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X3 reflected shock tunnel for extended flow duration

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Abstract

The X3 expansion tube is a major test facility, 65 metres long, designed primarily for the production of superorbital flow conditions. This paper reports on the results of a feasibility study for an alternative lower speed operational configuration whereby it can operate as a reflected shock tunnel for simulating flows in the flight regime from Mach 5 to 8. Due to its large internal diameter (182.6 mm) and significant length, it offers the potential for test times of the order of 10's of milliseconds. Due to the restrictions imposed by the free piston driver at such low shock speeds, the length of the driven section of the tube will be restricted to approximately 22 metres. This modification promises to provide a useful new operating capacity in situations where the phenomena to be studied require steady flow durations ~10's of milliseconds, compared to times of less than 1 millisecond obtained in expansion tube mode.

Keywords: "Hypersonics; ground test facility; expansion tube; reflected shock tunnel"

1. Introduction

The X3 expansion tunnel was designed for simulation of superorbital flows and high Mach number, high total

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pressure, scramjet flight conditions. It can support a driven tube length of up to 34 metres, has a bore of 182.6 mm, and has a free piston driver with 15 metres stroke. When operating in the expansion tunnel configuration, it has useful test flow durations of up to ~ 1 millisecond.

Due to its length and bore, its versatile driver and high pressure containing capability, it also has potential to be configured as a very useful reflected shock tunnel (RST) facility for lower Mach number and lower total enthalpy conditions with much longer test times. Preliminary analysis indicates that in this operating mode, flow durations up to the order of 10 milliseconds will be achievable at Mach numbers between approximately 5 and 8, and total pressures up to the order of 10 MPa.

At these low speed conditions the driver cannot support such long driven tubes in the RST configuration, because the free piston device cannot maintain the quasi-steady driver conditions long enough. Driven tube lengths of between 16 and 22 metres are considered to be appropriate for this application, as shown in Figure 1.

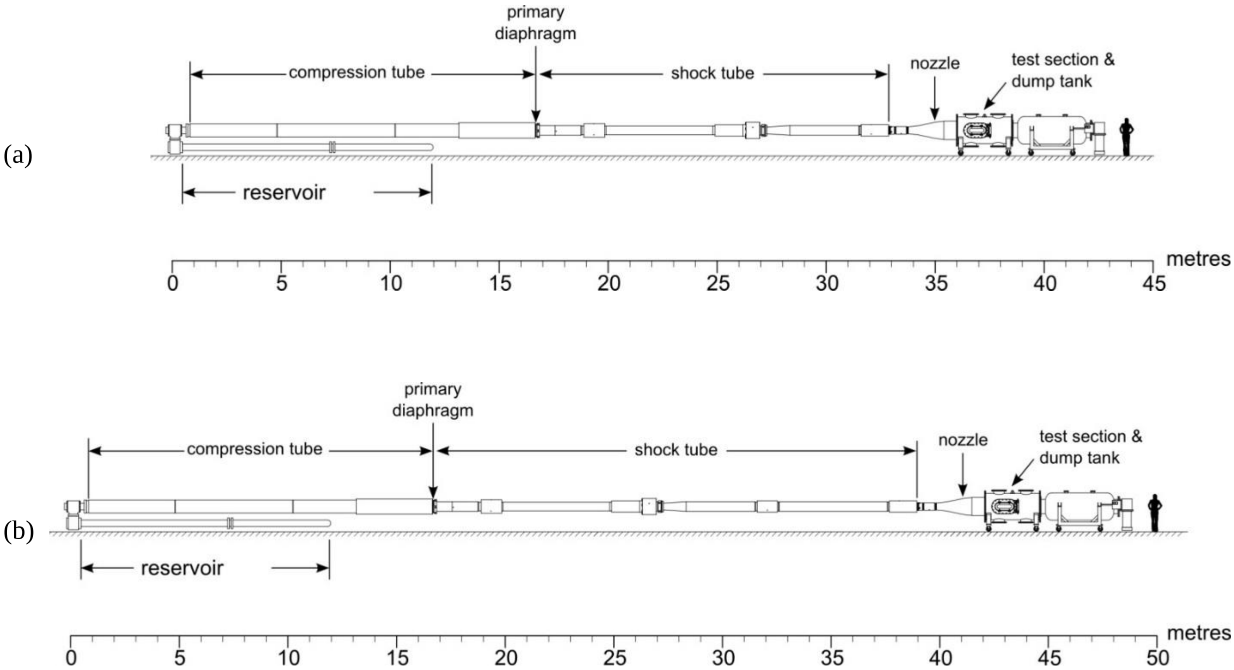


Figure 1 X3 configured as a reflected shock tunnel with driven tube lengths of (a) 16 metres, and (b) 22 metres.

2. Operation of the free piston driver

The theoretical test times available from reflected shock tunnels operating in the tailored interface mode are only achievable if the other unsteady flow processes associated with impulse facility operation can be isolated from the test section until after the useable test gas has drained from the reflected shock stagnation region. Two of the primary perturbing effects are the unsteady ‘u-a’ wave which expands the driver gas into the driven tube (shown in blue in Figure 2), and the reflected ‘u+a’ unloading wave (shown in green) which reflects off the end of the driver tube and which will eventually catch up with the test gas if the driven tube is sufficiently long. The relative lengths of the different tubular sections determine which of these effects will terminate the useable flow, and in a design

configured for maximum test time, all the perturbing effects will arrive at the test section just as the last of the test gas is used up. For the conditions relevant to this proposal, the arrival of the u+a wave is identified as the terminating parameter. This effect can be delayed as required by the use of a longer driver section, and this is the approach conventionally taken. However, the driver section has to be built to withstand very high pressures (typically up to the order of ~100 MPa), and the need for high driver gas sound speeds also requires the use of high temperatures, resulting in prohibitively expensive components when large scale facilities are required. In addition to this consideration, most of the driver gas is not used directly to transfer energy to the driven gas, but acts merely to set the upstream boundary condition required to delay reflection of the u+a wave created at diaphragm rupture.
The approach taken in the X3 facility is to use the free piston driver technique first pioneered by Stalker (1959) which uses a moving piston to both compress and heat the driver gas, and to provide a moving wall boundary condition which counters the loss of driver gas through the ruptured diaphragm, and maintains quasi-steady pressures and temperatures in the driver after rupture.

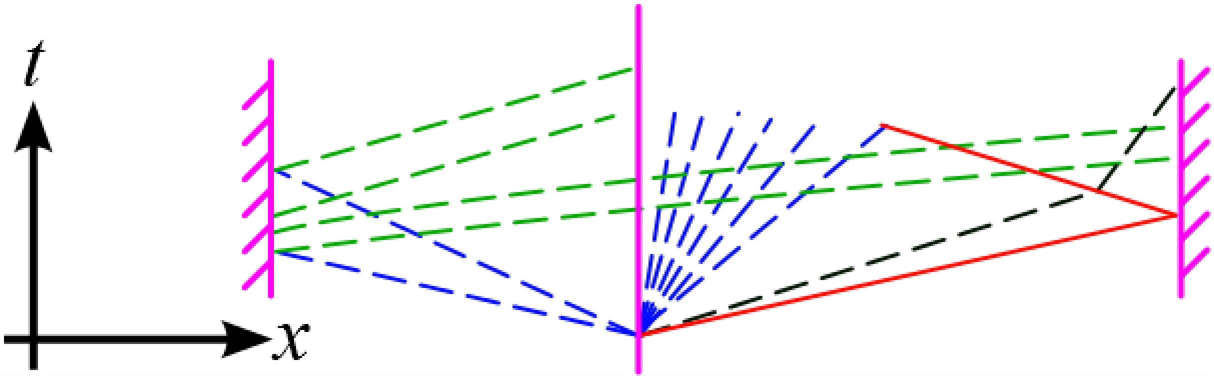


Figure 2 Reflected shock tunnel with conventional driver

The operation of the process is shown schematically in Figure 3. A representative sample of the typical pressure and temperature dependency after diaphragm rupture (from a different facility) is shown from numerical analysis in Figure 4, and the associated ‘steady’ flow conditions in the reflected shock stagnation region are shown in figure 5.

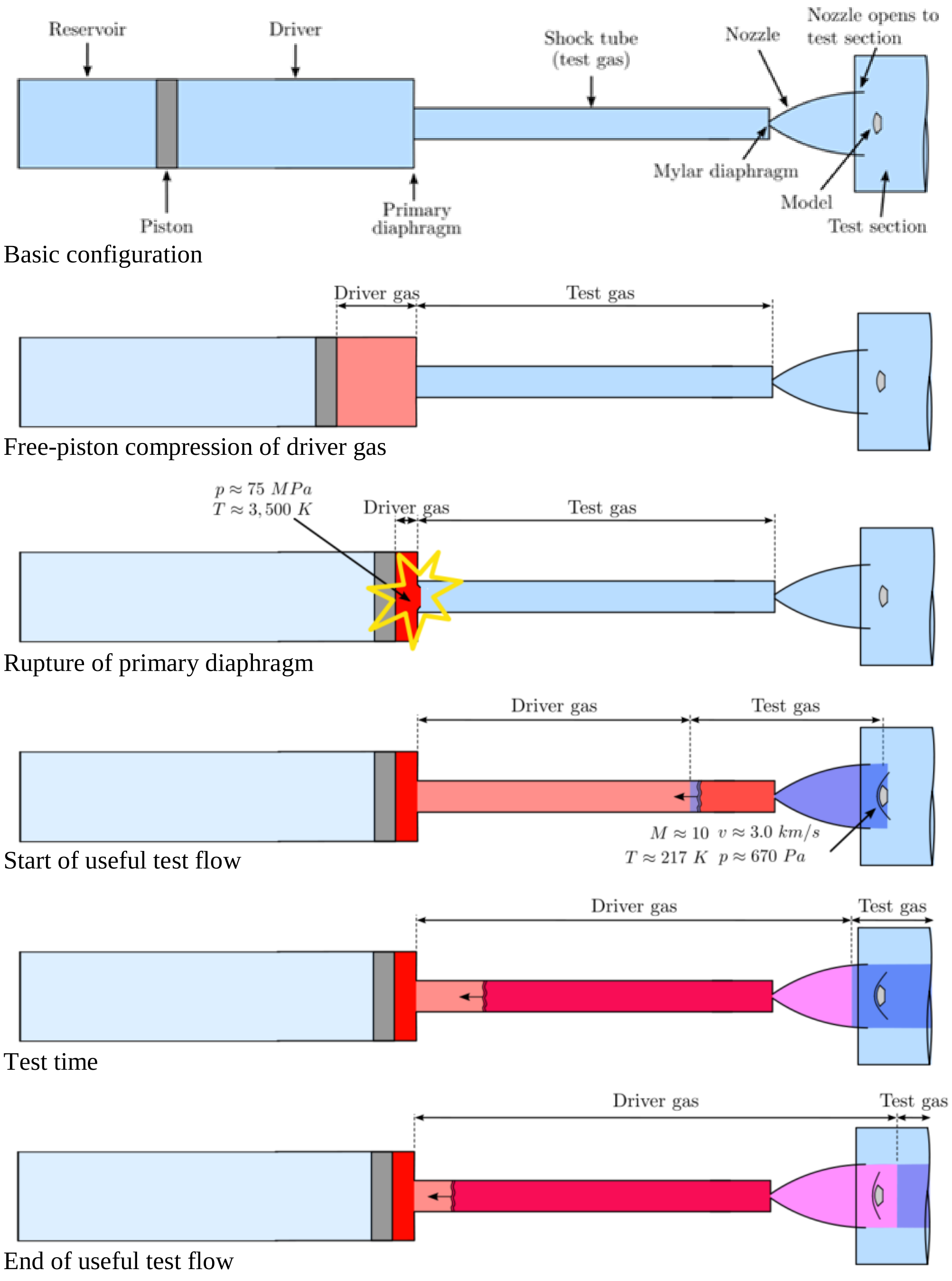


Figure 3 Operation of reflected shock tunnel and free piston driver

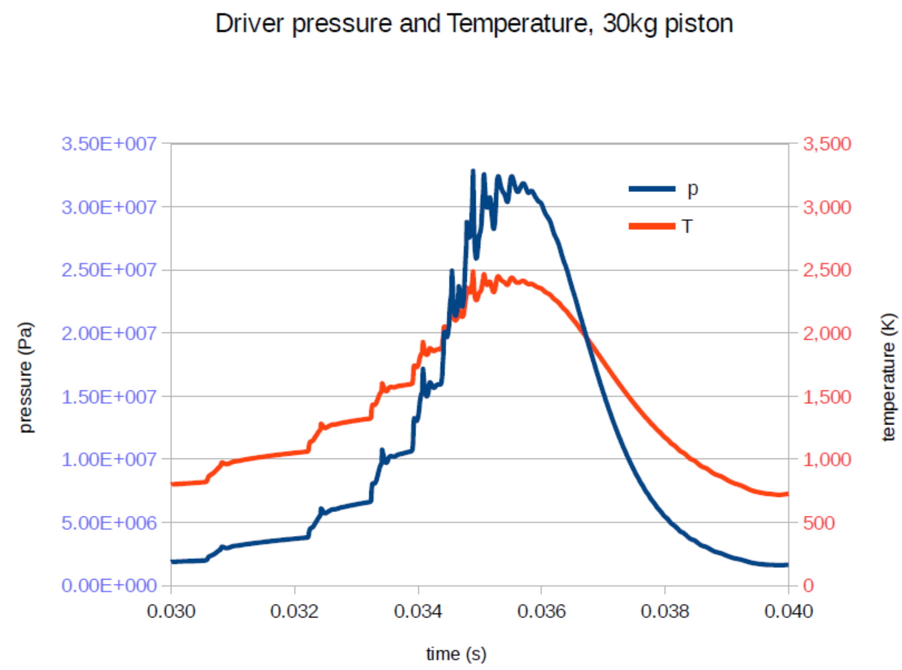


Figure 4 Numerical simulation of the post rupture driver conditions in a free piston driver

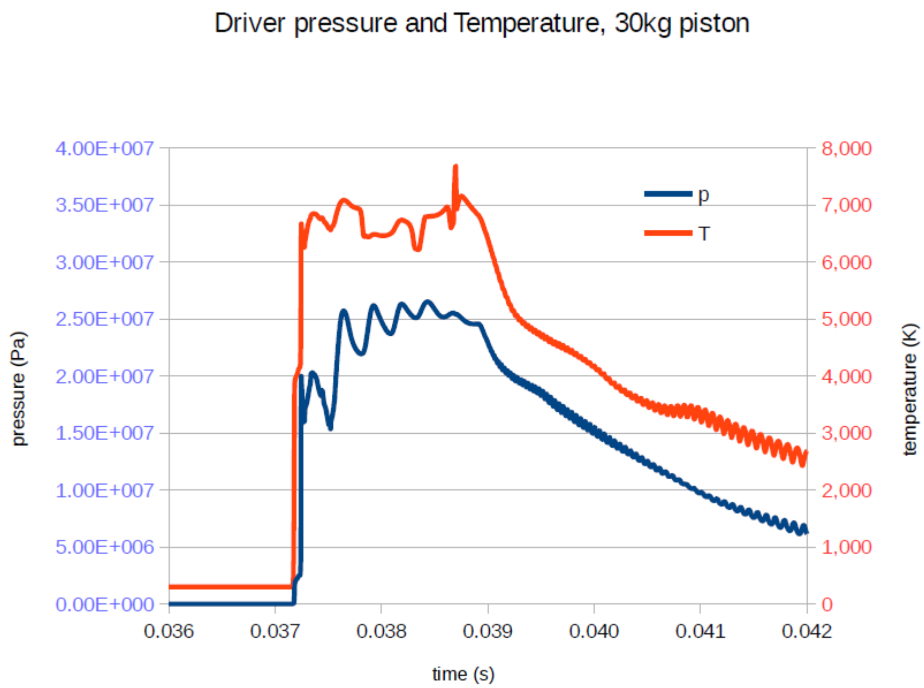


Figure 5 Numerical simulation of the stagnation conditions relating to figure 4

This application is unusual because the requirement for long testing time necessitates holding times of the order of 10's of milliseconds rather than single digit milliseconds. The 'holding time' of the driver is controlled by the piston dynamics, and the requirement to stop the piston before it reaches the end of the driver tube.

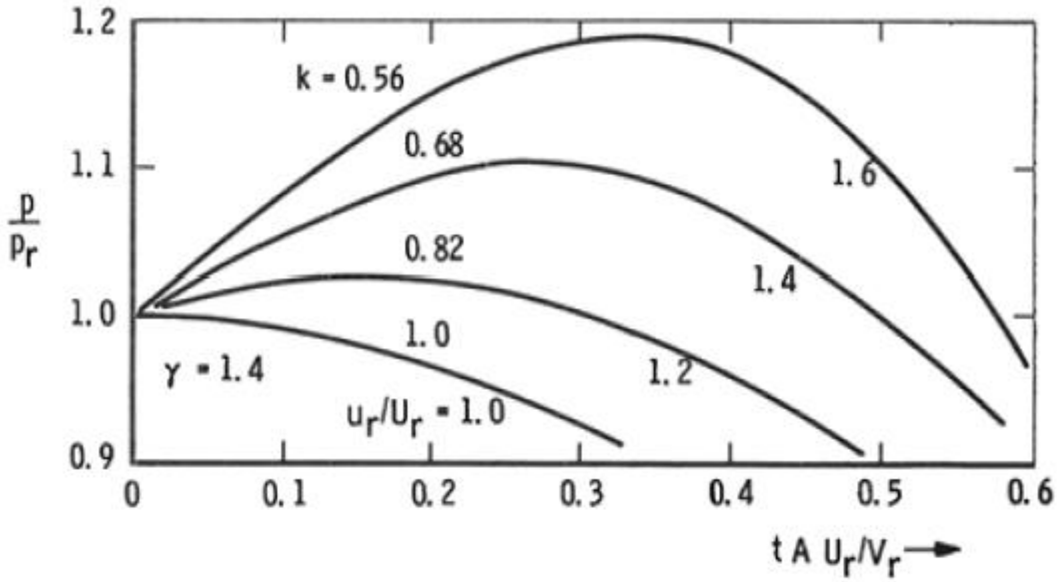


Figure 6 post rupture pressure variation in free piston driver (from Stalker 1959).

The transient behaviour is characterised by the piston velocity at rupture (u_r in figure 6), normalised by the piston velocity required (U_r) to instantaneously match the flow through the orifice at rupture. A value of u_r/U_r of ~ 1.4 is found to be a suitable value to give a good combination of long holding time and minimal pressure variations in the time of interest. The non-dimensionalised time ordinate on the horizontal axis incorporates piston area (A) and volume of compressed driver gas, V_r. Each condition requires an appropriately selected piston mass. When used under these conditions, the effective holding time is $\sim 0.5 \frac{V_r}{U_r A}$.

To maximise holding time one or both of the following steps are necessary:

- Increase V_r, which is done by reducing the compression ratio of the piston stroke
- Reduce the required piston velocity at rupture, U_r

Reducing the compression ratio is very effective, but requires more physical compression work to reach the same pressures, and results in a lower temperature and sound speed in the compressed driver gas, which necessitates the use of higher rupture pressures to reach the same shock speeds and flow enthalpy. Fortunately, the pressure requirements of the low Mach number conditions being targeted are relatively mild compared to the normal operating conditions for the facility, and this approach has been taken as there is reserve 'piston pushing' capacity. (The lower driver sound speeds can be compensated for by using a lighter driver gas (i.e. putting more Helium in the Helium/Argon gas mixtures used), but then this leads to the need for a higher associated piston velocity and reduces the holding time, thus partially offsetting the benefits of the longer slug of compressed gas).

The required piston velocity at rupture, U_r, can be reduced by using a lower sound speed in the driver gas (which is a function of compression ratio and gas composition) and restricting the orifice area after diaphragm rupture to extend the period over which the driver gas drains into the driven tube. Both of these actions mean that a higher pressure is required to drive the same shock speed, and again, the facility has reserve capacity due to the (relatively) low shock speeds. When extending the holding time in this manner, a higher piston mass is required, and we currently have pistons ranging between 100 and 280 kg, which are suitable for the proposed conditions.

Determining a suitable configuration for any selected flow condition requires optimisation of many parameters, including the lengths of the various tubular sections, driver gas and compression ratios, rupture pressures, piston mass and orifice plate diameters. Some of the preliminary analysis is shown in table 1 on the following page, with pressures set to ensure tailored interface operation, and a series of proof of concept studies is proposed to experimentally validate some of the condition. The reflected shock configuration could support nozzle throat diameters up to ~ 75 mm, which would require nozzle exit diameters between about 370 and 750 mm for exit Mach numbers from 5 to 7 (perfect gas inviscid estimate).

3. Conclusions

The modification of X3 for reflected shock tunnel operation is feasible, and an economically efficient way to extend the operating capability of the facility down to the low Mach number flight regime where longer test times than are available in expansion tubes are required to study certain features of hypersonic flows. Due to the need for longer piston 'holding times' in this configuration, the whole driven length of the facility will not be used, and a driven length of between 16 and 22 metres is proposed.

4. References

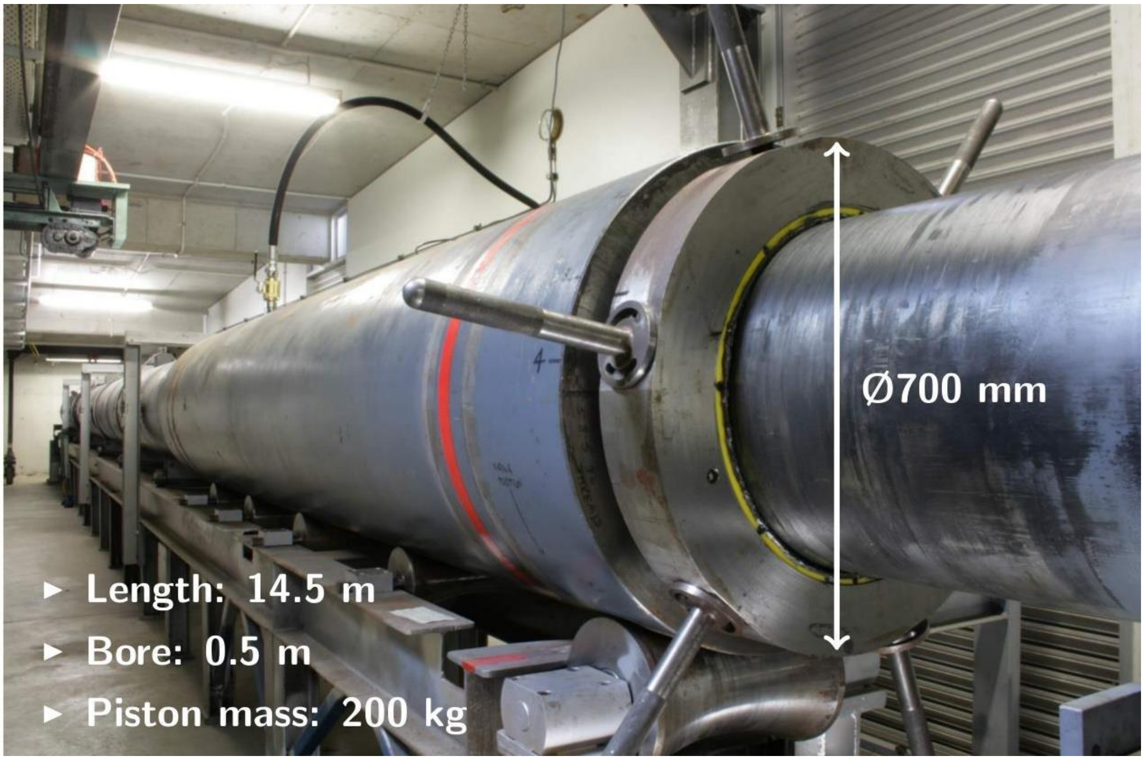
R.J. Stalker and R.W. Besant (1959): A method for production of strong shocks in a gas driven shock tube. *National Research Council, Division of Mechanical Engineering, Ottawa, Canada, Laboratory Memorandum, Gas Dynamics Laboratory Section*, 19th Oct, Report Number GD-81.

Gamma=1.4, Argon driver												
M6	**T4 (K)**	**Us (m/s)**	**T5 (K)**	**Ho5 (J/kg)**	**P5 (Pa)**	**P6 (Pa)**	**T6 (K)**	**rho6 (kg/r**	**U6 (m/s)**	**q (Pa)**	**slug lengt**	**drainage time (s)**
5	1932	1076.3	1508	1.51E+06	1.51E+06	2857	251	0.0396	1589	49992	2.220	0.0283
6	2629	1284.6	2054	2.06E+06	3.14E+06	1987	250	0.0276	1903	50066	1.882	0.0206
7	3450	1492.9	2695	2.71E+06	6.05E+06	1461	250	0.0204	2217	50127	1.689	0.0161
8	4395	1701.2	3432	3.45E+06	1.09E+07	1116	249	0.0156	2529	49982	1.568	0.0132
Gamma=1.33, Argon driver												
M6	**T4**	**Us**	**T5**	**Ho5**	**P5**	**P6**	**T6**	**rho6**	**U6**	**q**	**slug lengt**	**drainage time**
8	4123.079	1658.149	2867.605	3.32E+06	2.26E+07	1173.827	248	0.0165	2462	49958.06	1.223	0.0116
Gamma=1.3, Argon driver												
M6	**T4**	**Us**	**T5**	**Ho5**	**P5**	**P6**	**T6**	**rho6**	**U6**	**q**	**slug lengt**	**drainage tim**
8	3997.201	1639.341	2625.988	3.27E+06	3.33E+07	1201.77	247.7347	0.0169	2432	49993.65	1.080	0.0108
Cold Helium driver gamma=1.35												
M6	**T4**	**Us**	**T5**	**Ho5**	**P5**	**P6**	**T6**	**rho6**	**U6**	**q**	**slug lengt**	**drainage tim**
6.5	290.6655	1363.73	2098.523	2.32E+06	6.44E+06	1757.997	250.0102	0.0245	2023.019	50135.89	1.515	0.0167

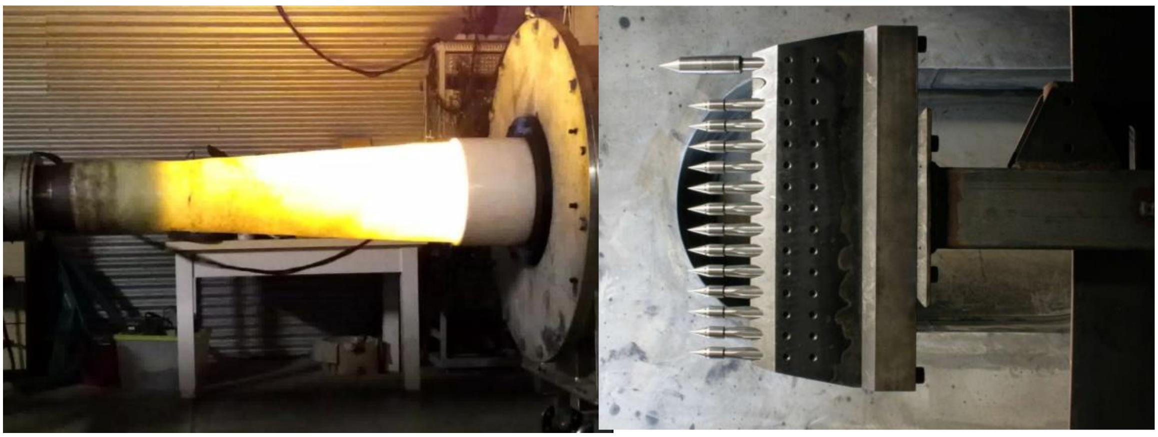
- Conditions subscripted 4 indicate driver
- Conditions subscripted 5 indicate reflected shock stagnation region
- Conditions subscripted 6 indicate expanded test flow
- Calculations performed with gammas of 1.4, 1.33 and 1.3 in the test gas to give some allowance of likely influence of real gas effects.
- Test section diameter is 1200 mm, length 2500 mm.
- Note: the theoretical drainage times all exceed likely holding time of free piston driver, which will effectively set the test time limit for the modified facility. This restriction could be removed if set up with a cold helium driver without piston as shown in the bottom row of figure 5. This could easily be done without physical modifications, but would use a lot of Helium.

Table 1 Estimated flow conditions from perfect gas analysis for 16 metre shock tube

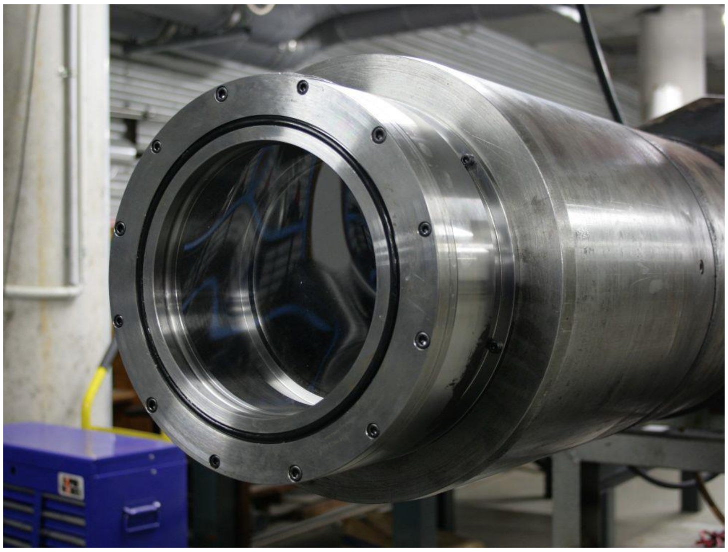
Pictures of the X3 facility as an expansion tunnel:



Free-piston driver.



Mach 10 nozzle for expansion tube configuration (left) and pitot rake (right).



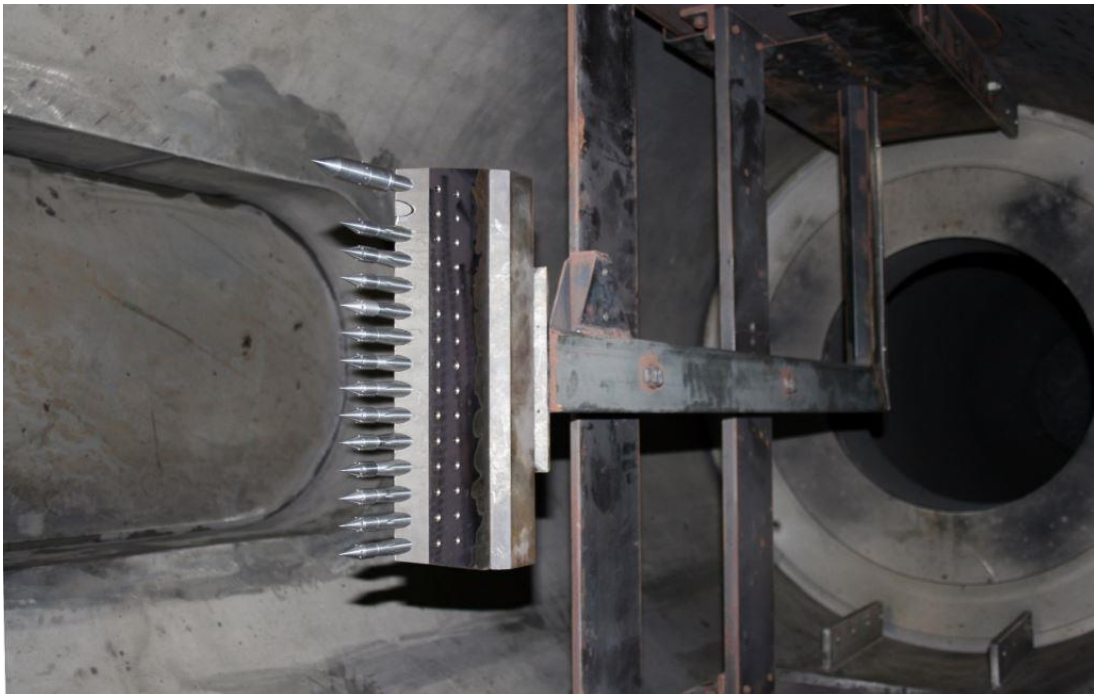
Vibration isolating diaphragm mount

Test section with Mach 10 expansion tunnel nozzle installed.

2 D scramjet in test section

2D scramjet in test section

Rail mounted Driven tubes with interchangeable sections



Pitot rake set up with conical measuring surfaces.