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Explosive Model Tarantula 4d/JWL++ Calibration of LX-17

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Abstract: Tarantula is an explosive kinetic package intended to do detonation, shock initiation, failure, corner-turning with dead zones, gap tests and air gaps in reactive flow hydrocode models. The first, 2007-2008 version with monotonic Q is here run inside JWL++ with square zoning from 40 to 200 zones/cm on ambient LX-17. The model splits the rate behavior in every zone into sections set by the hydrocode pressure, P + Q. As the pressure rises, we pass through the no-reaction, initiation, ramp-up/failure and detonation sections sequentially. We find that the initiation and pure detonation rate constants are largely insensitive to zoning but that the ramp-up/failure rate constant is extremely sensitive. At no time does the model pass every test, but the pressure-based approach generally works. The best values for the ramp/failure region are listed here in Mb units.

				Booster G for b = 2 $(\mu s^*Mb^2)^{-1}$	
zones/	LX-17			ufTATB	LX-14
cm	G_3	b_2	G_2	G	G
40	45	2.7	1650	600	600
40	45	2.7	2050	800	1200
80	45	1.0	125	800	800
80	45	1.0	140	800	800
120	45	0.5	55	800	1200
160	45	0.0	23	800	1200
200	45	0.0	24	800	1000

1. Introduction

Tarantula is a kinetic package created for reactive flow models of detonating explosives for the purposes of simulating detonation, failure, corner-turning with dead zones and gap behavior. The package has been inserted into JWL++ and Linked CHEETAH. Here, we use JWL++ for ease. The package was used successfully this year at our laboratory to predict the existence of dead zones in ambient LX-17 (TATB 92.5%/kel-F 7.5) before the experiment was fired. It was also used to estimate the degree of LX-17 response to boosters of different sizes.

A kinetic package is best described by the average reaction rate, which is the rate constant times the pressure to whatever power but without the (1-F) term. Figure 1 shows both simple linear and quadratic reaction rates as well as the Tarantula rate for LX-17 at 1.90 g/cc. The simple rates start reacting at zero pressure and so have no on/off threshold behavior. A quadratic rate is used in many of the simple JWL++ boosters here and also in Linked CHEETAH. The rate equation in this case would be

$$\frac{dF}{dt} = GP^2(1-F), \tag{1}$$

where F is the burn fraction, P the hydrocode pressure (real pressure plus artificial viscosity) and G is the rate constant. The average rate is

$$\left\langle \frac{dF}{dt} \right\rangle = GP^2. \tag{2}$$

This simple kinetic package can do the size effect reasonably well and the slowing down of the detonation velocity as it makes a gentle turn. We use pressure to the first power for low-density, improvised explosives, where the calculations are needed quickly and little data exists. We use pressure-squared for dense explosives, like the boosters in these problems. We know that simple JWL++ does not put in enough detonation front curvature at steady state and that a booster is mostly transient in behavior. This means that the simple JWL++ booster will not be correct but is better than program burn.

In order to do failure and dead zones, we need more than the simple model, so Tarantula has four regions. Below 0.075 Mb [7.5 GPa, pressure $(P+Q)_o$], nothing happens. From 0.075 to roughly 0.18 Mb, a low rate turns on slow initiation. At about 0.18 Mb, [18 GPa, $(P+Q)_1$)], the model ramps up rapidly toward detonation, which begins at about 0.32 Mb [32 GPa, $(P+Q)_2$]. There are two pressure thresholds. The first is the P_o threshold one seen in initiation, which causes the P-τ curve. The second is the ramp-up, which is cause of failure. This ramp-up becomes ever more steep as the zoning increases.

Tarantula is built on rate functions defined in the four regions as seen here:

$$\begin{aligned}
\frac{dF}{dt} &= 0, \quad < (P+Q)_o \\
\frac{dF}{dt} &= G_1\left[(P+Q)-(P+Q)_o\right]^{b1}(1-F), \quad (P+Q)_o \text{ to } (P+Q)_1 \\
\frac{dF}{dt} &= G_2\left[(P+Q)-(P+Q)_o\right]^{b2}(1-F), \quad (P+Q)_1 \text{ to } (P+Q)_2 \\
\frac{dF}{dt} &= G_3(1-F)^{1.5}, \quad > (P+Q)_2
\end{aligned} \tag{3}$$

where F is the burn fraction, t the time, P is the pressure, and Q the artificial viscosity, so that (P+Q) is the hydrocode pressure. The use of Q greatly helps with coarse zoning by adding additional pressure that keeps the rate constant low. With fine zoning, the influence of Q should wither away. The detonation region has a constant rate, with (1-F) empirically raised to the power of 1.5 specially to create a straight-line size effect curve for LX-17. A first-order solver handles the discontinuities between the regions. The model is used here in an analytic functional form but point-by-point programming with linear interpolation is also possible.

In order to compare, we set most of the numbers constant:

$$(P+Q)_o = 0.075 \ \text{Mb}, \quad (P+Q)_1 = 0.18 \ \text{Mb}, \quad (P+Q)_2 = 0.32 \ \text{Mb},$$
$$b_1 = 2, \quad G_1 = 130 \ (\mu s * Mb^2)^{-1}, \quad b_3 = 0, \quad G_3 = 45 \ \text{or} \ 50 \ (\mu s)^{-1} \qquad (4)$$

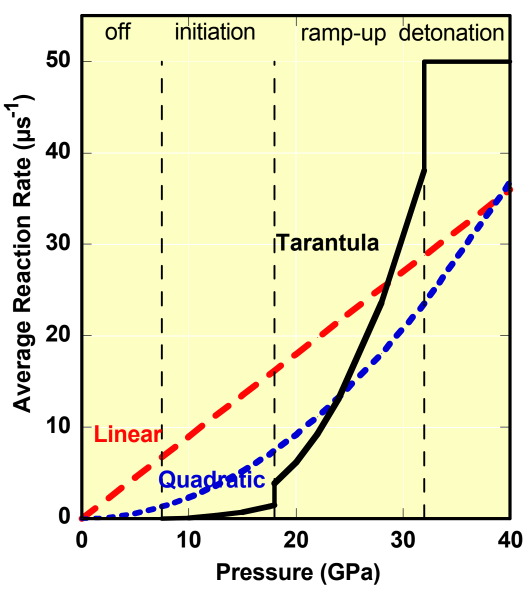

Figure 1. Average reaction rates for simple linear and quadratic reactive flow and for Tarantula, which has four different pressure regions.

This says that the initiation and detonation settings are held the same, as are the pressure boundaries between initiation-ramp and ramp-detonation. For ambient runs with LX-17, we use always

$$(P+Q)_o = 0.075 \ \text{Mb}. \qquad (5)$$

Figure 2 shows the various processes for calibrating Tarantula with ambient 1.90 g/cc LX-17 data. Initiation (constants b_1, G_1), ramp/failure (b_2, G_2) and detonation (b_3 = 0, G_3) can be set separately. Initiation is obtained by modeling the run-to-detonation times as obtained using long sabots fired with a gun. The key to the rest is the 4 mm copper cylinder, which is the smallest cylinder that should detonate. Once this detonation velocity is matched, we can run the 1-inch cylinder to make sure that the detonation is right at larger sizes. The size effect curve is straight, so that running these two points is enough to fix the rest of the curve.

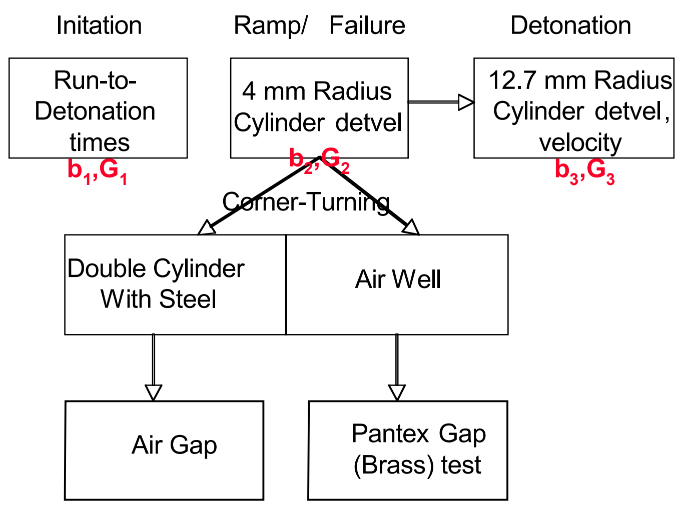

Figure 2. Schematic of the Process to calibrate the various parts of Tarantula.

Next, we follow the ramp/failure process down to the two corner-turning experiments. Once we fit these two, the ramp/failure adjustments are finished and we move to the two gaps as a check. In most runs, we found that the Pantex gap test and the air gap both crossed as expected for a 1.5 mm gap but both failed to cross, as expected, a 3 mm wide gap.

2. Setting up the Model

The code is a 2-D CALE-type Lagrange code with Eulerian relaxation usually being used away from the region of interest. All zoning is square; there is no radial zoning. As the zoning increases, the zone tangling gets worse, and the relaxation becomes more extensive. The relaxation being used is of the type with global set ifbackup 1 with backuprlx and backupfraction 1.0 being used. For the artificial viscosity, monotonic Q (default with qlin 0.5, qquad 0.75) was used.

The JWL++ JWL's being used are: LX-17 A=5.45, ufTATB 4.44, LX-14 6.44, Comp B 6.31, and LX-04 6.11. The Program burn JWL is LX-13 2.78. Without the complete JWL's, the specific rate settings given here will not work, but the structure and relationships are the important thing. In another code on different machines, all the numbers will change anyway, but the general result should be the same.

The first test is the 4 mm-radius LX-17 cylinder with 2.25 mm copper outside, which must show a detonation velocity, U_s, of 7.33-7.35 mm/μs. This is the smallest dependable size where detonation is expected. The result is a steady state one, so that the booster details do not matter. It also does not matter whether JWL++ or program burn is used for the booster.

After setting the LX-17 pair b_2, G_2 for the 4 mm cylinder, we can run the 3 mm cylinder, with a 1 mm copper wall, which is supposed to fail but rarely does. The model is not good enough to see the small difference between these two confined cases. It does, however, do unconfined failure accurately. We also need to confirm with the 1-inch copper cylinder with radius 12.5-12.7 mm and 2.5-2.6 mm wall, which should have a steady state detonation velocity of 7.54-7.56 mm/μs and a wall velocity of 1.46-1.50 mm/μs after 20 μs. This is the basic energy delivery test, as well as showing that the size effect curve is good.

Next, we turn to the two corner-turning experiments, both shown schematically in Figure 3. They are shown the way they look in the codes. The double cylinder (also called the German hand grenade) is a 2 x 2 inch LX-17 cylinder with a ½-inch dia. LX-14 handle 63.5 mm long. A piece of 6.35 mm-thick steel backs up the larger LX-17 cylinder and the LX-14 passes through a hole in it. What we measure is the breakout position at the distance x(mm) on the upside LX-17 face as shown in Figure 4. The results are:

Measured at ambient   13 to 16 mm from the steel
Acceptable in the model 10 to 19 mm.

For the air well (also called the hockey puck) at ambient, what matters is the relative time of arrival of the breakout at surfaces A and B. We expect breakout at surface A just before surface B, ie -0.5 to -1 mm, which means that surface B lagged surface A by ½ to 1 mm. See the example in Figure 5. We want:

Measured at ambient   -0.5 to -1 mm from the steel
Acceptable in the model -1.5 to +1 mm.

If it is slow by -4 mm, we get a big, long dead zone that piles up and slowly turns upward but barely moves towards surface B. If it is fast, the front will zip across the surface B with +4 mm lead showing a small, curling dead zone or maybe no dead zone at all. We have to hit inside these limits to have a chance to turn knobs and improve the results.

The double cylinder is initiated with a line detonation in simple JWL++, because being 8 radii long, we expect the front to be nearly steady state by the end. This makes this geometry simpler and this should be run first to set the rate constant of the LX-17. Fiddling with the rate constant of the booster does not help much, and we leave it constant. However, the air well has another knob for adjustment, which is the offset of the detonator. Insetting the detonator from the back edge makes the detonation front bend around more at the corner turn, so that the push is efficient and the edge lag for the TATB is larger. This knob must be considered empirical, although we know nothing really about how the bridge-wire actually works in this case. It sits right against the TATB on the outer face but there could be a region of build-up to detonation in the TATB. Both corner-turning geometries require fine-tuning of the boosters, which do not have the necessary degree of detail to be correct.

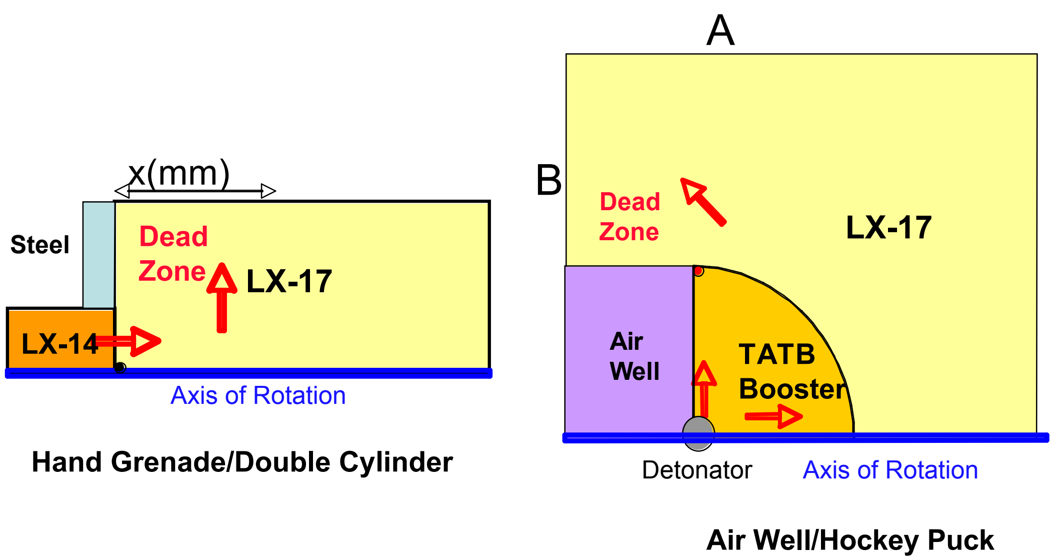

Figure 3. Schematics for the corner-turning experiments.

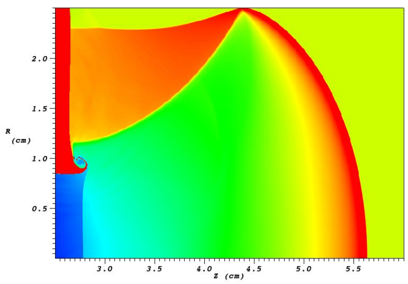

Figure 4. Hand grenade/double cylinder dead zone shown in a density plot (limits 0.5 to 2.5 g/cc) with the top leading point about to hit the top edge at about 17 mm to the right of the steel (red). This is a good run.

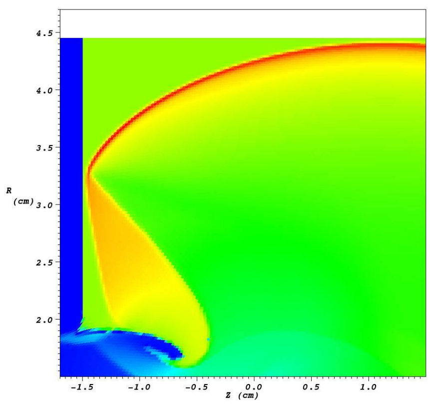

Figure 5. Hockey puck/air well with the front about to hit both sides at the same moment. This is a good run.

For the corner-turning, at 120 zones/cm and finer, zone tangling gets really bad. We find that going to Eulerian zoning makes running possible with monotonic Q. We use the global command ifbackup 2 with no other specific relaxation commands. Eulerian relaxation with the double cylinder is slower than Lagrange by about 2 mm. With the air well, Eulerian lags by about 1 mm, which is a lot if we are passing through the “knife-edge” region of best fit. At 160 and 200 zones/cm, there is not much choice but to go Eulerian, despite the uncertainty in relating the results to Lagrange.

After the corner-turning comes crossing gaps- one with material and one with air. The Pantex gap test tests the ability of the LX-17 to detonate or not after a shock wave passes through a brass spacer. The test consists of an LX-04 donor explosive with a brass spacer plate at the end and the receptor explosive on the other side of that. It was used only for TATB explosives, so that limited data exists. The LX-04 is bare, 1 inch in diameter and 38 mm long. Because of this, we estimated the LX-04 rate constant above, there being no size effect data. For LX-17, we expect no crossing for 3 mm of brass. In the code, we set pressure edits for 30 mm in the LX-17, and we expect to see the pulses die down in height to a small pressure. We also expect the detonation to cross for a 1.5 mm wide brass spacer, and the detonation will dip a little but revive to full height in the pressure edits. The detonator was an RP-1 (called SE-1 at the time) with a radius of 3.9 mm, and this length needs to be accurately inserted as a vfill line detonator.

An air gap works the same way but there is no shock wave in the air, only gas products being hurled across. The 1-pellet air gap is our local test using an RP-1 detonator, a 1x1 inch Comp B booster, a 1x1 inch donor LX-17 pellet, air gap, and 4 receptor LX-17 pellets. Pins line the edges of the receptor pellets and all explosive is bare. The 4-pellet receptor is 100 mm long and is needed to be sure that the detonation actually turns off or on. Again, pressure edits in the code show the result. We expect the detonation to cross at 1.5 mm gap and fail at 3.0 mm width. In the code, we must relax the air gap at time zero to have any hope of a correct answer. The reason is that the last zone of explosive in the donor is blown off and moves across the gap like a solid flyer, thereby creating high pressure when it hits. By relaxing the gap from the start, the flyer is diffused, sort of like breaking it into pieces, and the result is greatly improved.

There are two aspects to the air gap problem. One is whether the LX-17 on the far receptor side detonates or fails. The other is the delay on the far side, which is the sum of the time-to-cross plus the time-to-detonation. The order of the delay for a 1.5 mm gap is found experimentally to be about 0.3 μs, which requires an initiation model capable of reaching these small values, and which will probably happen only for high zoning. The present model, which cuts initiation off at 0.18 Mb cannot go smaller than about 0.5 μs. For this reason, the code delay is about 0.1 μs, all from time to cross the gap.

3. Simple JWL++ Rate Constants of Boosters

Tarantula is sensitive to type of booster that drives it. This, in turn requires setting the detonator to something more than a point. We have found that a program burn booster is generally too weak to drive Tarantula adequately. This is because program burn is usually low in pressure and has no spike at all. If we run basic Program Burn with equal breakout everywhere and no edge lag at 90^o relative to 0^o, we find with the air well that a dead zone forms but quickly bogs down in the turn, ie., we are way too slow in moving the necessary stuff around the corner. However, if we use for the air well a breakout contour on the program with a huge 1.0 μs edge lag between the axis and 90^o, then we get the proper dead zone behavior.

For this reason, we here use a booster of simple JWL++, but now we have to figure out the details. Our rule-of-thumb is that we need 4 zones in the reaction zone for reactive flow to reach "the edge of convergence". The edge of convergence is that point at which we get a reasonable detonation velocity and where changing constants can be done in a predictable manner. It is possible to run simple JWL++ on LX-17 at 5 and 10 zones/cm and get results, but any change causes weird effects. For LX-17 at 1-inch size, the edge lag seen in the detonation front curvature is about 1 mm. We take this to be roughly the reaction zone length. For 4 zones in the reaction zone, we need 40 zones/cm as the edge of convergence. We have:

$$\text{minimum zones/cm} = \frac{40}{\text{edge lag(mm)}} . \tag{6}$$

This is an average over the likely sizes to be used. Near failure, the edge lag is 0.5 mm so that the edge really is at 80 zones/cm. For very large parts, the edge would go to 20 zones/cm.

For pure dense HMX and LX-14 at 1-inch size, the edge lag is 0.2 mm, so that the minimum zoning goes to 200 zones/cm. At 1 inch, PBX 9404 and PBX 9501 shows 0.3-0.5 mm for 80-130 zones/cm. LX-04 has 0.5-0.6 mm for 70-80 zones/cm.

We are now interested in what happens if we model an ideal explosive with too-coarse zoning, an event that can't be avoided with the boosters. In Figure 6, we show the simple JWL++ results for a 4 mm-radius cylinder of LX-10 with a 1 mm copper wall at 40 zones/cm. The rate constants, G, are in the Mb units used in the codes. The detonation rates are roughly

$$\begin{aligned} \nu_f(b=1) &\approx GP_{max} \approx G(1.4 * P_{cj}); \quad G \approx 625 \quad (\mu s * Mb)^{-1} \\ \nu_f(b=2) &\approx GP_{max}^2 \approx G(1.4 * P_{cj})^2; \quad G \approx 1116 \quad (\mu s * Mb^2)^{-1} \end{aligned} \tag{7}$$

where we take the spike, P_{max}, to be roughly 1.4 times the JWL C-J pressure for about 0.56 Mb.

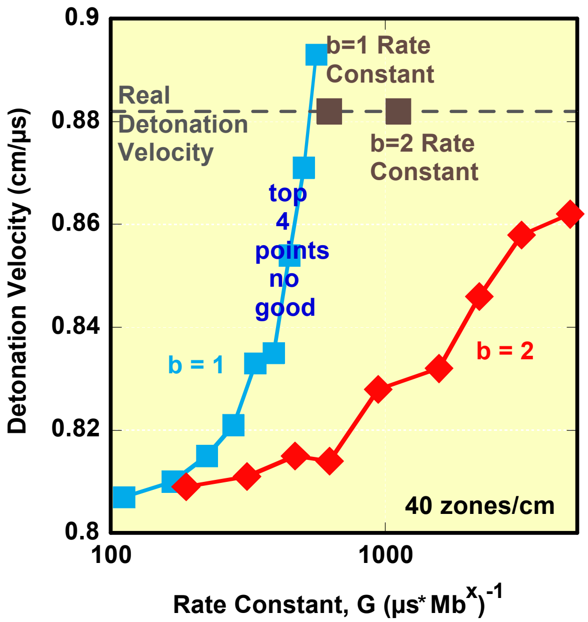

Figure 6. Dubious but useful exercise to find out if b = 1 or b = 2 is the best thing to use for a booster with too-coarse zoning. Simple JWL++ code runs with a 4 mm copper cylinder of LX-10 with an expected 0.882 cm/µs detonation velocity. Using b=2 gives more range although we don't get the right detonation velocity.

In Figure 6, at 40 zones/cm, the expected positions are the boxes on the gray 0.882 cm/µs detonation velocity line. The b=1 curve gets there, but the pressure pulses have completely degraded along the way. The b=2 does not get there, but the pressure pulse look good. Given that we are going to model LX-10 anyway, the b = 2 option appears to have more range to it.

We now check the detonation rates as listed in the size effect data. The detonation rate is inversely proportional to the slope of the size effect curve using this equation

$$\text{average rate } (\mu s^{-1}) \approx -\frac{D^2}{\partial U_S / \partial(1/R_O)}, \tag{8}$$

where R_O is the explosive radius and U_S is the detonation velocity for that radius and D is the detonation velocity extrapolated back to infinite radius. If the size effect data lies on a straight line in inverse-radius space, then we can get the slope from D and one point at $1/R_O$ on the line

$$\text{average rate } (\mu s^{-1}) \approx -\frac{D^2}{R_O(D - U_S)}. \tag{9}$$

For French old 5 μm TATB (not ultrafine) at 1.5-1.6 g/cc, we have 34-38 μs^{-1}. For LX-17 we have 36-45 μs^{-1} and for PBX 9502 36-43 μs^{-1}. We estimate the spike to be 1.4 times 0.26 for 0.36 Mb. Besides the error in the rate, the C-J pressure is known to no better than 10%, so that a 20% overall error is a good guess. Then, we have a rate constant of

$$G(LX-17) \approx \frac{40}{0.41^2} \approx 240 \pm 50 \quad (\mu s * Pa^2)^{-1}, \tag{10}$$

where b = 2. The results for various boosters used with LX-17 are listed in Table 1. The LX-04, used as the donor explosive in the Pantex gap test, has not had the size effect measured, so that the entry is a guess. A range is given, because running individual tests may change the medium value somewhat. This way of estimating gets us close.

The thresholds in our Tarantula model require better booster modeling, and this leads to the means of initiating the boosters. We usually start the nodes in JWL++ with a particle velocity, u_p, which should be that of the spike:

$$u_p = \frac{P_{max}}{\rho_o U_s}.$$

The expected set of u_p values are given in Table 1.

We also list in Table 1 the measured edge lags, L_o, where available. This is how far the edge of detonation front is behind the front point. We may take the edge lag as some measure of the reaction zone length, essentially the only there is. If we drew a line across the cylinder at the back, then L_o would be the reaction zone length on the axis. We use the rough equation

$$zones/cm \approx \frac{40}{L_o(mm)} \tag{11}$$

Table 1. Properties of LX-17 and boosters. We assume a booster b of 2.

	density (g/cc)	rate (μs^{-1})	Median f. Size effect	est. error band	Us (cm/μs)	Pmax (Mb)	up (cm/μs)
LX-17	1.90	40	240	190-290	0.76	0.41	0.28
Comp B	1.71	80	500	400-600	0.79	0.40	0.30
ufTATB	1.80	120	800	600-900	0.75	0.39	0.29
LX-04	1.865	not measd	800	500-1100	0.85	0.50	0.32
hi% HMX	1.83	380	1200	1000-1500	0.88	0.56	0.35

	Edge Lag (mm) at these Radii			Minimum Zones/cm at these Radii		
	5 mm	12.7 mm	25.4 mm	5 mm	12.7 mm	25.4 mm
LX-17	0.8	1.1	2.1	50	36	19
Comp B		0.5			80	
ufTATB		1.0			40	
LX-04		0.6	1.1		67	36
hi% HMX		0.3	0.5		133	80

to get the minimum “edge of convergence” zoning required. We see that this has no relation to the detonation rate and has to be known at each cylinder size. Near failure, it takes more zones than at a large size. Besides the fact that the final number is an estimate, we see that 40 zones/cm generally is not enough for the ideal explosives, which are those below LX-17 in the table and which have larger detonation rates.

4. Hemi-Spherical Boosters and Detonators

The air well has a hemispherical ufTATB booster and hemispherical detonator. As the booster rate constant G increases, the air well breakout goes from being too fast to being too slow, a result that seems backwards. But, if G is low, the detonation front is strongly curved near the edge, and the front jumps off in the direction of the corner-turn easily (dead zones “fast”). If G is high, the front is flat and it races by the corner, leaving a dead zone frozen in position at the starting gate (dead zones “slow”). The curvature has to be just right to make the turn properly. The air well sits on a knife-edge with too-fast and too-slow both easy to get with the right answer sandwiched in between. The double cylinder is easier to work with because we measure a side distance, which changes slowly with G. Pure Program Burn is always too slow, because it has a flat front like a very high-G JWL++ booster.

If we use a JWL++ ufTATB booster with a hemispherical detonator using an electric bridge wire, the size effect says we should set b = 2, G = 800. We found that point-lighting the origin either by nodes with velocity or with a program burn hemispherical core gave too flat a front until we turned down the TATB to b = 2, G = 300. We could keep the original desired b = 2, G = 800 if we inset a 6-zone line-initiation of node velocities 0.35 cm into the explosive. This caused the front near the back, flat edge of the booster at 90^o to slow down, thereby adjusting the timing going into the turn. The movement of the line detonation from the edge to the inset position increases the edge lag at the TATB surface from 0.1, which is what it is supposed to be, to 0.7 μs.

The offset in TATB does not really make sense except to get what we want. If we offset the detonator, the edge lag at the spherical TATB surface is about 0.5 μs (regardless of zoning), which is much larger than the 0.1 μs estimated in the air well experiment. Unfortunately, no hemidet TATB shot was ever done so this issue was forgotten. If we don't offset, the calculated edge lag is 0.1 μs, which is correct but the dead zone problem doesn't work. The reason appears to be that we need a steeply declining detonation front near the edge, but simple JWL++ supplies a too-smooth, quadratic front. This situation is not zone-dependent and appears also at 200 zones/cm, so that it is characteristic of simple JWL++.

Pure, point-lit Program Burn will always reach the edge of the TATB booster at the same time and the resulting dead zone formation is far too slow. It can be fixed at 40 zones/cm by using this contour:

Angle (deg)	Time (μs)
0	2.54
10	2.54
20	2.60
30	2.68
40	2.78
50	2.90
60	3.02
70	3.15
80	3.30
90	3.54

(12)

which results in having a huge 1.0 μs edge lag, which is unphysical but works.

5. Effect of Zoning on the Form of (b_2, G_2)

We ran our problem set at various zonings. The initiation part was kept the same and the detonation part changed only a little. The big changes came with the ramp/failure section. In Figure 7, we show various average ramp/failure rates that have been used, where the exponent b_2 ranges from 2.7 to 0. For non-zero b_2, we subtract 0.075 Mb; for b_2 = 0, we subtract nothing because the average rate is now constant.

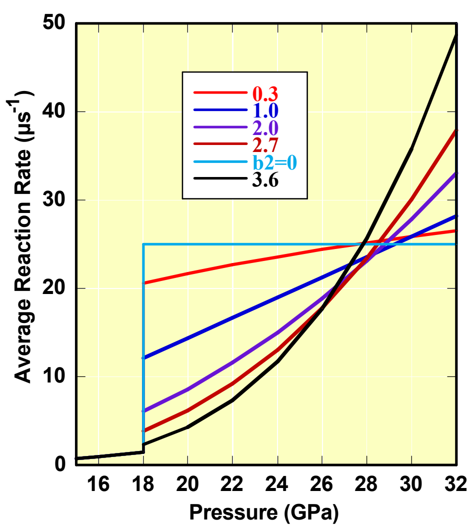

Figure 7. Average rates with various settings of the pressure exponent, b_2. If b_2 =0, the rate is square.

With simple JWL++ b=2 boosters, we now try the various average rates from Figure 7 for the main charge LX-17 and try to fit both the air well and double cylinder simultaneously. The results are shown in Figure 8. We find that we need b_2=2.7 at 40 zones/cm but that this changes to b_2=0 at 160 zones/cm, ie. the average rate becomes square. This unexpected result shoots down the idea that the 40 zones/cm results can be extrapolated to fine zoning with only small changes. It becomes ever more work to find the answer at high zoning.

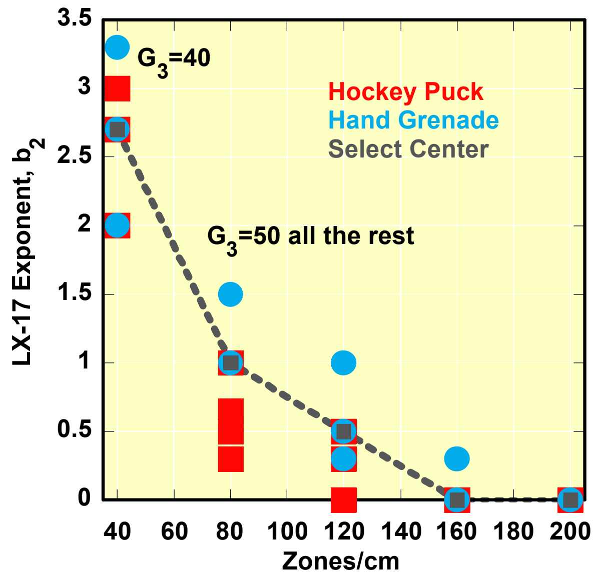

Figure 8. The range of LX-17 b_2's that fit corner-turning decline with increased zoning and near zero. Cylinder agreement at 4 and 12.7 mm is required always.

6. Effect of Booster Adjustment

Above, we tried to show what we thought the settings of the boosters should be. Unfortunately, the parameters become knobs in making the corner-turning calculations work. First, we consider the double cylinder. Figure 9 shows how we can modify the result simply by changing the booster rate constant, G. With a low G, we get no dead zone at all. For G larger, the curvature decreases and a dead zone forms. For G large, the detonation speeds by too fast to push the dead zone sideways and it stagnates. The region where the data lies is on the fast rise of the curves and just above. This is the knife-edge behavior we mentioned before. For 160 zones/cm, we see that the turn-on of the appearance of the dead zone is much more abrupt than at 40 zones/cm. We also see that program burn gives a single value. If it is too high, which it is, there is no way to adjust it.

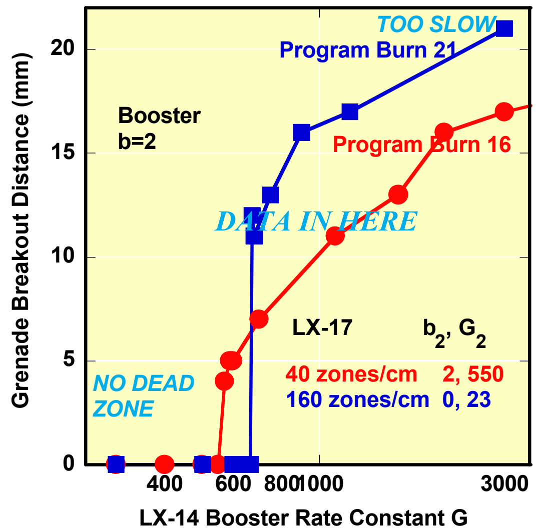

Figure 9. Double Cylinder results: as the b = 2 LX-14 booster G increases, we go from no dead zone through the proper breakout to too slow. It is easier to find the proper region at 40 zones/cm than at 160 zones/cm.

Next, we stay with double cylinders at 160 zones/cm, where we gravitated to $b_2 = 0$ as the best value. We want to see if higher b_2's can be used and still fit the corner-turning. The results are shown in Figure 10. The answer is yes, we can run with high b_2's, but we are forced to lower booster G's and the turn-on becomes ever sharper, making it more difficult to find the data region. At $b_2 = 0$, the experimental data lies on the plateau, which is easy to find. At $b_2 = 1.0$, the region we want lies just above the jump-up on a steeply-rising curve.

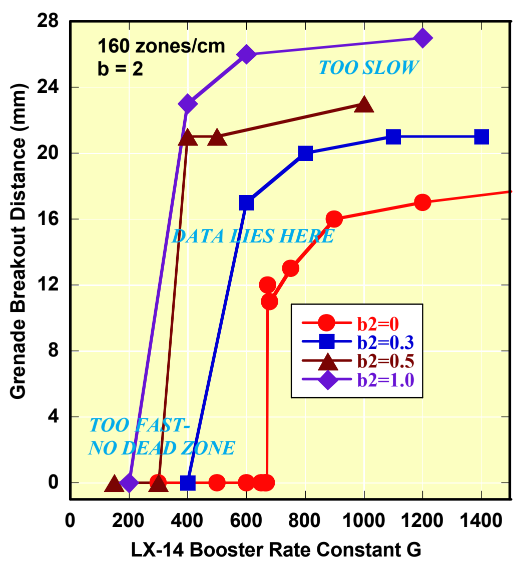

Figure 10. Raising b_2 for 160 zone/cm hand grenades pushes the booster G to lower values and makes the entire curve steeper and harder to work with. Going to $b_2 = 0$ makes it easier to find an answer.

7. Changing the P_1-P_2 Region Width

We are now going change other variables that have been left constant so far. We are going to run at 160 zones/cm, which we think might be converged. Also, we use LX-17 b_2 = 0 with the G_2 that agrees with the 4 mm copper cylinder, so that 23 < G_2 < 27. Figure 11 shows the double cylinder results, where we try four different P_1-P_2 region widths. The same steep curve appears as a function of booster G with the desirable position being just above the cliff face. However, P_1-P_2 may be shifted to move this cliff face up or down in booster-G space, so that some desirable value of booster G could be used.

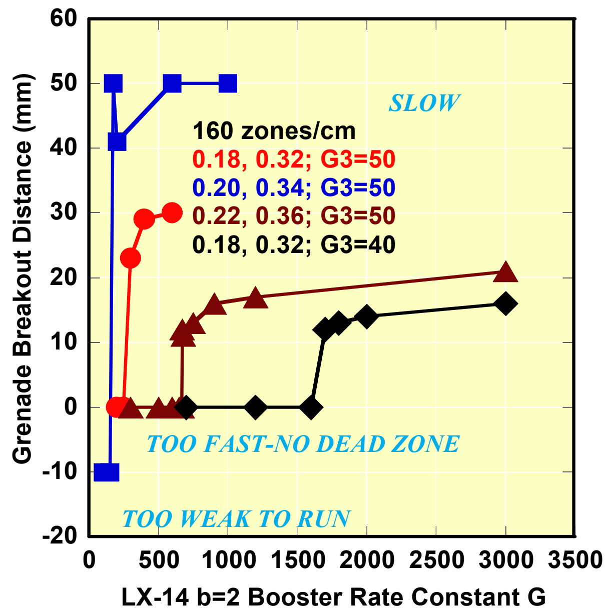

Figure 11. Effect of changing the P_1-P_2 region size at 160 zones/cm for the hand grenade. The LX-17 rate is set at b_2 =0; G_2 = 23 to 27.

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