ARMY RESEARCH LABORATORY

Experiments in a 120-mm Ram Accelerator at Elevated Pressures

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13. ABSTRACT ***(Maximum 200 words)***

Ram acceleration is an emerging propulsion technology in which a projectile similar in shape to the centerbody of a ramjet aircraft engine is injected into a tube filled with a combustible gaseous mixture. As the projectile moves into the tube under supersonic conditions, shocks occur on and around the projectile. If the gases ignite, the combustion can be self-sustaining, generating a localized high-pressure region that travels with the projectile producing acceleration. Velocities of more than 2.6 km/s have been experimentally demonstrated, while theory predicts velocities above 7 km/s are obtainable.

The U.S. Army Research Laboratory (ARL) is studying the physics of the ram acceleration process through an integrated experimental and computational fluid dynamics effort. ARL operates the world's largest ram accelerator at 120-mm bore size.

Initial experimental results at this facility are presented. In addition, data from experiments at gaseous fuel pressures up to 102 atm are presented. Impact of "high pressure" operation on facility design and application are considered. Finally, future plans are summarized.

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1. BACKGROUND

1.1 The Process. Ram acceleration is an emerging propulsion technology capable of accelerating large masses to hypervelocities. Ram acceleration is produced when a suitably shaped projectile is injected at supersonic velocity into a tube prefilled with a combustible gas mixture. As the projectile enters the tube, gas shocks are produced. These shocks heat, slow, and pressurize the gas, causing combustion to occur around and behind the projectile. This combustion process travels with the projectile producing continuous acceleration over the length of the accelerator tube. The in-tube ram accelerator concept, developed by the University of Washington's (UW) Aerospace and Energetics Research Program, is an offshoot of ramjet engine technology (Hertzberg, Bruckner, and Bogdanoff 1988; Knowlen, Bruckner, and Hertzberg 1992; Hinkey, Burnham, and Bruckner 1992). The process is shown in Figure 1.

1.2 The Army Research Laboratory and Ram Acceleration. In 1991 the U.S. Army Research Laboratory (ARL) embarked on a program entitled Hybrid Inbore Ram Acceleration (HIRAM) (Kruczynski 1991a, 1991b). The term "hybrid" naturally rises from the fact that, currently, ram accelerators require a prelauncher to bring the ram projectile up to take over velocity for the ram process. The HIRAM program was designed to develop a launcher for economically and routinely accelerating 7-kg masses to velocities approaching 3 km/s for hypervelocity launch and terminal effects studies. The HIRAM system was designed with significant expansion capability to study other applications such as terminal missile defense and ground-launch-to-space.

The ARL test facility consists of accelerator tubes made from retired 120-mm M256 tank guns, machined and mated. Transition from the solid propellant launcher to the accelerator is made through a transition/vent section. This section serves the dual purpose of decoupling the conventional launch gun recoil from the accelerator (sliding interface) and venting the backpressure from the conventional charge combustion. The HIRAM facility was initially designed to accommodate five 4.7-m-long accelerator tubes for a total combined length of 23.5 m. Expansion to 60 m is possible. The initial experiments reported here were performed using a single 4.7-m accelerator section. Gases are supplied from a bottle farm and diaphragm compressor capable of supplying five different gases at pressures up to 341 atm. A large vacuum pump installed near the accelerator is capable of evacuating any part of the launch/vent/accelerator assembly as desired.

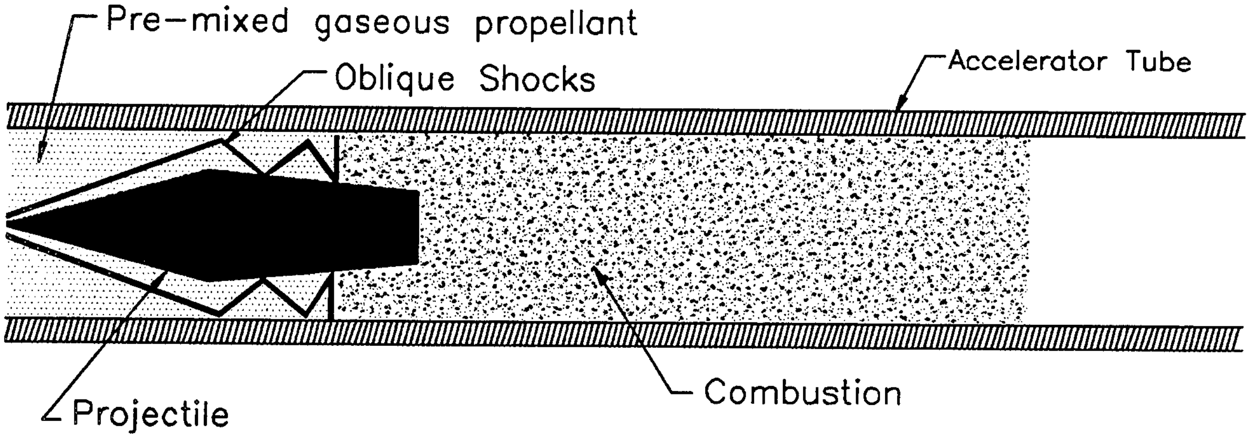

Figure 1. Schematic of ram acceleration process.

Instrumentation within the accelerator tube includes wall-mounted quartz pressure transducers and photodiode gages. High-speed movie and still-frame (smear) cameras are employed at various locations around the accelerator. Doppler radar and other devices are used to measure projectile exit and inbore velocity. Gas samples are taken just prior to firing for later analysis. The projectile is made of high-strength aluminum alloy and weighs 4.29 kg. Kruczynski (1991b) provides additional details about the HIRAM facility.

1.3 Scaling Tests. Following 19 months of extensive experimental and computational fluid dynamics (CFD) efforts, the HIRAM program was successful in demonstrating ram acceleration in the largest ram accelerator in the world, at 120-mm bore diameter (Nusca 1991a, 1991b, 1992; Kruczynski and Nusca 1992; Kruczynski 1992). The results from these initial firings in a 4.7-m-long accelerator tube are shown in Table 1. These tests represented the second time the technology has been successfully scaled (see Giraud et al. [1992] and Giraud, Legendre, and Simon [1992] for details of the Institute of Saint Louis [ISL] 90-mm cal. work).

2. "HIGH-PRESSURE" FIRINGS - THE RATIONALE

2.1 Accelerator Fill vs. Combustion Pressure. In firings conducted at the UW ram facility, a relatively linear relationship between the accelerator fuel/oxidizer/diluent pressure and the peak combustion pressures achieved during operation was established. In general, combustion pressures were about 15 to

Table 1. Scaling Tests in 120-mm Ram Accelerator

Test No.	Entrance Velocity (m/s)	Exit Velocity (m/s)	Velocity Gain (m/s)	Average Acceleration G's
15	1,175	1,419	244	7,800
16	1,178	Injection Test		
17	1,190	862	Unstart	
18	1,180	1,440	260	8,400
19	1,182	1,410	228	6,200

20 times the level of the fuel/oxidizer/diluent pressure (Kruczynski 1992). This relationship had been verified at fuel/oxidizer/diluent pressures up to 50 atm in experiments at the UW.

In the remainder of this report the term fuel/oxidizer/diluent will be referred to simply as fuel.

The ARL ram acceleration facility is unique among current facilities in its ability to operate at much higher fuel pressure. The current design of the HIRAM facility allows for operation at fuel pressures exceeding 100 atm. The series of "high-pressure" firings reported herein was designed to exploit this ability and develop data for fill vs. combustion pressure at much higher pressures than previously obtained.

2.2 Performance. The second reason for conducting these "high-pressure" firings is based on HIRAM performance requirements. With projectile properties such as throat diameter, cone angle, afterbody angle, and material identical, the projectile mass increases much more quickly than the projectile area available for the propulsion pressures to act upon as systems are scaled up. Table 2 compares typical physical data and empirical performance estimates to obtain 10,000 G's of constant acceleration in the three current facilities.

It is apparent from Table 2 that as accelerator scale increases, either operating pressures or accelerator lengths must be increased to obtain similar velocity gains. Indeed the ability of the ram accelerator to trade off length with operating pressures (acceleration) and vice versa is one of the technologies' greatest attractions.

Table 2. Typical Properties of Current Ram Accelerators

Property	System Caliber (mm)		
	38	90	120
Projectile mass (kg)	.09	1.23	4.29
Throat Area (m^2)	0.00066	0.00385	0.00665
Mass/Area (kg/m^2)	136	320	645
Combustion Pressure for 10 kG's Constant Acceleration (Atm)	132	309	625

As previously mentioned, in the HIRAM system, it was deemed desirable to operate at higher pressures than previously attempted to shorten the required accelerator length for the comparatively heavy projectile.

2.3 Chemical Kinetics. The final reason for these higher pressure firings was the possibility of learning more about the chemical kinetics of high pressure methane combustion for use in CFD codes. It was felt that increases in peak and average combustion pressures at several elevated pressures might be empirically related to combustion rate coefficients. These data might be used to fine-tune inhouse CFD codes until more robust data were available. This work is still in progress and will be reported in the future.

3. "HIGH-PRESSURE" FIRINGS

As shown previously in Table 1, the first HIRAM firings were conducted with fuel pressures of 50 atm and a fuel mixture (on a molar basis) of $2O_2 + 10N_2 + 3CH_4$. This fuel mixture (and projectile entrance Mach number) was kept constant in the high-pressure series. At a fuel-to-combustion pressure ratio of 20, this would produce combustion pressures near the HIRAM's safe operating limit of 2,000 atm at fill pressures of 100 atm.

Figures 2–5 show typical pressure vs. time curves measured at the accelerator wall as the projectile and combustion pass a point approximately midway into the 4.7-m-long accelerator section. Figure 2 is

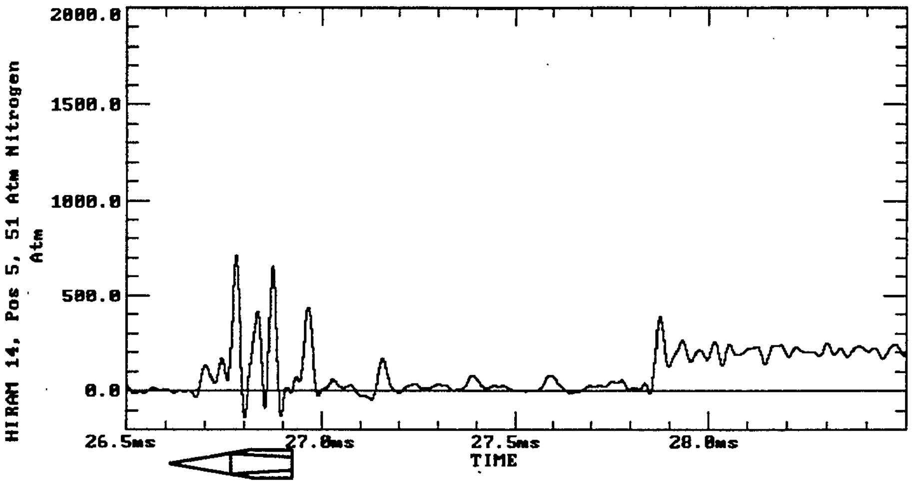

Figure 2. HIRAM shot into 51 atm nitrogen. Projectile scaled to local velocity.

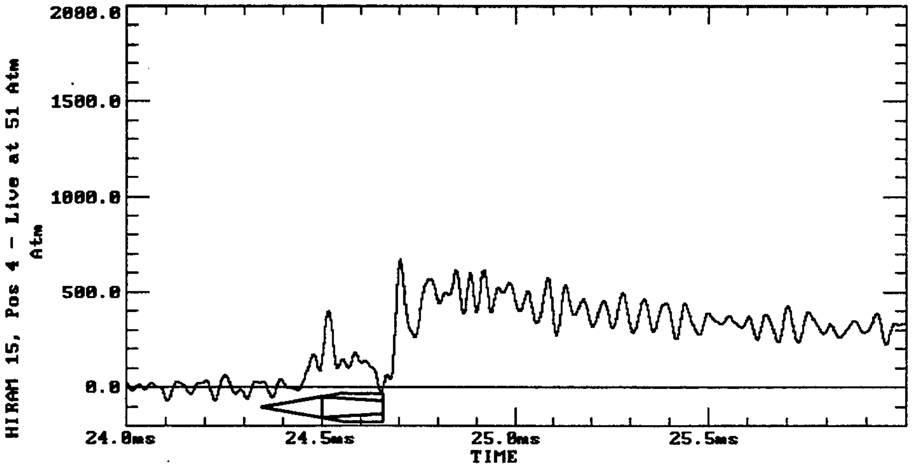

Figure 3. HIRAM shot into 51 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

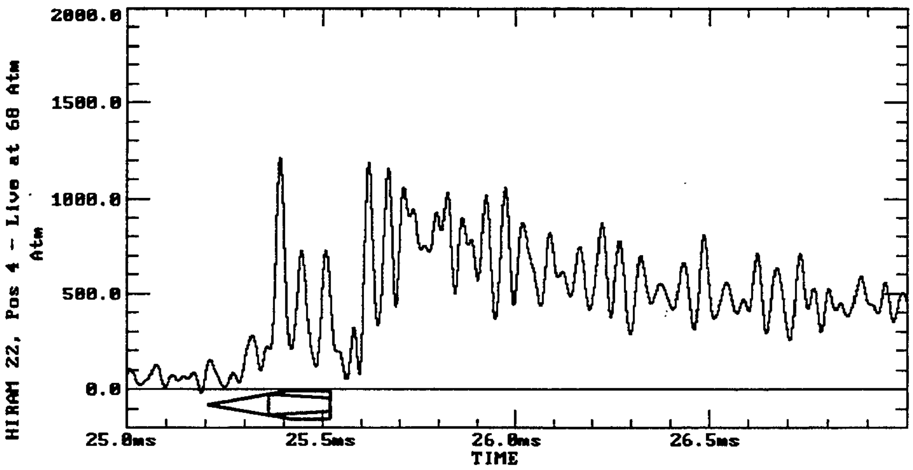

Figure 4. HIRAM shot into 69 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

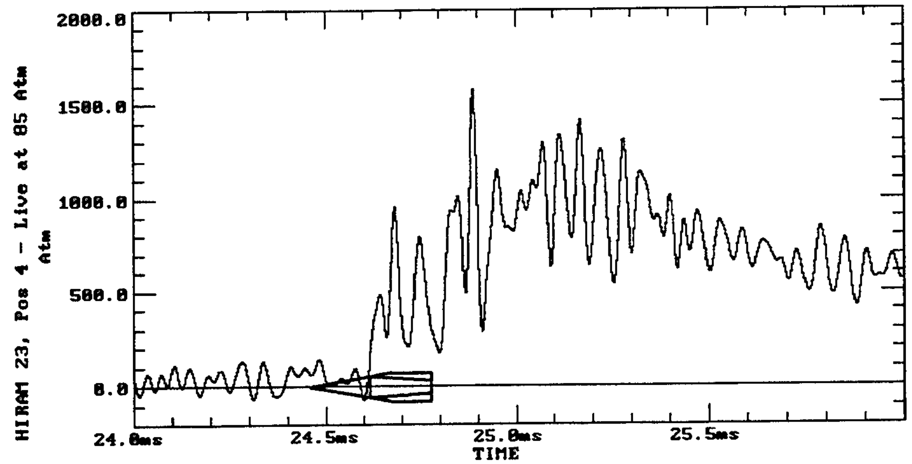

Figure 5. HIRAM shot into 85 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

for an inert firing with the accelerator charged to 51 atm of nitrogen. Figures 3–5 show data from live gas shots conducted with fuel pressures of 51, 69, and 85 atm. Note that Figures 3–5 (plotted with the same maximum ordinate) show a steady progression of combustion pressure levels as fuel charge pressures are raised. High-speed movies of the projectile and combustion exiting the accelerator reveal that as the combustion pressures rise, the intensity of combustion increases (as revealed by increased light emission).

Figure 6 shows the relationships between the fuel fill pressure and the resultant peak combustion pressure. Note, that for this fuel mixture and entrance Mach number, the ratios of peak combustion pressure-to-fuel charge pressures are 13, 18, and 19, respectively. Although there seems to be a slight increase in this ratio as the fuel pressure is increased, these values are consistent with those reported earlier by UW at lower pressures and higher heat release values (Kruczynski 1992). Note that the relatively low pressure ratio value for the 51-atm shot may indicate that this fuel mixture is at the low end of allowable heat release values to sustain combustion.

The velocity gain vs. fuel and combustion pressure relationship is not completely clear due to several effects. For instance, in the shot with 69 atm of fuel pressure, a small steel nosetip used at the front of the aluminum projectile to assist in piercing the diaphragms came off at some point in the accelerator. Although the projectile did not unstart (combustion moves forward of projectile), there was considerable combustion activity around the nose area at projectile exit. This combustion along with additional drag from the large, flat, exposed frontal area combined to reduce the velocity gain in this shot to 65 m/s. For

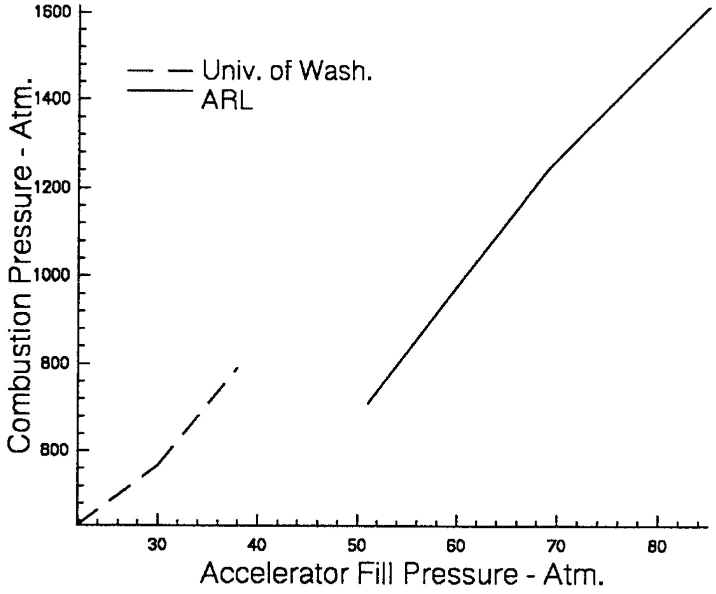

Figure 6. Plot of peak combustion pressure as a function of fuel pressure.

reference, the shot with 51-atm fuel pressure achieved a 249-m/s velocity gain. The shot at 85 atm achieved a 297-m/s gain. Although this is not quite the velocity gain expected for the drive pressure produced, some of the difference is probably accounted for by higher drag at the increased fuel pressures and some combustion activity ahead of the throat due to faster fuel kinetics at the higher pressures. Also, variability in fuel composition could reduce the velocity gain.

In short, there are too few data points at this time to draw conclusions relative to velocity gain at these higher pressures although a positive trend is clearly seen in the 85 atm shot. A shot conducted at a fuel pressure of 102 atm resulted in an unstart shortly after entry into the ram accelerator and is detailed in the next section.

4. "HIGH-PRESSURE" UNSTART

A shot attempted with the fuel pressure at 102 atm resulted in an unstart after a meter of projectile travel in the accelerator. Figures 7–10 show the pressure curves at various positions in the accelerator during this shot. In Figure 7, the projectile has just entered the accelerator and the initial pressure plot shows a started diffuser much like previous successful shots. The next position (1.15 m into the accelerator), shown in Figure 8, reveals an incipient unstart condition. In Figures 9 and 10, the "combustion wave" is seen to overtake and outrun the projectile.

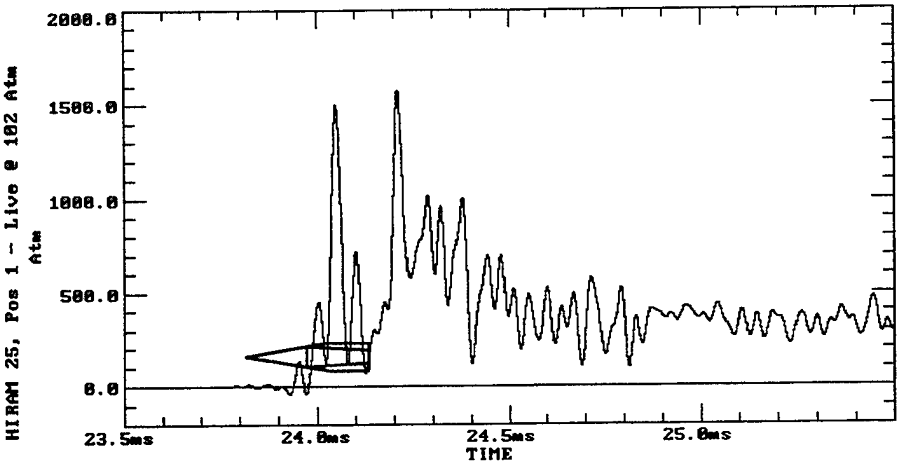

Figure 7. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Diffuser is starting.

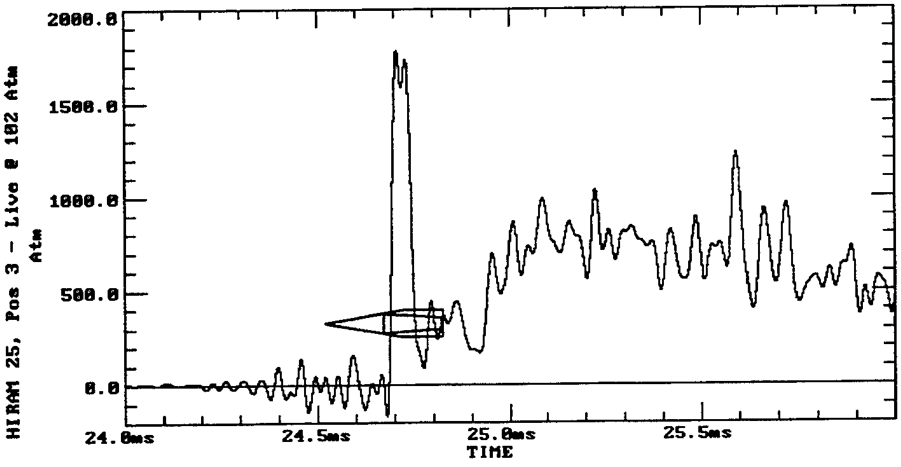

Figure 8. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Incipient unstart condition.

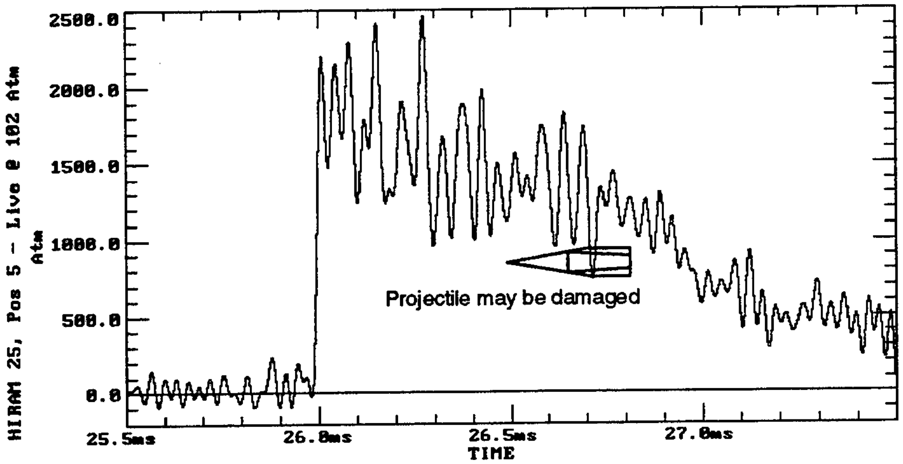
Projectile may be damaged

Figure 9. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Combustion wave is masking projectile location.

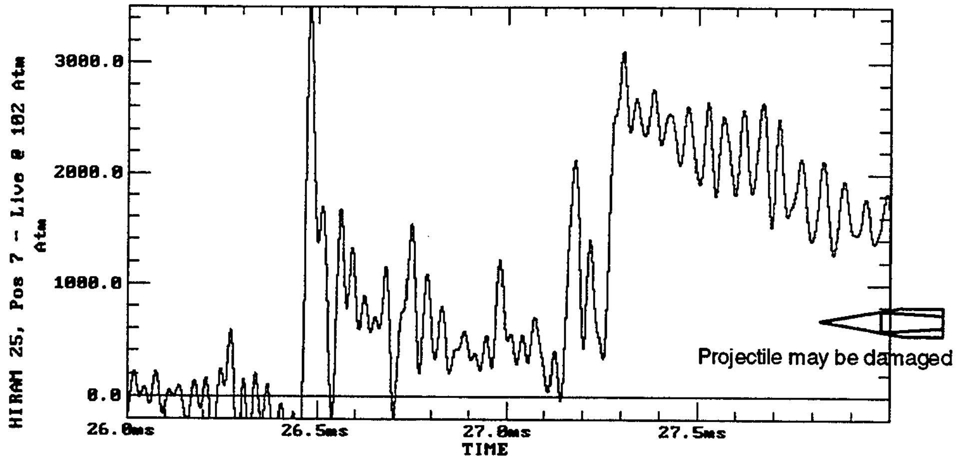

Figure 10. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Detonation wave has outrun projectile.

High-speed movies of this shot clearly show two zones of combustion at the accelerator exit. The first is a narrow combustion zone that breaks the end diaphragm. This is followed by a larger "dark zone" that exists for about a millisecond before a second and larger (and more violent) combustion occurs. This photographic evidence matches the pressure forms seen in Figure 10. Additional insight into these high-pressure phenomena is contained in Nusca (1993).

The exact cause for this, and many unstarts, is not certain. There are several possibilities that may, or more likely, may not be independent. The most obvious is that for this fuel mixture, the pressure increase causes chemical reactions to occur so rapidly, the projectile cannot "outrun" the intense combustion that occurs at the projectile-obturator interface. However, there was little evidence that this would occur from the earlier high-pressure firings up to 85 atm.

A second suspected unstart mechanism could be nonuniform mixing of the fuel gases that would cause local pockets of higher energy gases (Knowlen 1993). The HIRAM system is the only system that currently uses the partial pressure method to obtain proper gas ratios. Although samples taken at time of firing reveal that the mixtures are generally within the range desired, there is considerable variation from test to test. This variability is of some concern and is under further study. Of nine live-fuel shots performed to date in the HIRAM system, two have resulted in unexplained unstarts.

Finally, the structural integrity of the projectile may, in some cases, be suspect. In the two unstarts just noted, the projectile was broken into several pieces as detailed by exterior photography. It is more likely, however, that the unstart is the cause of projectile failure as high-pressure combustion drives through the throat and large deceleration loads are applied. This too is undergoing additional study.

5. EFFECTS OF UNSTARTS ON HARDWARE

During an unstart, the pressure may rise to levels 50 times the fuel pressure. This is contrasted with the 20 fold rise typically induced during normal operation. Designing a system with a pressure safety margin for unstarts may significantly increase tube length for a given velocity gain. For instance, an accelerator tube with a yield stress of 7,000 atm to be operated with a safety factor of 2 would require that operation be limited to fuel pressures no greater than 70 atm, 7,000 over 2 × 50. For applications where shorter tubes are of more interest than low acceleration levels, this constraint can be daunting.

During the high-pressure tests previously described, a conscious decision was made to operate with fuel pressures sufficient to cause combustion pressures in excess of accelerator and projectile yield strength in the event of an unstart. It was felt by the investigators that sufficient evidence existed that such events might either be artifacts of gage response, or of such short duration that the accelerator tube would not respond to the narrow, short-duration pressure spikes. Gage malfunctions cannot be ruled out as the cause for these spikes, however, considerable data exists at UW that supports the conclusion that these are indeed real events (Knowlen 1993).

During several recent unstarts in the HIRAM system, the design yield strength of the accelerator tube has been exceeded by 10% or better based on short-duration pressure spikes measured at the accelerator wall. These pressure spikes vary in duration from approximately 0.05 to 0.1 ms. Subsequent inspections of the tube inside with a borescope (visual inspection) and outside with magnetic particle and eddy current techniques revealed no wear or damage of any type. The long-term effects of overloading the tube in this manner on fatigue life are not clear.

The authors ARE NOT recommending that these short-duration pressure spikes be ignored. However, for protected test ranges where a tube failure could be safely contained, the risk involved in an occasional moderate pressure unstart approaching or slightly exceeding the yield stress of the tube material may be an acceptable calculated risk. As ram accelerator phenomenology is better understood, and the technology is focused on well-known and repeatable conditions (such as would be encountered in a fielded weapon), it should be possible to design systems in which unstarts would be eliminated or reduced to an acceptable level.

6. SUMMARY AND CONCLUSIONS

It has been shown that:

- Ram acceleration technology can be scaled relatively easily to larger bore sizes capable of carrying useful payloads.

- Ram accelerators can be safely operated at fuel pressures over 100 atm and combustion pressures approaching 1,700 atm. Safe operation at even higher pressures is thus quite possible. The ability to operate a ram accelerator at "high pressures" is of considerable value for applications more concerned with short launchers than high acceleration loads.

- High-pressure unstarts, while a cause for continued concern, do not necessarily limit the upper operating range of ram accelerators for some applications.

7. FUTURE

Future work in the HIRAM facility will key on flow visualization and other diagnostics, and increased performance (optimization) techniques.

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