 2 μm AP) – based propellants of high loading leads to an exaggerated impression of the role of the binder.

- One of the difficulties in taking into account the enormous data in literature is that many aspects are not fully described. Since propellant processing procedures can add to the woes of producing propellants with reproducible properties, and some authors do not even compare their results with those of earlier workers on important parameters and explain the differences if any, there is need to exclude some of them.

- The experiments by Steinz and Selzer as well as Strand on depressurization and T-burner are also on propellants with widely separated particle sizes (170 and 17 μm sized AP). Drawing firm conclusions from these data has to be done cautiously.

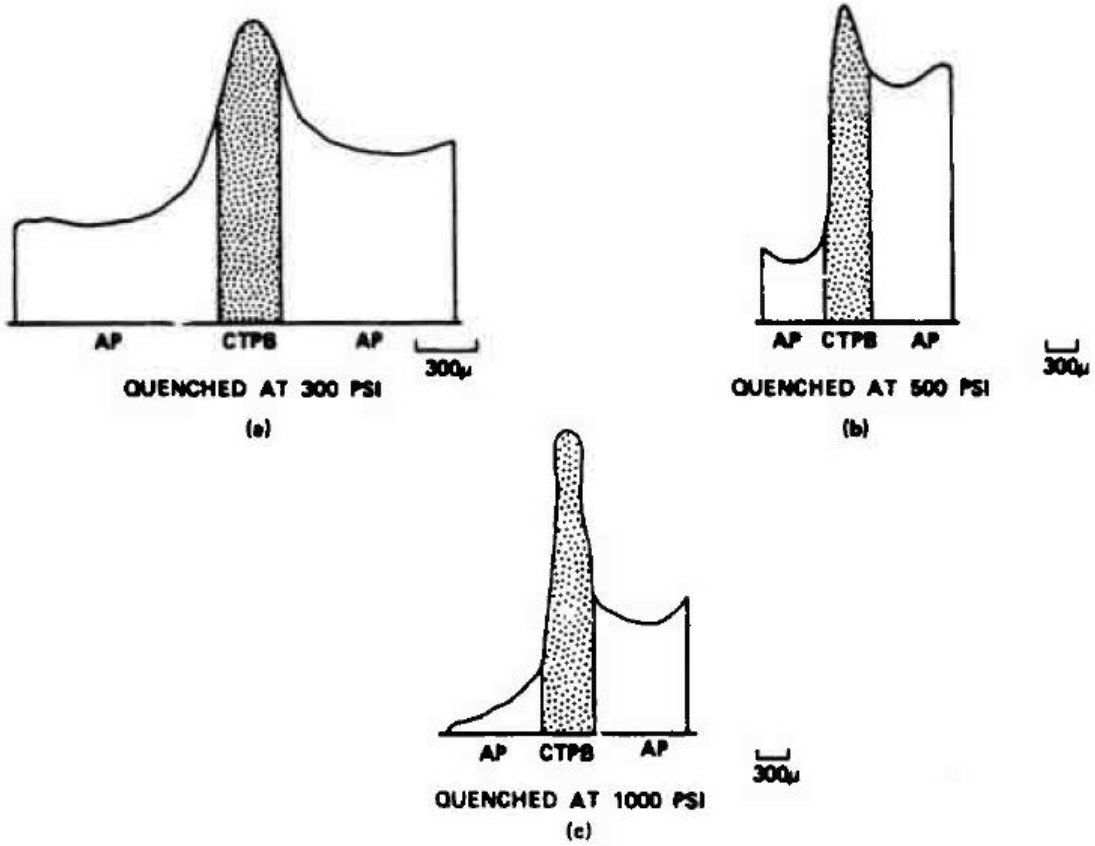


FIG. 2.12. Profile of CTPB Sandwiches Showing the Effects of Ambient Pressure.

Comment: A sandwich model study by Boggs has shown that liquid melt layers in CTPB –AP sandwich shows melt flow at 7 mm/s across the surface for a 4mm/s burn rate sandwich. How important this is for propellants and high energy propellants needs evaluation.

Fredrick's studies

Binder details

INGREDIENT	SERIES I % BINDER	SERIES II % BINDER
R-45M (HTPB)	66.3	59.9
IPDI	5.0	-
DDI	-	11.4
DOA	25.5	25.5
HX-752	1.2	1.2
Agerite White	2.0	2.0

AP size distribution

NOMINAL DIAMETER	$\bar{D}$ μ	σ	ANALYSIS
2	9†	1.60	suspension
16	20	1.80	suspension
25	21	1.60	suspension
400	400	1.10	SIEVE
400s*	355	1.05	SIEVE
600	614	1.10	SIEVE
SALT*	355	1.05	SIEVE

Propellant details

DESIGNATOR IPDI	DESIGNATOR DDI	OF_p	16 μ AP Wt%	400 μ AP Wt%	BINDER Wt%
G-I	G-II	4.0	52.0	35.0	13.0

Burn rate data

p_c, atm	GI (IPDI)	G2 (DDI)
17.0	5.00	3.40
34.0	7.00	4.40
68.0	11.10	5.20
134.0	16.00	7.50

Motion Picture results-87% Solids Propellants, 1000 psi, IPDI

OBSERVATION	$OF_p = 4.0$ G-I	$OF_p = 3.0$ H-I	$OF_p = 2.0$ J-I
$\dot{r}_{1000}$ (in/sec)	.36	.27	.31
flame cover	total	total	total
smoke	little	little	very little
surface roughness	±100μ	±150μ	±300μ
binder flow	10%	20%	15%
coarse particles	not ejected	not ejected	not ejected
comments			

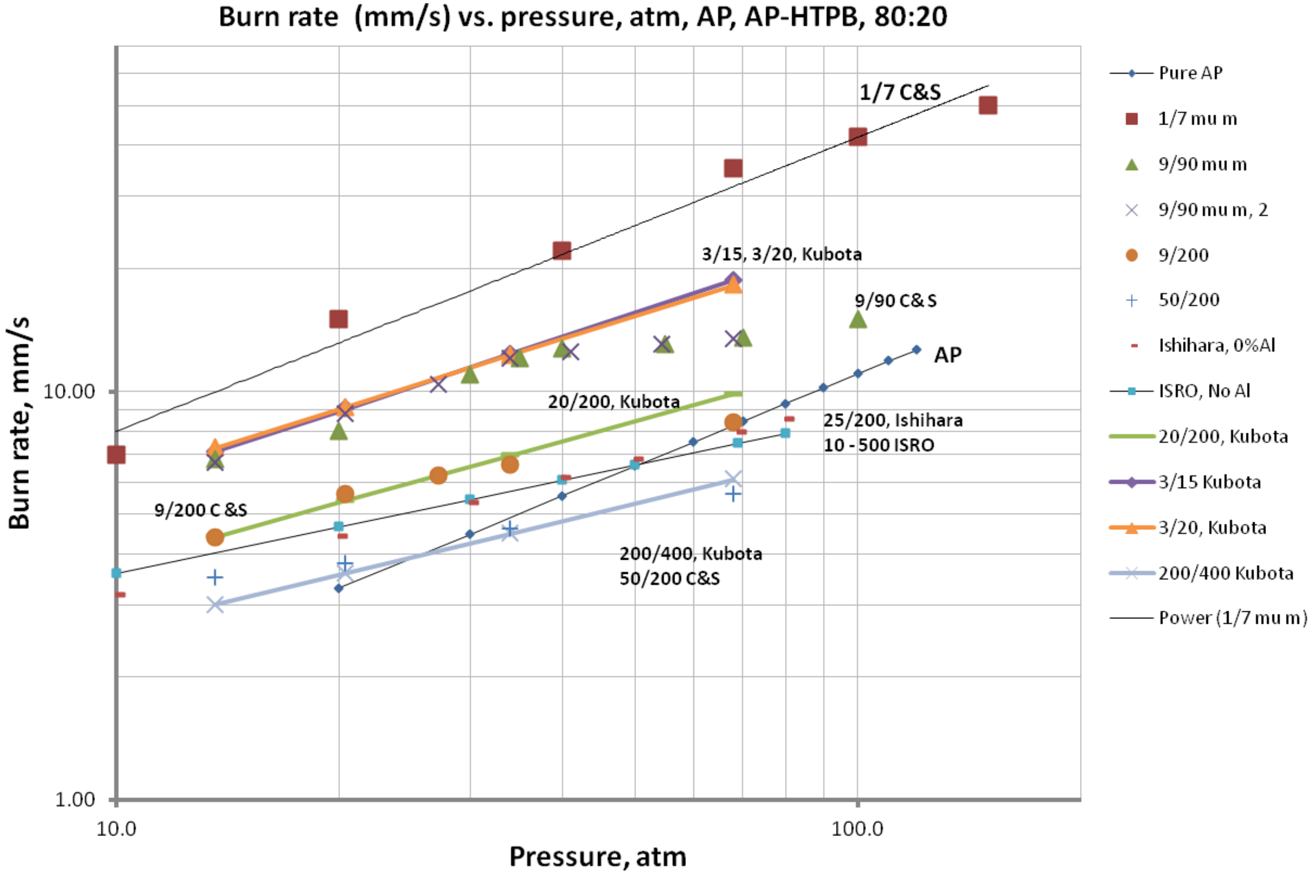
Reasons for the burn rate difference bet. IDPI and DDI:

The initial de-polymerization of the IPDI cured binders is more energetic. This energetic breakup produces reactive species that would promote combustion. The DDI binder, in contrast, has a much less energetic initial de-polymerization which does not produce reactive species.

These can also have effect in unsteady combustion process.

Burn rate data on AP-HTPB model propellants

AP sizes microns	Coarse : fine	AP:HTPB	$r = a\,(p/70)^n$ mm/s		Authors
			a	***n***	
1:7	1:1	82:18	**32.0**	**0.75**	C ohen &Strand, 1982
5	-	80:20	**34.0**	**0.76**	Langelle, 1997
3:15	1:1	80:20	**19.0**	**0.60**	Kubota, 2002
3:20	1:1	80:20	**18.5**	**0.57**	Kubota, 2002
20:200	1:1	80:20	**10.0**	**0.50**	Kubota, 2002
200:350	1:1	80:20	**6.06**	**0.47**	Kubota, 2002
200:400	1:1	80:20	**6.17**	**0.44**	Kubota, 2002
20:200	1:1	86:14	**13.6**	**0.50**	Kubota, 2002
25:200	1:1	82:18	**8.00**	**0.48**	Ishihara, et al, 1991



Ref: **AP burn behavior** – premixed flame structure with burn rate ***r (mm/s) = 8.4*** $(p_c/68)^{0.77}$ (for AP, all $p_c > 20$ atm)

1 µm/7µm propellant ***r (mm/s) = 32*** $(p_c/68)^{0.75}$

These have similar slopes and can be expected to have premixed flame behavior. Hence small particle size imply about 1 to 7 microns

At lower ***p***, the energy from the diffusion flame enhances the burn rate significantly. The burn behavior at higher ***p*** is controlled more by AP and hence, the burn rate approaches the burn rate of AP. **In this process, the value of pressure index comes down.**

Notice that some burn rate curves intersect that AP curve and the burn rate is below that of AP. This means that energy from the gas flame is being shielded by surface phenomena, presumably melt layers of fuel?

From the previous data

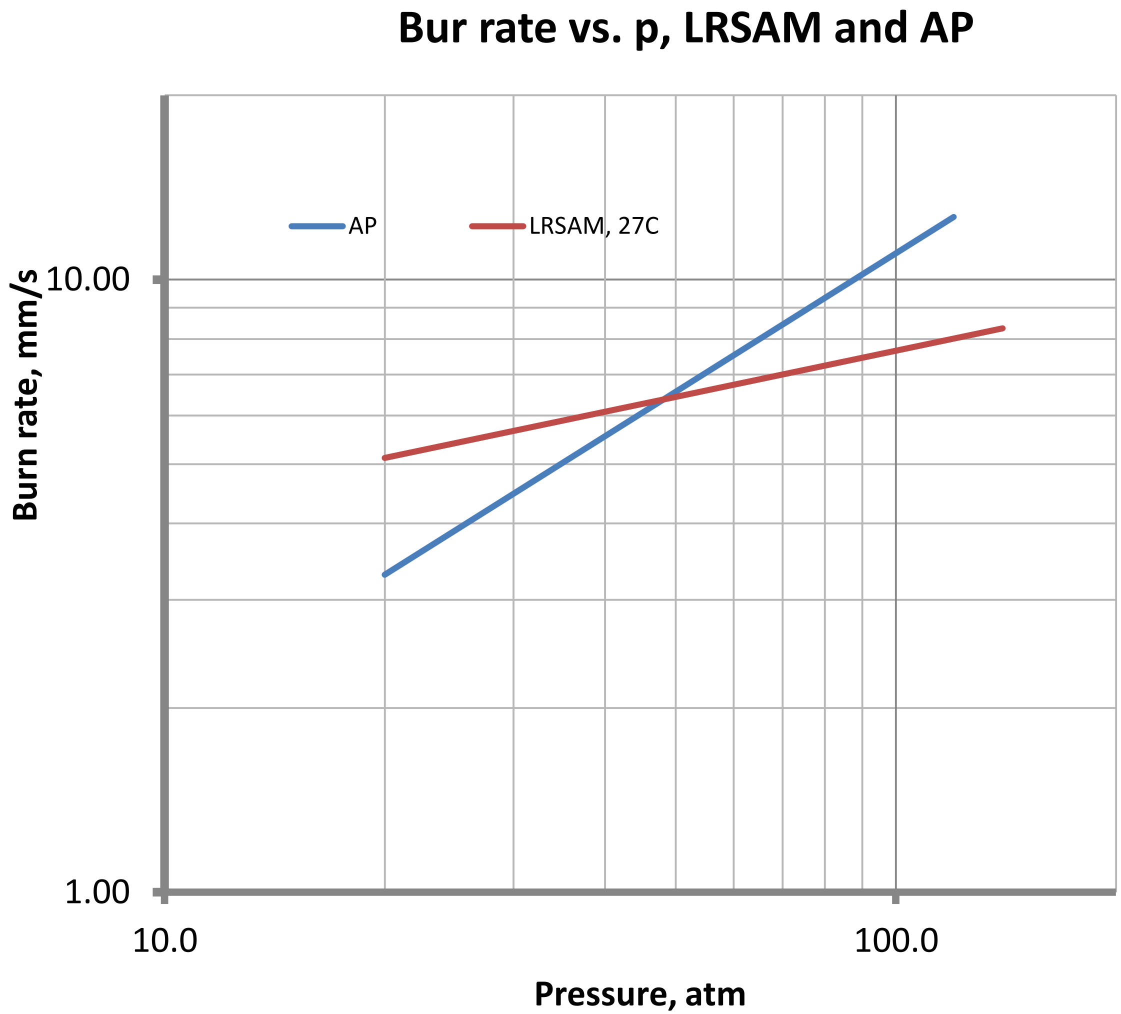
Propellant characterized by small-to-large particle size; AP-HTPB and Al in some cases	Intersection with AP burn curve occurs at p_c (atm)
Cohen, 9 µm/ 90 µm, 1:1 ratio	>120
Cohen, 9/200	65, 68
Ishihara, 0 % Al 25/200	55
ISRO, 0 % Al, many sizes	50
Ishihara, 10 % Al, 5Al, 25/200	68
Ishihara, 20 % Al, 5Al, 25/200	120
Cohen 50/200	35
ISRO, Al +AP, sizes <75, 45 to 355, 355 to 500	35

If the intersection with AP occurs at lower pressures, the issue of melt layer affecting the burn behavior becomes increasingly significant.

Suggestion that emanates from this observation –
Choose the particle size distribution such that the cross-over pressure is high.

This means that it is desirable to design a propellant system that has a burn rate equal to or better than 8 mm/s at 70 atm.

Burn rate behavior with LRSAM vs. AP

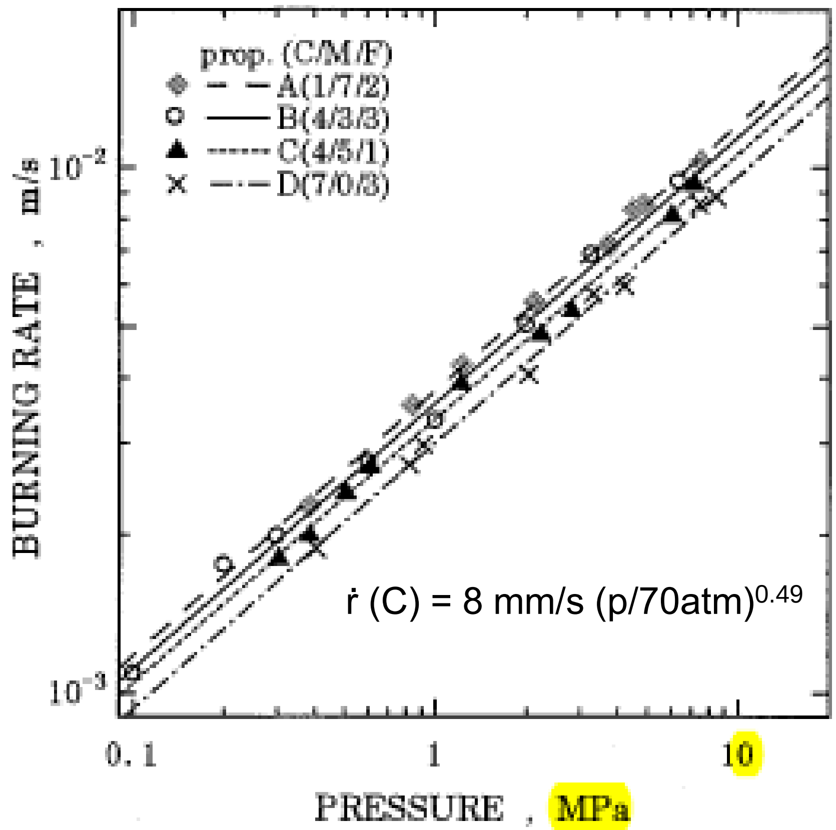


Comment. There is a large region in which the burn rate is below that of AP

Table 1 Oxidizer mixing ratio of propellants.

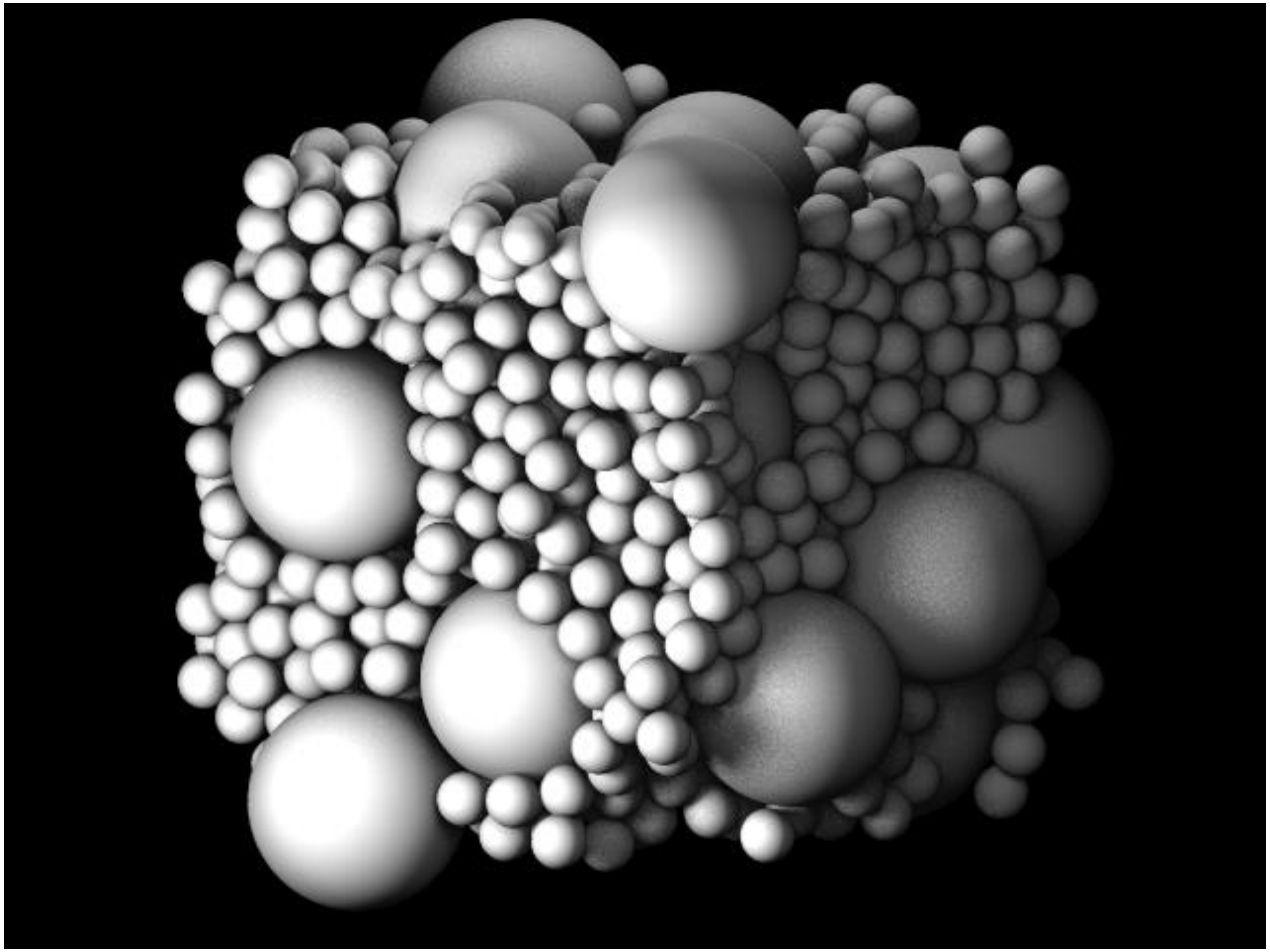
Prop.	Coarse	Medium	Fine
A	1	7	2
B	4	3	3
C	4	5	1
D	7	0	3

The propellant used was a nonmetalized composite propellant with AP 80 % in weight, HTPB 14.67 %, dioctyl adipate 3.96 %, isophorone diisocyanate 1.15 %, and tris{ l-(2-methyl) aziridinyl} phosphine oxide 0.22 %. Four different propellants were prepared with varying the distribution of coarse, medium, and fine AP particles, of which mean diameters were 200 *μm, 50 μm, and 15 μm,* respectively. The oxidizer mixing ratios are shown in Table 1. The densities of the propellants were 1.58+0.005 g/cm^2.

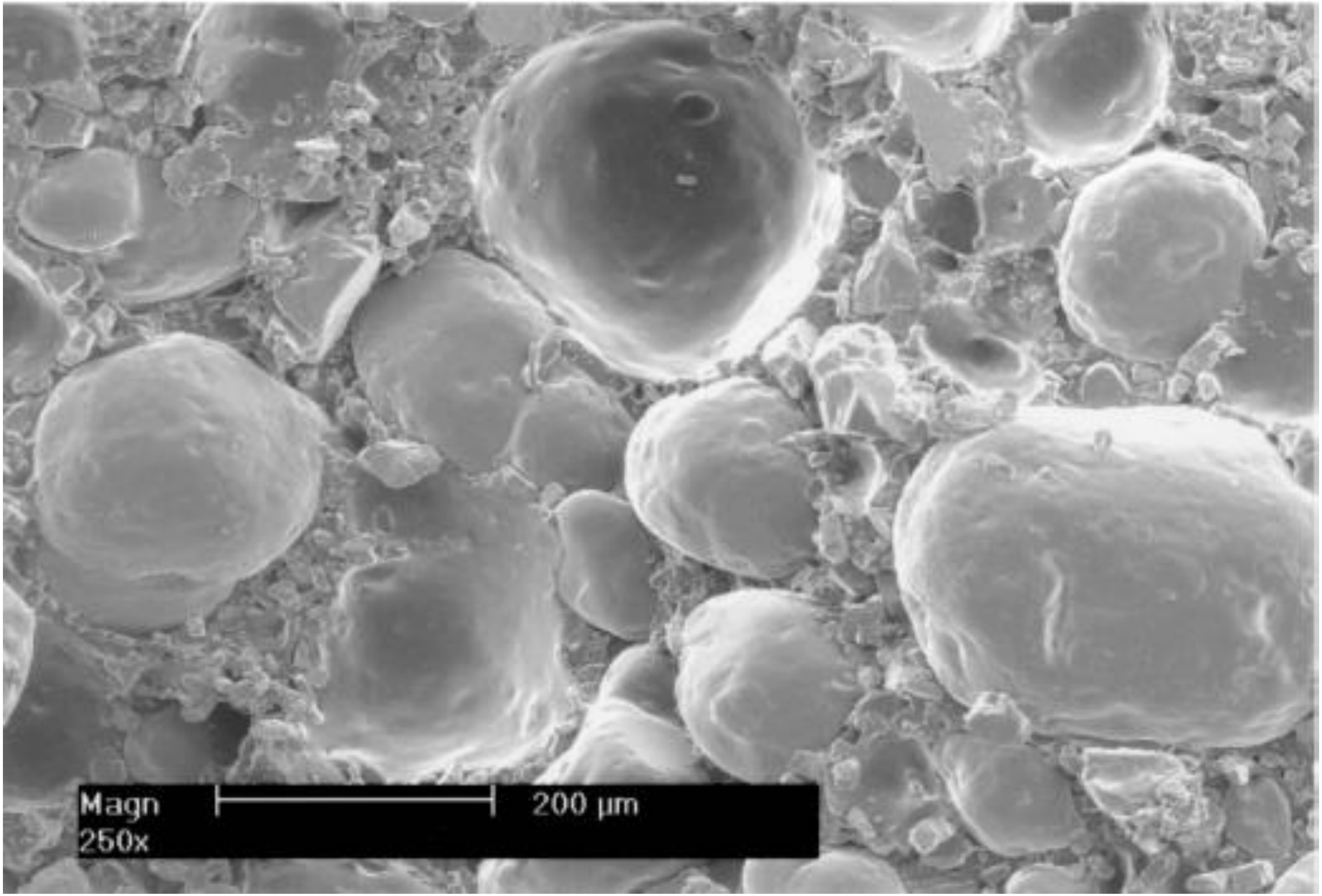


An experimental study on low frequency combustion instability of composite propellants, Masafumi Tanaka and Kazunori Nakaji. AIAA 1998-2552

How important is oxidizer packing?



Packing of 9 µm :90 µm sizes in 1:5 ratio



Is this how the composite solid propellant surface looks like?

What do we learn from model propellants?

AP sizes μm	Coarse : fine	AP: HTPB (w)	AP, (s): AP, (l): HTPB (v)	Surface area, AP (s), AP (l) m^2/kg prop	Est. Binder Thickness, μm	O/F Small: large	$r = a (p/70)^n$ mm/s		No of particles Small-to-large
							a	***n***	
1 : 7	**1:1**	**82:18**	0.35:0.35:0.30	**2100 : 257**	**0.13**	**2.5:17.5**	**32.0**	**0.75**	**343**
5	**-**	**80:20**	0.67:0.33	**804**	**0.41**	**4.1**	**34.0**	**0.76**	**--- (Langelle)**
3 : 15	**1:1**	**80:20**	0.335:0.335:0.33	**672:140.2**	**0.40**	**2.5:7.5**	**19.0**	**0.60**	**125**
3 : 20	**1:1**	**80:20**	0.335:0.335:0.33	**672:105**	**0.42**	**2.4:15.9**	**18.5**	**0.57**	**296**
9 : 90	**1:1**	**80:20**	0.335:0.335:0.33	**224 : 22**	**1.34**	**2.2:22**		~0.2	**1000**
20 : 200	**1:1**	**80:20**	0.335:0.335:0.33	**100:10**	**3.04**	**2.2:22**	**10.0**	**0.50**	**1000**
20 : 200	**1:1**	**86:14**	0.345:0.345:0.21	**103:10**	**1.85**	**3.6:36**	**13.6**	**0.50**	**1000**
25 : 200	**1:1**	**82:18**	0.35:0.35:0.30	**84:8.6**	**3.23**	**2.6:20.8**	**8.00**	**0.48**	**512**
50 : 200	**1:1**	**80:20**	0.335:0.335:0.33	**40:10**	**6.70**	**2.5:10.0**			**64**
50 : 200	**1:3**	**80:20**	0.16:0.51: 0.33	**15.7:15.2**	**10.3**	**1.6:6.4**			**64**
90 : 200	**1:5**	**82:18**	0.12:0.58:0.30	**78:17.5**	**3.14**	**10:21.2**			**11**
200 : 350	**1:1**	**80:20**	0.335:0.335:0.33	**10.:5.8**	**20.7**	**3.2:5.7**	**6.06**	**0.47**	**5.3**
200 : 400	**1:1**	**80:20**	0.335:0.335:0.33	**10:5.0**	**22.0**	**3.0:6.0**	**6.17**	**0.44**	**8**
AP_Pellet	-	-	-	-	-		**8.0**	**0.77**	-

AP density: 1950 kg/m³; Fuel density: 1000 kg/m³

Case 1. 82 % loading, 1 micron and 7 micron in equal proportions.

Mass-wise : AP 0.82 kg - 0.41 kg of 1 μm and 0.41 kg of 7 μm Binder: 0.18 kg

Vol wise : AP 0.42 lit - 0.21 lit of 1 μm and 0.21 lit of 7 μm Binder: 0.18 lit

Vol fraction : AP 0.70 lit - 0.35 lit of 1 μm and 0.35 lit of 7 μm Binder: 0.30 lit

No. of particles of 1 μm in 0.35 liter = 0.35/π (1 micron)^3/6 = 0.35 x 10^{-3} x (6/ π) /10^{-18} = 0.67 x 10^{15}

No. of particles of 7 μm in 0.35 liter = 0.35/π (7 micron)^3/6 = 0.35 x 10^{-3} x (6/ π) /(7^3 x10^{-18}) = 1.95 x 10^{12}

Total surface area (6 vol/d) = 6 x 0.35 x 10^{-3}/(1 micron) + 6 x 0.35 x 10^{-3}/(7 micron) = (2100 + 257) = 2357 m^2

Binder thickness is obtained assuming that all the surface is covered by the binder: Thus,

Binder thickness (bt) x surface area = binder volume. This means bt = 0.3 x 10^{-3} m^3/2357 m^2 = 0.13 μm

For practical propellants

ISRO Propellant: →
Total AP area = 70.3 m^2;
Binder thickness = 270 x 10^{-6}/70.3 = 3.8 µm

AP d, µm	% Frac (v, lit)	A_s = 6v/d m^2 (AP)	O/F = d/3*b.th	Number particles
550	0.015	0.165	48.2	1
450	0.105	1.4	39.4	2
320	0.13	2.43	28.1	5
175	0.20	6.85	16.2	31
90	0.04	2.67	7.9	228
50	0.14	16.8	4.4	1530
15	0.10	40.0	1.3	50,000
HTPB	0.27	--	--	--

Very fuel rich and so can lead to liquid flow over surrounding regions

AP d, µm	Wt fracn	Volume fraction	A_s = 6v/d m^2 (AP)	O/F d/3*b.th	Number particles
550 µm	0.04	0.035	0.22	19.4	1
450 µm	0.27	0.245	1.85	15.9	2
320	0..27	0.245	2.60	11.3	5
175	0.18	0.17	3.16	6.2	31
90	0.08	0.07	2.74	3.2	228
50	0.04	0.035	2.46	1.8	1530
HTPB	0.12	0.20	--	--	--

DRDL - LRSAM Propellant
My construct close to what is provided

Total AP surface area = 20.6 m^2
Binder thickness = 9.2 µm

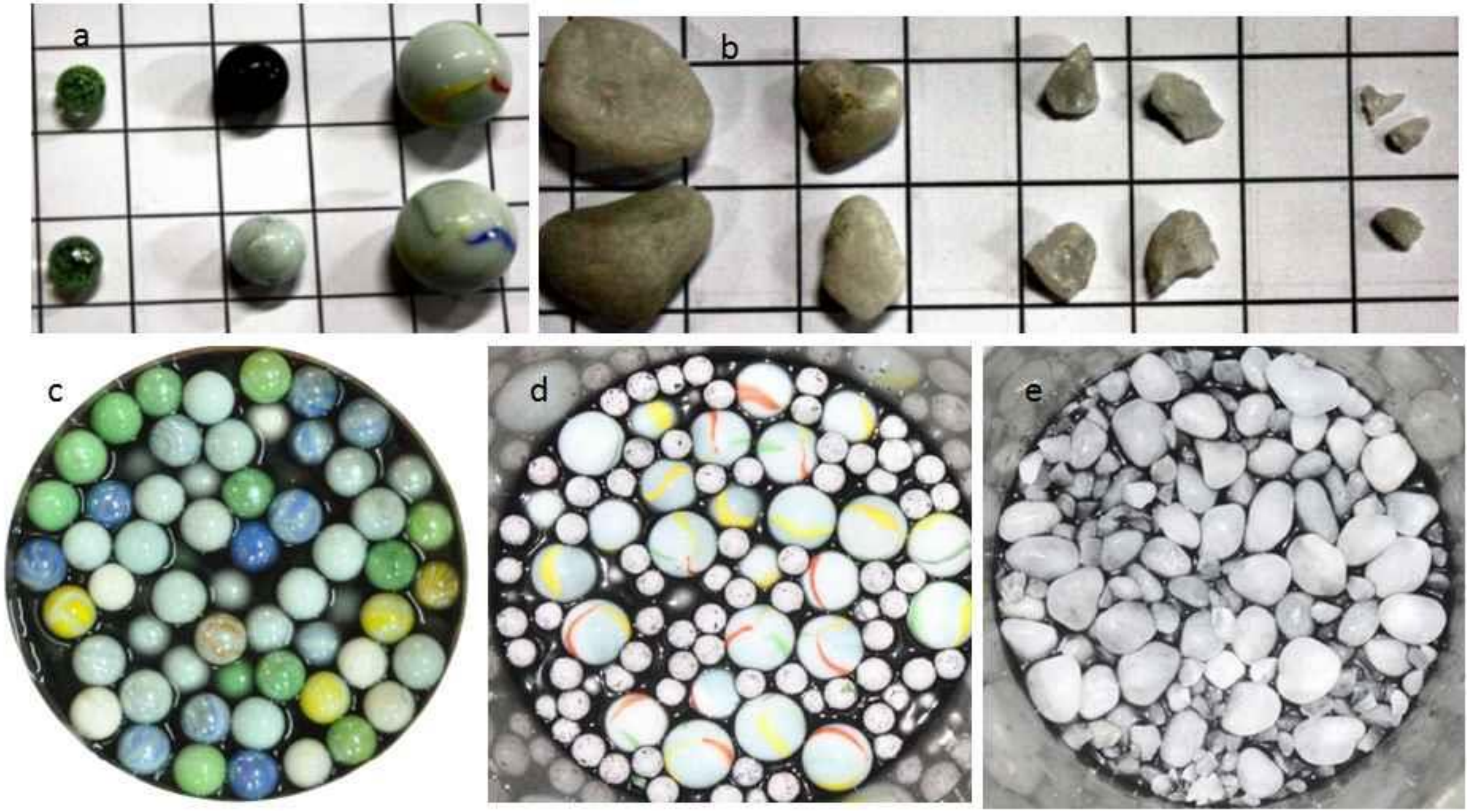
An excel sheet showing the importance of particle sizes

	Frac	Size, µm	Mass AP/binder, kg	vol, m³	Particle vol, m³	Particle surf. area, m²	No. Particles	Total surface area, m²	Binder thickness, µm	O/F]i
Case 1: From: Fredrick, Purdue report										
AP	0.38	400	0.38	1.95E-04	3.35E-11	5.0264E-07	5.82E+06	2.92		615.23
	0.1	25	0.1	5.13E-05	8.18E-15	1.96344E-09	6.27E+09	12.31		38.45
	0.39	2	0.39	2.00E-04	4.19E-18	1.2566E-11	4.77E+13	600.00		3.08
						Total AP surface area:		615.23		
Binder	0.13		0.13	1.30E-04					0.21	
LRSAM Composition - perceived.										
AP	0.04	550	0.04	2.05E-05	8.71E-11	9.50E-07	2.35E+05	0.22		19.41
	0.27	450	0.27	1.38E-04	4.77E-11	6.36E-07	2.90E+06	1.85		15.88
	0.27	320	0.27	1.38E-04	1.72E-11	3.22E-07	8.07E+06	2.60		11.29
	0.18	175	0.18	9.23E-05	2.81E-12	9.62E-08	3.29E+07	3.16		6.18
	0.08	90	0.08	4.10E-05	3.82E-13	2.54E-08	1.07E+08	2.74		3.18
	0.04	50	0.04	2.05E-05	6.54E-14	7.85E-09	3.13E+08	2.46		1.76
						Total AP surface area:		13.03		
Binder	0.12		0.12	1.20E-04					9.21	
Case 2: From: Fredrick, Purdue report										
AP	0.435	200	0.435	2.23E-04	4.19E-12	1.26E-07	5.33E+07	6.69		30.09
	0.435	25	0.435	2.23E-04	8.18E-15	1.96E-09	2.73E+10	53.54		3.76
						Total AP surface area:		60.23		
Binder	0.13		0.13	1.30E-04					2.16	
AP	0.76	200	0.76	3.90E-04	4.19E-12	1.26E-07	9.30E+07	11.69		3.17
						Total AP surface area:		11.69		
Binder	0.24		0.24	2.40E-04					20.53	
AP	0.76	25	0.76	3.90E-04	8.18E-15	1.96E-09	4.76E+10	93.54		0.40
						Total AP surface area:		93.54		
Binder	0.24		0.24	2.40E-04					2.57	

Note the highlighted numbers:

The actual surface area goes up dramatically with decrease in particle size.

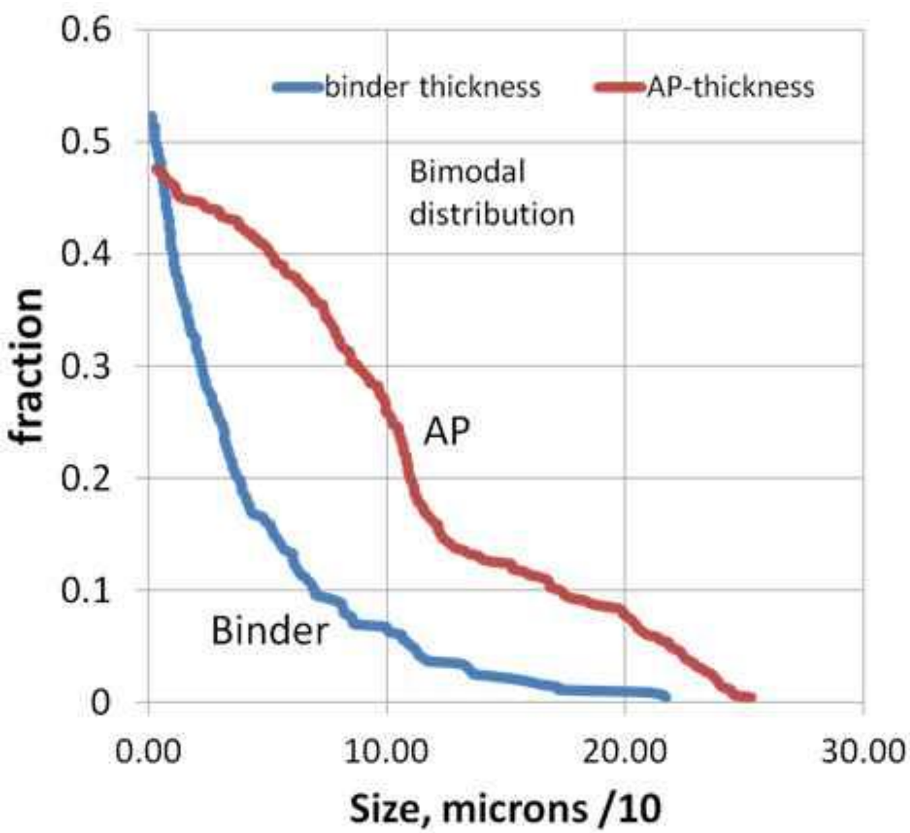
Changes in binder thickness and the local O/F affect the combustion process.

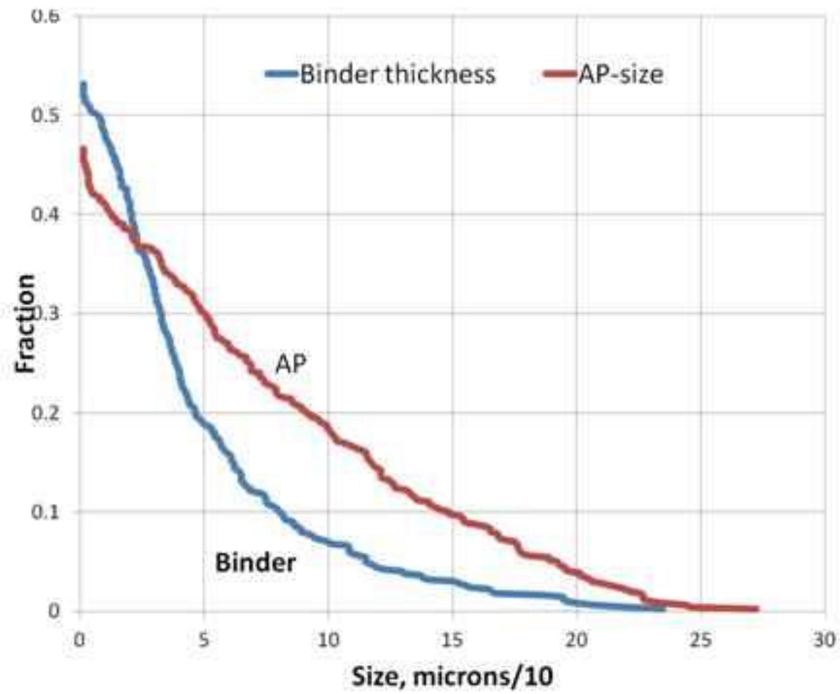


a. b show spheres of diameter 11, 16 and 25 mm (size ratio of 2.3:1) and pebbles of varying sizes with a size ratio of 7:1.

(c), (d) and (e) are the pictures of a packing in a cylinder of uniform size spheres, bimodal distribution of spheres and pebbles respectively. The volumetric loading of solids in water was 60, 70 and 72 % respectively. These correspond to 80, 85 and 80 % solid loading in solid propellant (B.E student thesis, Model experiments on particle-liquid mix simulating solid rocket propellant packing features, 2012).

Perceived size distribution on the surface





The distribution of thickness of binder and particulate matter with experiments scaled to maximum particle size of 250 microns.

Small AP size and small binder thicknesses occupy larger fraction due to the distribution pattern. Studies of high energy propellants show that they behave as a combination of “package” behavior (rich premixed) and normal distributed (diffusion) behavior.

These data form an input for modeling the propellant combustion behavior more realistically.

Links between steady combustion and instability

- Low pressure index, *n* is desirable from steady combustion view point. This does not mean ones needs to below the normal composite propellant burn rate index of 0.4 because the instability is weakly dependent on *n.*
- Liquid layer over the propellant surface may be the principal cause of the problems. If this is reactive, it is more serious (this is a new surmise not explicit in the literature).
- It is preferable to have as low a melt layer as possible. Perhaps, particle size distribution should avoid too much of coarse or fine particles. Very fine particles may bring down binder thickness but also lower the local air-fuel ratio encouraging melt layers.
- If ingredients are needed to be added to tailor the burn rate, it is useful to seek high melt temperature ingredients or those that encourage charring of the binder.

Link to analysis

1. We need to be able to model unsteady conduction as accurately as we can
2. We should relate the c-phase and g-phase behavior through a model to simulate de-pressurization behavior
3. We should be able to explain the large burn rate (much larger than given by $\dot{r} = a\, p_c^{\,n}$) in the depressurization-pressurization cycle.
4. We should be able to make calculations of the propellant response function through a model that has the input of steady state properties of the propellant.
5. We should be able to make a calculation of the pressure time curve of an actual motor with validated information of the response function
6. It is desirable if all these can be done in a single framework of conceptualization.

These will now be presented by Dr. Varun….

Therefore,

- Determining the particle size distribution as accurately as possible is important to deal with problems of instability; they also help obtain ensure consistent and repeatable performance.

- Statements from literature on the influence of particle sizes on stability need to understood in the light of packing and the related burn behavior.

- Select models like one of Beckstead (1981) and the work of Fredrick (1988) recognize the importance of binder. Enough work to characterize the binder and associated ingredient behavior has not been done. Regression and melt behavior under high transient heat flux should be undertaken.

- One must seek binder-bound approach to all aspects, certainly instability because deep de-pressurization and pressurization may affect the surface architecture.

Suggested way forward

The task force becomes an executive group to discuss and take recourse to following actions

1. Characterize the oxidizer particle size distribution to higher degree of accuracy.
2. Characterize the binder and associated ingredients under high transient heat flux.
3. Perform motor tests first at – 30 °C as instability is more prone to low temperatures. Establishing stability at low temperatures including perhaps pulse tests ensures stability at higher temperatures provided the propellant is the "same".
4. Perform end-burning (and selectively side burning) grain based depressurization studies to characterize the non-linear behavior. These are more easily accomplished compared to T-burner studies.
5. Perform analysis of test results already conducted and those that will be conducted to a higher degree of fidelity – a subgroup should get entrusted with this task immediately. This must become a standard procedure of the DRDL-HEMRL group
6. Carry on with the analysis of the kind being pursued at IISc – both DRDL, computational group and IISc being involved.
7. Several tests should be done in more than one laboratory/institution and round-robin experiments be done to ensure reliability and all-round ownership of ideas.
8. There should a well directed, periodically discussed national effort over an year instead of isolated projects. It is only this way knowledge is built up nationally.

Thanks. . .