Appendix A

Safety Assessment

This Appendix contains a duplicate of the GALCIT Laboratory Safety Assessment filed at GALCIT. It describes the facility, potential hazards, and steps taken to mitigate them.

GALCIT Laboratory Safety Assessment

Facility or Experiment	Explosion Dynamics Laboratory Hydrogen Jet Combustion Facility
Location	Guggenheim 14/14A, bottle farm on the SE corner of Guggenheim
Responsible Faculty or Staff	Joseph Shepherd
Research Associates or Students	J. Christopher Krok

Introduction

The Hydrogen Jet Combustion Facility is designed to examine the transient combustion and explosion processes that occur when a high-temperature jet of hydrogen and steam is injected into a combustible atmosphere of air, steam and hydrogen. The facility constructed at Caltech is a second-generation experiment based on a facility and experiments carried out at the Rensselaer Polytechnic Institute (RPI) in Troy, NY, from 1990 to 1993. In that facility, design and operational issues were studied and over 125 experiments were completed in a two-year period of operation (Krok 1992, Ross 1993).

The design philosophy for our explosion test facilities is to insure complete containment and control over the experiment at all times. Although these experiments are designed to examine explosive events with uncertain outcomes, the initial conditions are always well defined and peak conditions can be bounded. The facility is designed as a pressure vessel to contain any possible event that can occur within the test envelope (with the exception of the schlieren windows; see later discussion). When appropriate, these events include detonations and transition to detonation.

These tests will result in a transient and spatially nonuniform load on the containment system. Although these loads are outside the scope of the existing design guides (Harvey 1974), it is possible (Shepherd 1992) to define an equivalent maximum working pressure using gasdynamic estimates of the pressure transients and elastic response of the vessel structure to dynamic loads. The pressure vessel is then designed using available standards such as the ASME Boiler and Pressure Vessel Code. Standard mechanical engineering practice was used to compute the moments and forces on all other components. The calculations are realistic as possible using hand computations and include the reduction in strength due to potential material flaws, stress concentrations and fastener limitations. The design goal is to specify a containment system that will operate within the limits of the materials with a factor of safety for design basis events and without catastrophic failure (within the ultimate strength of the material) for exceptional events. We have used these techniques to design a number of explosive facilities, including a detonation tube at BNL, the previous jet combustion facility at RPI and the detonation test section currently in use on the T5 free-piston shock tunnel at GALCIT.

In addition, safety features have been designed into the facility to minimize this exposure of the operators and building occupants to potential hazards, and to control and mitigate accidental gas releases. We have solicited the advice of the Safety Office of Caltech, pressure vessel manufacturers and the gas supply vendors in developing and implementing these safety features. The facility and these safety-related features are described in this document.

Lessons learned from RPI The facility at RPI was operated without any significant safety-related incidents, i.e., events which had the potential to injure the operators or bystanders. There were two events that were not part of the normal operating regime, but did no damage. These were two incidents of accidental ignition with the mixing system open, due to ignition system triggering by electrical interference. To prevent this in the GALCIT facility, the ignition system now has remote power and arming control, as well as a logic circuit that blocks power to the ignition modules unless all valves are closed.

Brief Description

After reviewing operation of the original facility at RPI, the new facility was designed to better simulate the desired test conditions, and made stronger to expand the experimental envelope and incorporate more safety features. The new facility is built around two pressure vessels: (1) the driver, a 6-inch diam. tube 4-ft. long; (2) the receiver, a 36-inch diam., 64-inch long pressure vessel. The total volume (driver and receiver) of the CIT facility is about 1.3 m^3. The driver and pressure vessel are connected with a special hydraulic closure of a design similar to that used in the 6-inch GALCIT shock tube. Figure 1 shows a schematic layout of the experiment.

The new facility has a 20% greater total volume over the old one, and the distribution of volume between driver and receiver is much different. The RPI facility had a 1:1 volume ratio, while the GALCIT version has a 1:40 ratio. The MAWP of the receiver has been increased by 25% to allow for combustion of more energetic mixtures. Some of the original support hardware has been reused, such as the gas fill panels and the ignition systems. Safety improvements have been added to this equipment wherever possible. The pressure vessels are new, and design and safety considerations were made at CIT. Other new systems include the electro-pneumatic valves, ignition safety and lockout system, and outside bottle farm. Although experience gained at RPI was used in the design of the GALCIT facility, the design calculations for new fixtures were done from scratch at CIT. Previous computations were re-examined for the RPI components that were reused. Every aspect of the facility was reconsidered from the standpoint of operations and safety.

A typical experiment begins with both the driver and receiver evacuated to less than 1 mbar. The driver is then filled to 1 bar with a rich mixture of hydrogen and oxygen, and the receiver is filled to 1 bar with a mixture of 50/50 air/diluent (nitrogen or steam), and some small percentage (0 to 10%) of hydrogen. The driver mixture is ignited by the discharge of a 15 kV pulse from an EG&G TM-11 trigger generator through an automobile spark plug. The diaphragm separating the driver and receiver is ruptured by the pressure rise, and a hot jet of hydrogen and steam enters into the receiver. If

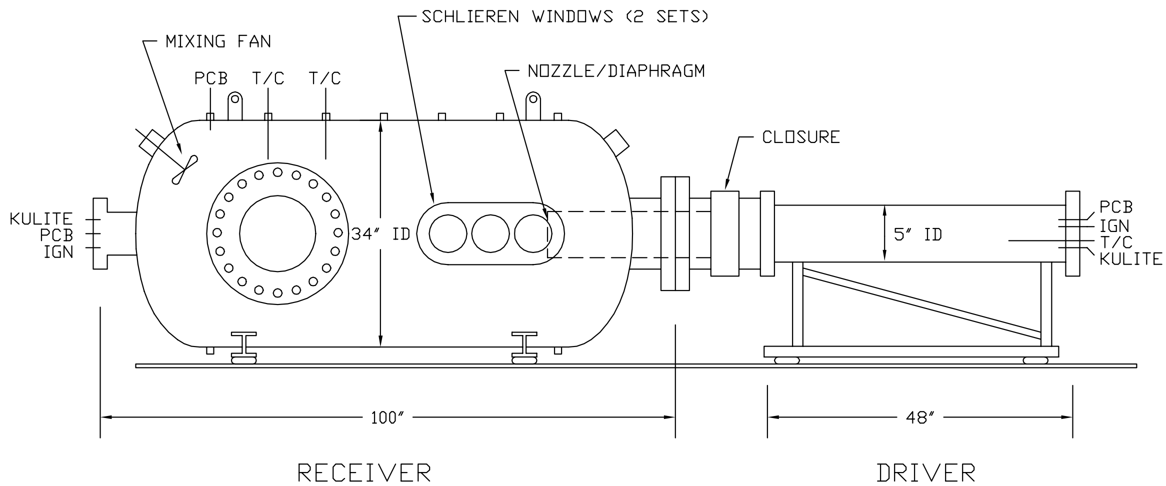


Figure A.1: Basic layout of experiment, showing both vessels.

critical conditions (sufficiently large jet diameter/or high enough hydrogen concentration in receiver) for jet combustion or deflagration exist, a combustion event will occur in the receiver.

With 10% hydrogen in the initial receiver mixture, this results in a peak pressure of approximately 4.1 bar (60 psi) in the receiver. The most commonly used driver mixture is 80% hydrogen and 20% oxygen; combustion of this mixture results in a peak pressure of 9.7 bar (140 psi) in the driver. Figure 2 shows a typical driver pressure history from the experiments done at RPI. A typical receiver pressure history is presented in Figure 5. Both of these traces illustrate the transient nature of the experiment and the short duration for which the vessels actually experience high pressures.

The experiment concludes by venting the combustion products (water, nitrogen and oxygen) through the vacuum pumps into the exhaust system and then into the atmosphere outside the laboratory. The exhaust system is a continuously-operating, high-velocity vent that is installed on the roof of the 2nd floor of "new" Guggenheim. Typically, the combustion products are diluted with air and the steam is condensed out prior to or during the venting process. If a combustion event does not occur, then the mixture is either diluted until it is nonflammable (less than 4% hydrogen) or else fuel and/or oxygen is added until a flammable condition is reached and the mixture is burned. If the receiver mixture doesn't burn initially, then it is already very close to the flammability limit. Thus, if dilution is chosen, no more than 40% nitrogen (400 mbar partial pressure) needs to be added to insure an inert mixture. This is added through the gas handling panel. The gas system can measure up to 2 bar absolute, and the standard starting condition is 1 bar, so the system can handle the additional pressure from dilution. Mixtures are always tested for flammability by several firings of the ignitors before the gasses are pumped out. This technique was used successfully at RPI so that combustible mixtures were never pumped through the vacuum lines or exhaust system.

The driver will always burn unless the mixture is grossly incorrect, e.g., nitrogen is added instead of oxygen, or if both ignition systems fail. Both of these events are

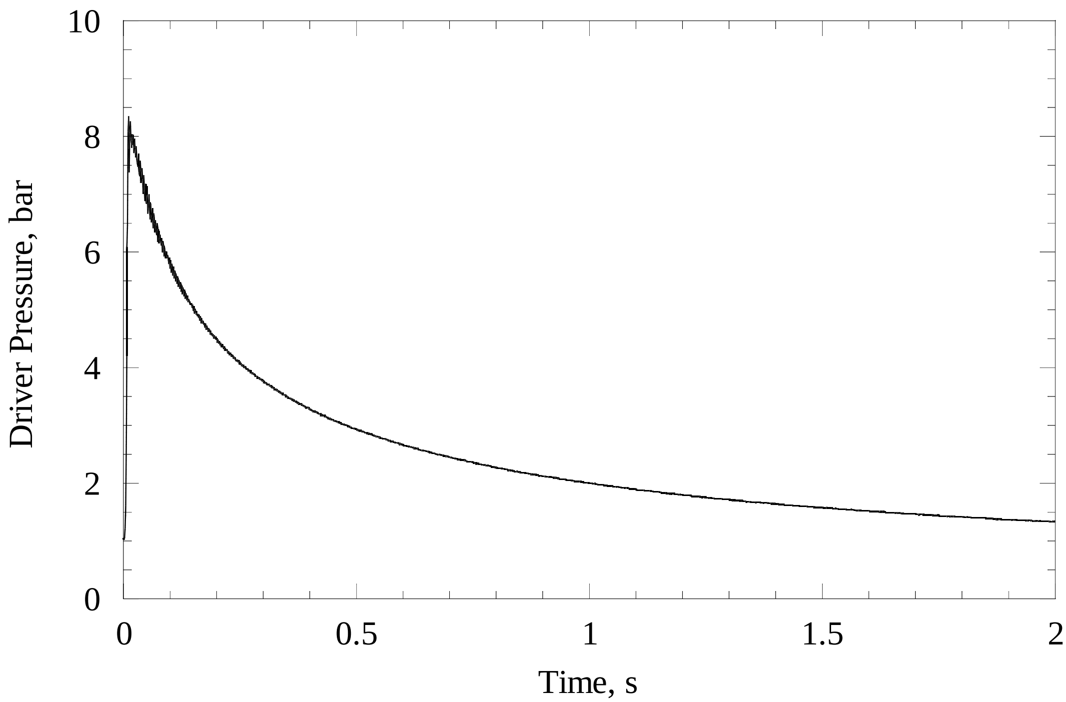


Figure A.2: Typical driver pressure trace from experiments at RPI.

considered to be highly unlikely.

Experimental Procedure

The main steps of the procedure to be followed during each experiment are listed below. The actual checklist to be used in operating the experiment is given at the end of this document.

1. Test emergency ventilation system.

2. Attach diaphragm and appropriate nozzle to end of hydraulic closure.

3. Close, clamp, and pressurize closure.

4. If needed, heat receiver vessel with steam and turn on electrical heaters. (Heaters are controlled by two Omega CN6071A proportional controllers connected to SCR73Z-230 power controllers. The vessel temperature is monitored in the control room and kept below the maximum design temperature of the vessel.)

5. Evacuate vessels with appropriate vacuum pump: liquid ring pump if water vapor is present, main rotary pump if tanks are dry.

6. Close both vacuum valves and wait 15 minutes. If pressure rises more than 1 mbar, find and fix leak. (Prior experience has indicated that if O-rings and Swagelok fittings function under vacuum, they will do so under pressure if properly installed. O-ring grooves have been designed so that they seal preferentially under internal

pressure. Moreover, the system has been hydrotested and helium leak tested under pressure.)

7. Open gas feed valve on receiver, and isolation valves 1 and 2 on driver.

8. Fill both vessels with desired mixtures using method of partial pressures. Monitor pressure gauges for leakage. Close receiver gas feed valve.

9. Run mixers for ten minutes.

10. Close driver isolation valves, and ensure that all other valves are closed.

11. Run data acquisition software, entering appropriate data on screen.

12. Turn on master ignition power key switch. Arm and fire driver when ready.

13. Save data, and safe firing system.

14. Open receiver gas feed and driver isolation valves. Add enough air/oxygen to burn remaining hydrogen. Follow mixing and firing procedure from above, without data acquisition.

15. Evacuate water vapor with liquid ring pump, or vent tank up to atmospheric pressure with air, depressurize closure, and separate tanks.

Design Considerations

The design considerations and safety related features of the key components of the facility are described below.

Compressed Gas Supply Design

Gases are supplied to the experiment from a bottle farm located outside Guggenheim, along the east wall of the addition (see Figure 3). There are four high-pressure manifolds; one for hydrogen (5 DOT-3A class cylinders), one for oxygen (3 DOT-3A class cylinders), one for nitrogen (4 DOT-3A class cylinders) and one for argon (2 DOT-3A class cylinders). The cylinders are connected to the manifolds by flexible, braid-armored pigtails. The manifolds are connected to two-stage regulators (0-1 bar) and shut-off valves. The gases can only enter the building at a maximum pressure of 1 bar gage, minimizing any potential leak rate within the building if a line or valve failure occurs.

The gas bottles are restrained by seismically-rated brackets, which use a chain and screw tightener to hold the bottles firmly against the wall at the top and the bottom. The oxidizer and fuel cylinders will be separated by a rated firewall and a canopy will be placed over the cylinders later this fall. The tubing between the bottle farm and the control system is 0.5-in diameter seamless 316 stainless steel, with an 0.049-in wall thickness. This tubing has a working pressure of 240 bar (3500 psi), so it can withstand full bottle pressure in the event of regulator failure. The tubing is securely mounted to the building and interior walls via Unistrut brackets.

Precautions with compressed gases

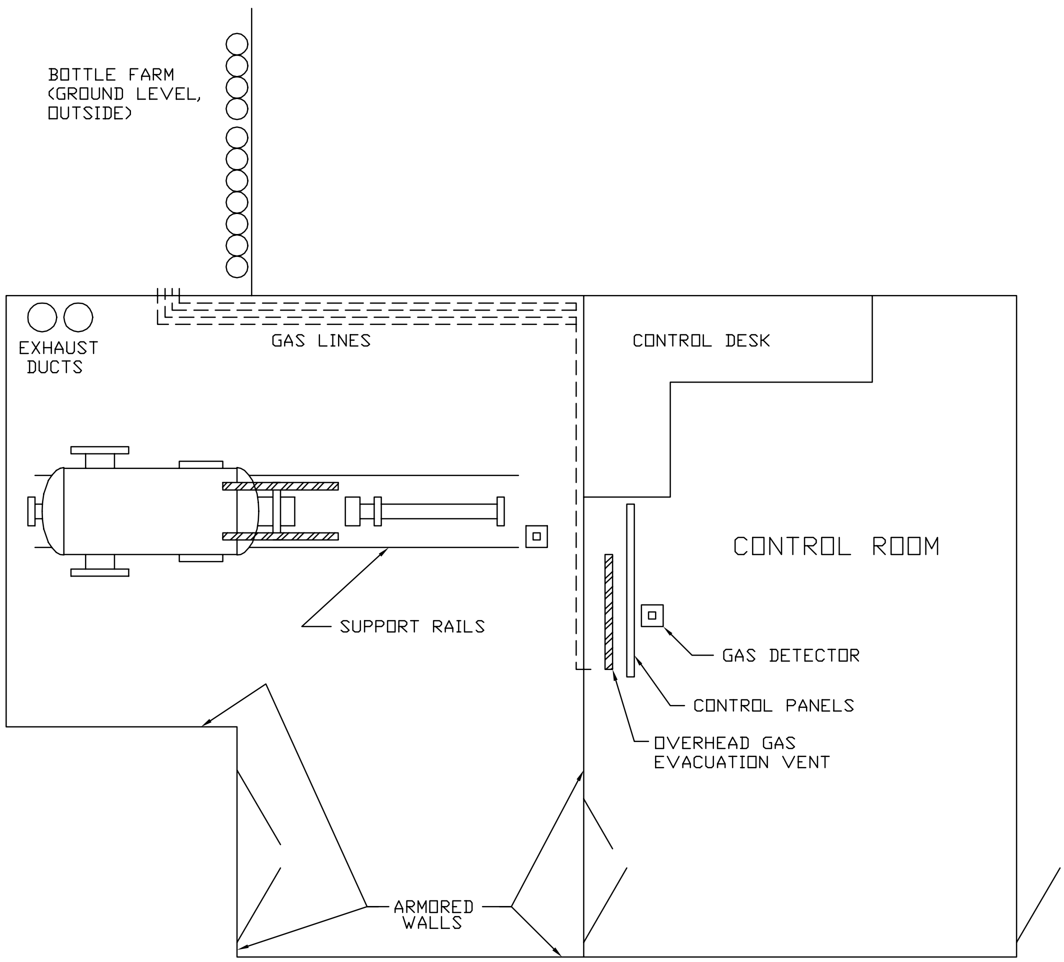


Figure A.3: Floor plan of the Explosion Dynamics Laboratory, 14/14A Guggenheim and bottle farm outside on the upper level.

The gases used in this experiment are argon, nitrogen, oxygen, and hydrogen. There are obvious potential hazards (CGA 1990) when using such gases in a confined space such as our laboratory. The amount of gas present in the lab is minimized by locating the high pressure gas outside of the building, and by not using any secondary mixing reservoirs. There are three types of potential hazards that we have specifically considered:

1. Suffocation (nitrogen, argon and hydrogen).

   The argon and nitrogen are inert, and could be a hazard through displacement of oxygen in the lab. This would be difficult to detect, but unlikely, since fresh air is continually forced into the lab via the building HVAC system. Should the HVAC or emergency purge systems fail, the experiment will not be continued. Failure of these systems would likely be due to a general electrical power outage, which would close the valves and isolate the vessels. Manual gas supply closure would follow.

2. Increased fire hazard (oxygen).

   Enriched oxygen in the lab atmosphere would enhance flammability of items in the lab. This threat will also be reduced by the influx of fresh air from the building HVAC system.

3. Explosion hazard (hydrogen).

The hydrogen gas is the main cause for concern, due to its flammability. Hydrogen is combustible between 4 and 70% by volume in air. A number of design and operational procedures have been included to minimize the potential hazard. These are:

1. All plumbing is heavy wall stainless steel with Swagelok-type fittings.

2. Pressure and quantities of gas within the building are minimized.

3. The gas supply lines are shut off externally (at the bottle farm level) when not in use and internally at the gas supply panel at all other times except when filling with that gas. At the bottle farm, the gas is shut off via a valve between the manifold and the regulator. If the system will be down for an extended period, the bottle valves will be closed as well. In the lab, the procedure is to have all gas supply and metering valves closed except when in use.

4. Plumbing system is pressurized and leak-tested using a helium leak detector purchased specifically for that purpose.

5. The laboratory is equipped with an emergency air ventilation system.

   This system provides for an intake of 500 cfm from the makeup air system and the exhaust of a somewhat larger (800 cfm) amount through a high-velocity exhaust fan mounted on the roof of "new" Guggenheim. The exhaust motor and fan assembly are of explosion proof construction.

The four ceiling intakes for this exhaust system are directly over the gas supply control panels, the driver tube, and the other explosion vessel located in the experimental area (see Figure 3). The vents are located at "high-points" in the ceilings. The ceilings are designed with a slope toward these points and are sealed except for some minor penetrations, the air intakes and the emergency exhaust systems. In case of a major leak into the region above the ceiling, there are three exhaust vents (100 cfm each) located within the space between the ceiling and the concrete floor. This ceiling space is separated between the experimental and control areas. Two of the vents are located in the experimental area and one in the control area. In the case of the experimental area, the ceiling is taped wallboard; in the case of the control room, the ceiling is lift-out acoustical tiles with seals. These acoustical tiles are sealed with a plastic coating to reduce gas penetration. The vent system is either actuated automatically due to gas detection or manually by a switch in the control room.

6. The hydrogen supply is equipped with an emergency shut-off valve.

   A electro-pneumatic valve is located in the hydrogen supply line (outside of building). This valve is opened by remote control only when gas is needed for the experiment. At all other times, it shall be closed. The valve requires both electrical power and air pressure to operate; if one of these is lost due to an accident (i.e., earthquake), the valve will automatically close. The valve is rated to 345 bar, so it can withstand full bottle pressure if the regulator fails.

7. The laboratory is equipped with a flammable gas detection system that is interlocked to the gas supply and the ventilation system.

   There are two flammable gas detectors (Sierra Monitors model 2001) that will actuate when hydrogen is detected at the 400 ppm level (a factor of 100 below the flammability limit). The shut-off valve described above will be closed automatically if either of the detectors are actuated. At the same time, a warning light and an audible alarm is sounded and the emergency venting system is actuated. The detector locations are shown in Figure 3. Further description of this system is provided below.

8. The only exhaust system from the test vessel or the supply system is through a continuously-operated high-velocity vent to the exterior of the building.

9. The operators are physically separated from the test vessels by a wall covered with a steel shrapnel barrier (see Figure 3). The experiment is remotely operated by a mimic panel using electro-pneumatic valves.

When the facility is not in use, it is left either under vacuum or at atmospheric pressure. There is no provision for purging the supply lines, as these gasses are nonreactive with stainless steel under these conditions. To prevent contamination, the gas supply lines are closed and left at or above ambient pressure (0-15 psig) when not in use.

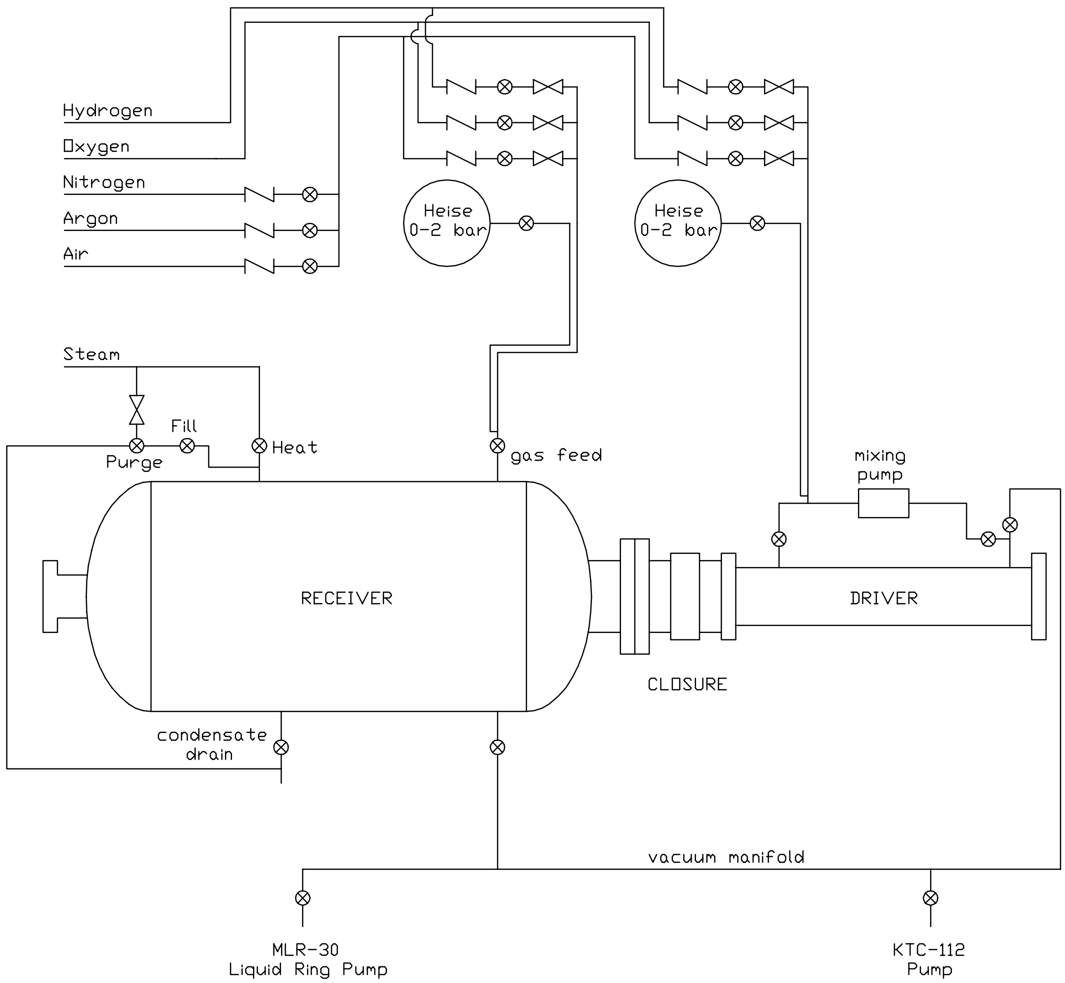


Figure A.4: Gas Supply system for the Hydrogen Jet Combustion Facility.

Driver Design Considerations

The design load for the driver is a detonation of a stoichiometric mixture of hydrogen and oxygen. The CJ pressure for this mixture is 19 bar (initial conditions of 1 bar and 300 K) and the peak reflected pressure is 45 bar. Allowing for the maximum dynamic load factor of 2 (Shepherd 1992), the equivalent maximum average working pressure the vessel should be designed for is 90 bar. This factor of 2 is the upper bound of the response of an undamped elastic system to a step load. It is a general result, not specific to any geometry (Biggs 1965), and used in both the driver and receiver design. In addition to pressure considerations, the driver should be designed from a ductile material with a high ultimate strength in order to accommodate any potential pressure transients that might result from DDT events.

The driver is constructed of a four-foot length of six-inch-diameter, seamless stainless steel (316) tubing with a half-inch wall thickness. Stainless steel (316) flanges 2.0-inch thick and 11-inch diameter are welded to each end of the tubing. Eight 7/8-inch SAE grade 8 bolts are used to connect the flanges to the end plate and the closure assembly. Using an allowable stress of 16.7 kpsi, the corresponding hoop stress would limit the maximum allowable working pressure to 2780 psi (189 bar).

The end flanges are double-welded, and are estimated (using the allowable stress) to take a pressure load of 350 bar. The bolts retaining the blind flange are 7/8-in grade 5, and capable of retaining the end flange under a pressure of nearly 760 bar, so even with preload they will be able to readily withstand 189 bar. The plumbing fittings are all 3000-lb class, and the connecting nipples are schedule 80 stainless steel. These are the same fittings that were used on the RPI apparatus.

Derating this for the stress concentrations at the penetrations, we conclude that the maximum working pressure of this assembly is at least 90 bar. Since the allowable stress used in making this computation includes a substantial factor of safety already, this design can safety accommodate the design load without any safety implications.

Hydrogen embrittlement may be an issue when pressure vessels are used with hydrogen. Three conditions (Harvey 1974, Nelson 1951) are required for hydrogen embrittlement to occur:

1. A high hardness microstructure.
2. Penetration of hydrogen into the metal or pre-existing hydrogen within the metal.
3. Stress, either residual or imposed.

None of these conditions exist in the driver. In general, hydrogen embrittlement in type 316 stainless is never a problem (Harvey 1974) unless the material is used at very high temperatures to contain hydrogen at high pressures (greater than 1000 bar). Data from the U.S. Air Force Metals Handbooks indicate that 304 SS only suffers a 4% loss in strength when exposed to pure hydrogen at 345 bar for 24 hours.

Type 316 stainless steel has a low hardness microstructure and is formulated to resist stress corrosion by hydrogen. There will be extremely limited penetration of hydrogen in the vessel due to low pressures and temperatures in comparison to typical hydrogen embrittlement conditions. For most of the test, the hydrogen and the vessel will be at room temperature and the hydrogen partial pressure will be less than one atmosphere. After ignition, the pressure and temperature rise to their peak values within milliseconds, but heat transfer to the tube walls cools the gas rapidly and the pressure reaches subatmospheric values within 5 to 10 seconds, as shown in the driver pressure plot. The burn also reduces the hydrogen concentration to 50%.

Cumulative exposure is not considered to be a problem with this facility, as the hydrogen embrittlement process requires a threshold in pressure-temperature conditions before it will even occur. This threshold is not approached in this facility. Both the driver and receiver vessels were designed for hydrogen service. Per the references stated above, there are no restrictions on the lifetime of the vessel for our pressure-time history. The pressure exceeds one bar for approximately 4 seconds per test, and at 100 tests per year, this yields about 7 minutes of cumulative operation with a hydrogen partial pressure of 1 to 3 bar at most.

The facility is expected to be used for at least 10 years. For this duration, fatigue life will not be an issue for this facility. At 100 tests per year, this yields a total of 1000 cycles which places the facility in the low cycle regime of fatigue (Shigley 1990). In this regime, the fatigue strength approaches the tensile strength. Since the facility design incorporates a substantial safety factor (four in the receiver design), the operational stresses are substantially lower than the fatigue limit. Fatigue failure of the components is thus not an issue for the projected lifetime. If the maximum stress incurred in operation is less than the endurance limit (typically one-half of the tensile strength for carbon and alloy steels), the lifetime is effectively infinite. This is most likely the case in our facility.

Closure Design Considerations

A specialized closure assembly design originally developed at GALCIT for the 6-inch shock tube is used to connect the driver to the receiver. This closure is made of forged stainless steel (303 and 304) components and a forged steel (1040) clamp ring that carries the load. Estimates of the axial stress and stress produced by the moment load on the clamp indicate that the performance will be within the allowable stress even with a pressure as high as 136 bar (2000 psi) within the driver section. Radial loads are carried by the main structure of the closure, which is hydraulically sealed when in operation. The hydraulic action provides an axial clamping force of 120,000 lbs on the diaphragm. This closure was successfully used in the previous experiment at RPI.

After the closure was partially modified and installed on the GALCIT facility, it was hydrotested in-situ with the driver at 1500 psi. Pre-shot checkout includes visual inspection of seals, O-rings, closure position, and for hydraulic fluid leaks. When the closure is pressurized, a gage on the pump indicates hydraulic pressure. This gage also has a pressure switch, which is connected to the firing interlock. If the pressure drops below 2000 psi, the firing system will be locked out, and the green light on the control panel will extinguish.

Receiver Design Considerations

Conditions in the receiver vessel are generally much more benign than in the driver.

However, it has been designed to withstand higher pressures than before. In the worst case, we would have a detonation in stoichiometric hydrogen-air at one atmosphere initial pressure. The equivalent pressure produced by a reflected wave with a dynamic load factor of two is 76 bar. The vessel is designed for a maximum average working pressure of 51.7 (750 psi) bar, and was hydrotested to 73 bar (1100 psi). In most cases, the vessel will be filled with more dilute mixtures, and operated at higher initial temperatures, so that the reflected and compensated pressure will not exceed 56 bar. The highest pressure generated in the receiver in the RPI experiments was about 7 bar (Figure 5).

The receiver is a mild carbon steel (ASTM A516-70) pressure vessel 36 inches in diameter, 64 inches seam-to-seam. There are four 600-lb class nozzles and flanges welded to the tank and a number of smaller penetrations. All flange closures are also rated to 600-lb class and are attached with grade 8 (ASTM A574) fasteners. A specially designed flange is used to attach 6-inch diameter windows to each side of the test section. These windows are used for flow visualization of the jet and combustion events within the receiver. There are three axial window locations but only one of these is used at a time. The others are filled with steel blanks when not in use.

The vessel was built and certified to the standards of Section VIII of the ASME Boiler and Pressure Vessel Code. This includes a full X-ray inspection of all welds, and a corrosion allowance of 0.0625 inches. The preliminary design of the vessel, including size and location of flanges and ports, was done at Caltech. Final design and material selection and sizing was done by R. L. Morton Welding Inc., Valley Acres, CA, fabricator of the vessel. All of the materials used in the tank were accompanied by mill reports on chemical composition, yield strength and elongation testing. Discussions with the metallurgist at R. L. Morton identified fracture toughness as being a material issue for an explosive test vessel. This is one of the key reasons for the material choice. To insure material quality, material samples were also impact tested for toughness. The Charpy impact tests were carried out at -40 and -50 degrees Fahrenheit, and the material specimens required at least twice the minimum allowable energy to fracture. The final report on the vessel fabrication and the material certifications is available on file in 14A Guggenheim.

The design pressure (MAWP) of the tank is 750 psi at 250 °F. The pressure was chosen on the basis of the calculated peak pressures in the event of a hydrogen-air detonation within the receiver. Previous tests have all been with deflagrations and the observed peak pressure has always been less than 6 bar (90 psi) in the receiver. The vessels used at RPI had a design pressure of 600 psi, and the peak pressure measured in the driver was 9 bar (125 psi).

This was a case with a very large orifice between the two tanks, and the identical size of the two vessels caused a high level of pressurization in the receiver. If an over-pressure event does occur that exceeds the hydrotest rating of the vessel, then it will be mechanically inspected and retested if necessary.

Hydrogen embrittlement is not an issue in this vessel either. None of the key factors mentioned above are satisfied for the receiver vessel. Tests (Nelson 1953) with mild carbon steel vessels indicate that embrittlement does not occur at hydrogen partial pressures less than 1500 psi when the vessel temperature is less than 500 °F.

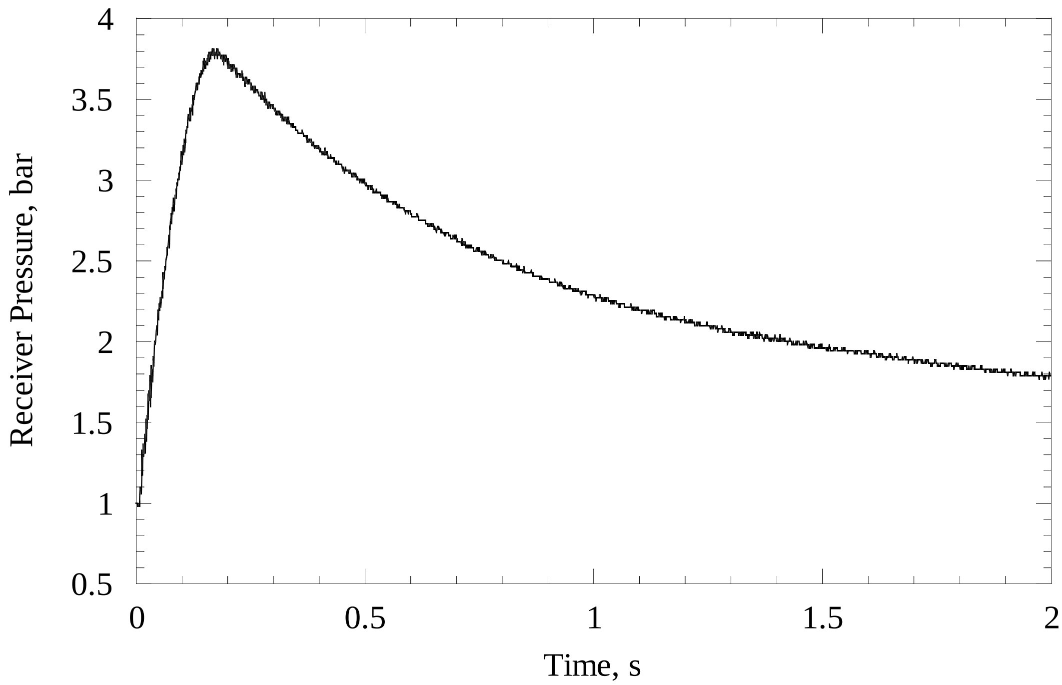


Figure A.5: Highest receiver pressure trace recorded in experiments at RPI. Note that experimental setup was different than it is now.

Operational Safety Precautions

There are several measures incorporated into the check list to ensure the facility integrity and that the safety systems are operating properly.

Key checks before each test include: visual inspection of the facility and bottle farm, measuring the leak rate after pump down; and checking the operation of the remotely operated valves.

The emergency gas evacuation system will normally remain idle, so it is important to test it regularly to ensure correct function in case of a release. The detectors can be tested before each run by releasing flammable gas near the sensor, or waving an acetone-soaked rag nearby. This will also activate the evacuation blower, which can be tested by smoke or tell tales. We plan to equip the vents (in the winter of 1995) with positive flow indicators to ensure that the system is operating at the correct flow rate.

After any seismic events, the entire facility will be visually inspected, the lines and vessels will be tests under vacuum, and the gas lines pressurized with helium and leak checked with a helium detector.

Potential Hazards

We have considered a number of potential hazards and discuss each below.

1. *Hydrogen Leak Into Laboratory Area.* Since the pressure vessels are filled with gas at or below atmospheric pressure, a hydrogen (or inert gas) leak into the room is unlikely. The gas bottles and regulators are located outside the building, so that the gases are only at 1 bar in the feed lines that run to the experiment. However, the

possibility exists that an open valve, a leak in one of the pressure vessel connections, or a leak in one of the Swagelok fittings could release hydrogen into the laboratory environment. To protect against this, we have hydrogen / combustible gas detectors strategically located in each room (SMC model 2001-10, calibrated to activate at 400 ppm hydrogen). In the control room, the detector is located above the gas panels, the only source of hydrogen in that room (see Figure 3). The ceiling in that room is sloped upward towards the detector, as the hydrogen gas will rise and seek the highest point in the room. In the experiment area, the ceiling is sloped upwards to an inverted "trough" over the experiment. This trough contains another combustible gas detector and intakes for the hydrogen exhaust system.

If the detector goes into alarm mode, it activates a latching relay which has several functions. First, it activates a warning light and buzzer in the lab. Second, it shuts off the hydrogen supply valve at the bottle farm, preventing further hydrogen from entering the lab. Third, it is connected to the ventilation system to turn off the air handler and turn on the evacuation system (this is a 1200 cfm exhaust fan located on the roof). This system can not be reset until the detector returns to "safe" mode. There is no way to turn off the detector system unless the power is removed. This would then remove power from the supply valve, stopping the gas supply anyway.

Another situation that could introduce hydrogen into the lab area would be accidental, manual opening of the tanks when they are filled with a combustible mixture and if they were pressurized to greater than atmospheric pressures. Normal operation is to only pressurize the tanks to 1 bar (absolute) initial pressure prior to the test. Therefore in normal operating conditions, opening the vessels to the atmosphere would not constiute a hazard unless the gas supply system was left on.

However, it is possible for the operator to fill the tanks to higher pressures and excessive hydrogen concentrations since the supply manifolds operate at pressure of 1 bar gauge. This would require gross negligence on the part of the operator since the valves used to introduce and control the flow rates of the various gases are manually operated. To reduce the possibility of such negligence, we plan to modify the facility to require continuous operator action (holding down a push button) in order to fill with hydrogen gas. This requirement will force the operator to be physically at the control panel and able to monitor the pressure at all times during the fill process.

A typical experimental condition would be 10% hydrogen in the receiver, and 80% hydrogen in the driver. The volume of the receiver is 1.4 cubic meters, and that of the driver is 0.026 cu m. These fractions would yield a total volume of 0.16 cu m of hydrogen at atmospheric pressure. The volume of the room is 96 cu m, so the fraction of hydrogen in the room would only be 0.2%. Since 4% hydrogen is required to have any type of combustion at all, this would be a non-flammable mixture. It is possible for flammable concentrations of hydrogen to exist locally, but the HVAC circulation and hydrogen buoyancy would quickly disperse and mix these local concentrations.

2. *Vessel Breach Due To Overpressure.* The peak pressure that could occur in this system is 76 bar, based on a reflected detonation of a stoichiometric mixture of hydrogen and oxygen (including a factor of 2 for dynamic loading). The tank is designed to withstand 51.7 bar, and ASME code incorporates a substantial factor safety is determining the allowable stress. In the case of the receiver, the allowable stress used in the design is 1/4 of the ultimate tensile strength of the material. The welds and penetrations have been designed with a similar factor of safety in this vessel resulting in an ultimate capacity of about 200 bar. Thus, we have a safety factor of 2 for the worst possible case. We conclude that catastrophic failure of this vessel is not a credible failure mode.

   However, as discussed below, the windows or other secondary components may fail under extreme loads. As additional protection, the walls of the experimental area are lined with 1/8-in steel plate to protect the surroundings from any fragments that may be ejected from the tank. These could include transducers, igniter plugs, or window fragments. Note that the 76 bar pressure quoted above can not be obtained within the present operating envelope. This value is used to provide an extreme upper bound on the maximum pressure that might be encountered under abnormal conditions. As mentioned earlier, the highest pressures encountered at RPI were 9 bar. We have considered the strength of the transducer and ignitor mounts, and determined that these will not fail even at the 76 bar level. The force on the transducer will only be 31 lbs, and that on the spark plug will be 216 lbs. These loads produce acceptable stress levels. Therefore, only the windows are subject to failure at 76 bar. These are discussed in the next section.

   The 1/8-inch steel wall will provide useful protection from glass and small metal fragments. Peak fragment velocities are difficult to estimate, but a useful rule of thumb is that the upper limit will be the sound speed in the emerging gas, which will be between 300 and 1000 m/s. Typically, much lower velocities are obtained from ruptured or bursting vessels due to the inertia of fragments and rapid decrease in gas velocity in the jet flow outside the vessel. It is possible to get higher values in an underexpanded jet. Using the estimation techniques discussed in Baker et al. 1985 a 1/8"-thick 1020 CRS plate will withstand (50m/s (normal impact). The penetration velocity varies inversely with particle size and density so that smaller, higher velocity fragments would also be stopped.

3. *Schlieren Window Failure Due To Overpressure.* The 150 mm dia. by 25 mm thick windows used for the schlieren can withstand a pressure of 31-38 bar, much greater than the typical pressures of 4 bar. This estimate was calculated from elastic theory for a simply-supported circular plate. The key parameter in this calculation is the maximum tensile strength of the window material (BK7). Unlike most materials, there are no reliable values of yield strength for glass, as it depends strongly on the surface condition and mounting technique. A value of 5 ksi was used in the

maximum pressure calculation, based on a range of values given by Melles Griot. Glass suppliers commonly quote values up to 10 ksi. We have exposed glass disks of similar aspect ratio to detonation waves resulting in stresses up to twice this value without failure.

In this facility, if a detonation occurs, the peak pressure may exceed the estimated load capacity of the windows, resulting in window failure. As mentioned in item (2), operators and bystanders are protected from this by controlling the experiment from a separate room, and the steel plate on the walls surrounding the apparatus. In addition, the boxes containing the schlieren system will always be in front of the windows, and will help to contain any glass fragments that may be produced.

To eliminate the possibility of window failure, we will only operate the facility with less than 20% hydrogen in air; a reflected detonation in this mixture would result in acceptable peak pressures. If we go to richer mixtures, the window frames can be modified to accept 1.5-inch thick windows, which would increase the failure pressure by a factor of about 2.25. Additional failure protection could be provided by a 3/8 inch thick aluminum plate on the schlieren system opposite the windows.

Failure of the windows could also result in a blast wave, but it is difficult to make an accurate estimate of its strength. The source term is highly transient and analogous to the muzzle blast from a gun. The effective driving pressure will be time dependent but will initially be much closer to the constant-volume explosion pressure, about 8 bar for stoichiometric hydrogen-air, than the detonation pressure. With the above precautions, we consider window failure to be a highly unlikely event. If the operating envelope is enlarged to include near-stoichiometric hydrogen concentrations, then an appropriate blast and consequence analysis will be considered.

4. *Misfire.* A misfire occurs when there is a combustible mixture in either vessel and the ignition system fails to ignite it. This can occur if the electrodes on the spark plugs become fouled or there is an electrical system failure. If the amount of hydrogen in the system is small enough, the mixtures can be inerted by addition of nitrogen, and then pumped out of the vessels. Or, extra oxygen or hydrogen can be added to sensitize the mixture, and the glow plugs can be used to ignite it.

5. *Mixture Ignition With Containment Valves Open.* All of the valves on the driver and receiver vessels are remotely operated with positive indication of the valve position in the control room. The ignition system is interlocked with the valve indicator switches so that ignition can not occur unless the valves are closed.

   If an accidental mixture ignition occurs with the gas supply / tank containment valves open, a pressure wave will travel through the gas supply tubing. This pressure will not exceed the 90 bar mentioned in item (1), and all of the plumbing can safely handle this pressure. The tubing components have a minimum pressure rating of 241 bar, and the weakest valve in the system can withstand 103 bar.

The only weak point in the system is the Heise gage located on each gas supply panel. These are only rated for 2 bar and will be damaged if overpressurized. The gages are quite robust, constructed with a heavy, cast metal body and blowout backs. The manufacturer does not have data on failure pressure available for these gages, but from similar models, they suggest that the failure pressure would be at least 40% greater than full scale.

The gages have their own isolation valves which will be closed after the vessels are filled with the proper mixtures. If the gage is pressurized to failure, the operator will be protected by a 1/4-in thick sheet of Lexan mounted over the face of the gage. Lexan is a very tough material, which can withstand a large amount of plastic deformation without fracturing. The gage faces are constructed of 1/8 inch Plexiglas, so the Lexan shields should be able to safely deflect any fragments.

Failure of these gages would require multiple failures in the operating procedure. Two possible scenarios are: 1) regulator fails, operator doesn't follow checklist, opens supply and metering valves with vessel valve closed, and fails to take corrective action; 2) Operator does not follow checklist, gage valve left open, vessel valves open, interlock system fails to function, and ignition occurs.

6. *High Voltage Ignition System.* Two TM-11A high voltage trigger modules are used to ignite the mixtures in the tanks. These modules generate a 15 kV pulse, and this voltage is considered to be lethal regardless of the current supplied. The wiring for these modules will be protected, and they are connected to AC power such that they can only be turned on from the control room, with a key.

7. *Seismic Damage To Vessels.* The vessels are both mounted on linear bearings which allow them to translate in one direction. Safety brackets are mounted on these rails to prevent the vessels from jumping the track. Also, the gas lines connected to the tank are flexible, minimizing the possibility of damage or breakage.

8. *Miscellaneous.* In addition to the built-in safety devices, the laboratory also contains emergency equipment such as fire extinguishers, first aid kits, and personal protective equipment (safety glasses, dust masks, ear muffs, etc.) to be used while working.

References

1. Baker et al. **Explosion Hazards and Evaluation**, Elsevier, 1983.

2. Biggs, J. M. **Introduction to Structural Dynamics**, McGraw-Hill 1965.

3. GGA 1990 **Handbook of Compressed Gases**, Third Edition, Compressed Gas Association, Inc., Chapman and Hall, NY.

4. Harvey, J. F. 1974 **Theory and Design of Modern Pressure Vessels**, Van Nostrand Reinhold, NY.

5. Krok, J. C., 1992, *Hydrogen Combustion Facility and Experiments*, Master of Science Thesis, Rensselaer Polytechnic Institute, Troy, NY.

6. Nelson, G. A., 1951, "Metals for High-Pressure Hydrogenation Plants," Trans. ASME **73**, 205-213.

7. Ross, M. C., 1993, *Transient Jet Diffusion Flames in Hydrogen-Air-Nitrogen Atmospheres*, Master of Science Thesis, Rensselaer Polytechnic Institute, Troy, NY.

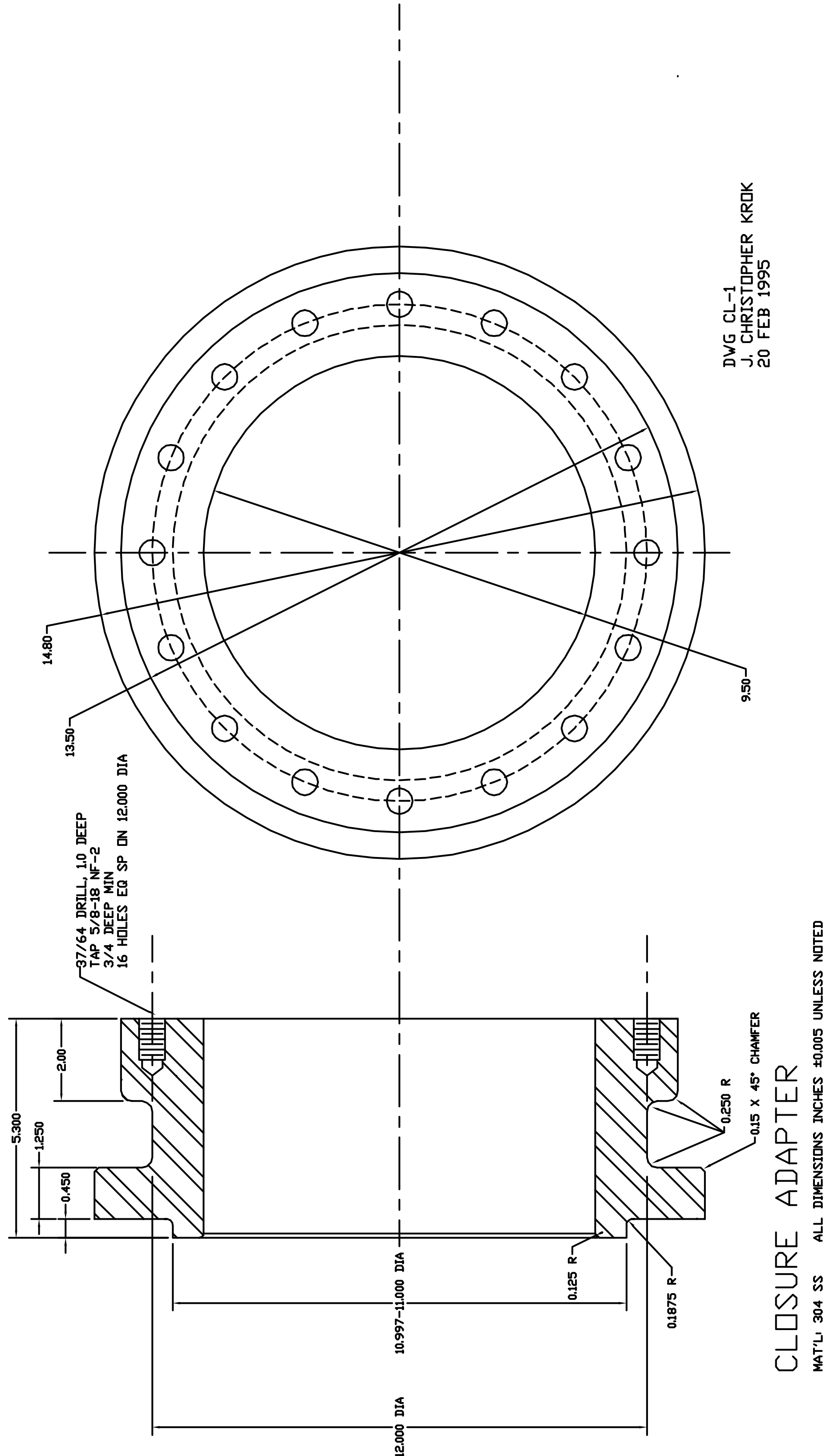
8. Shepherd, J. E., 1992, *Pressure Loads and Structural Response of the BNL High Temperature Detonation Tube*, BNL Technical Report A-3991, Brookhaven National Laboratory.

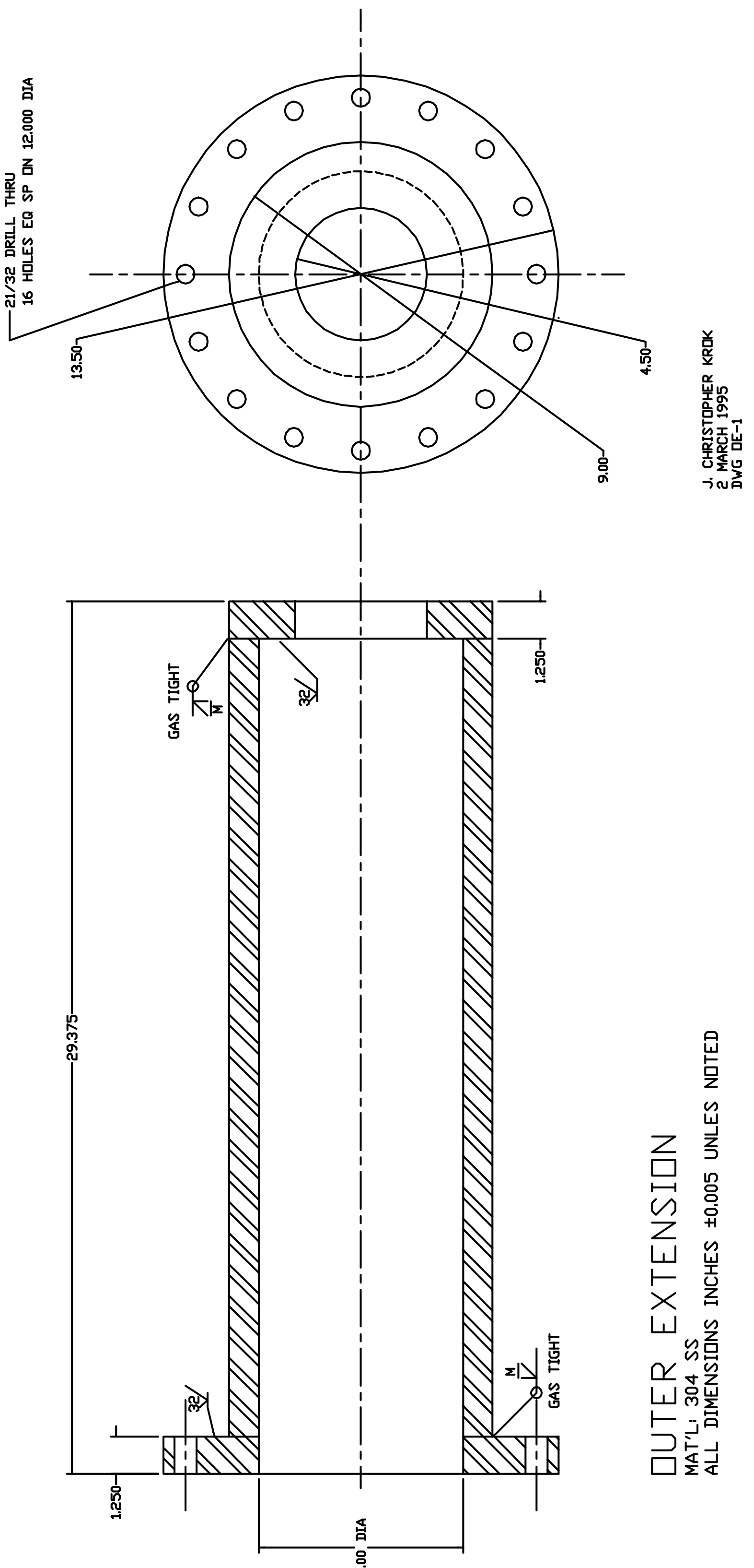
9. Shigley, J. E. and Mischke, C. R. *Mechanical Engineering Design*, McGraw-Hill, 1989.

Appendix B

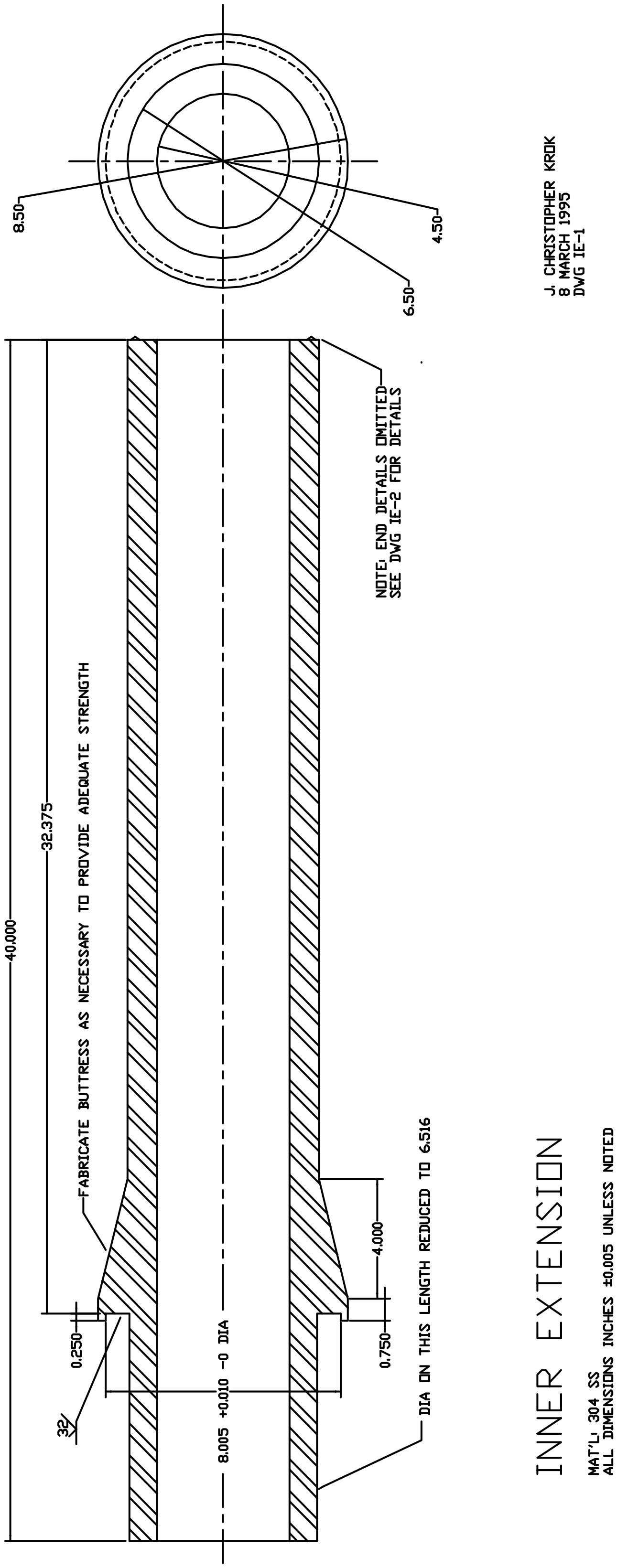
System Drawings

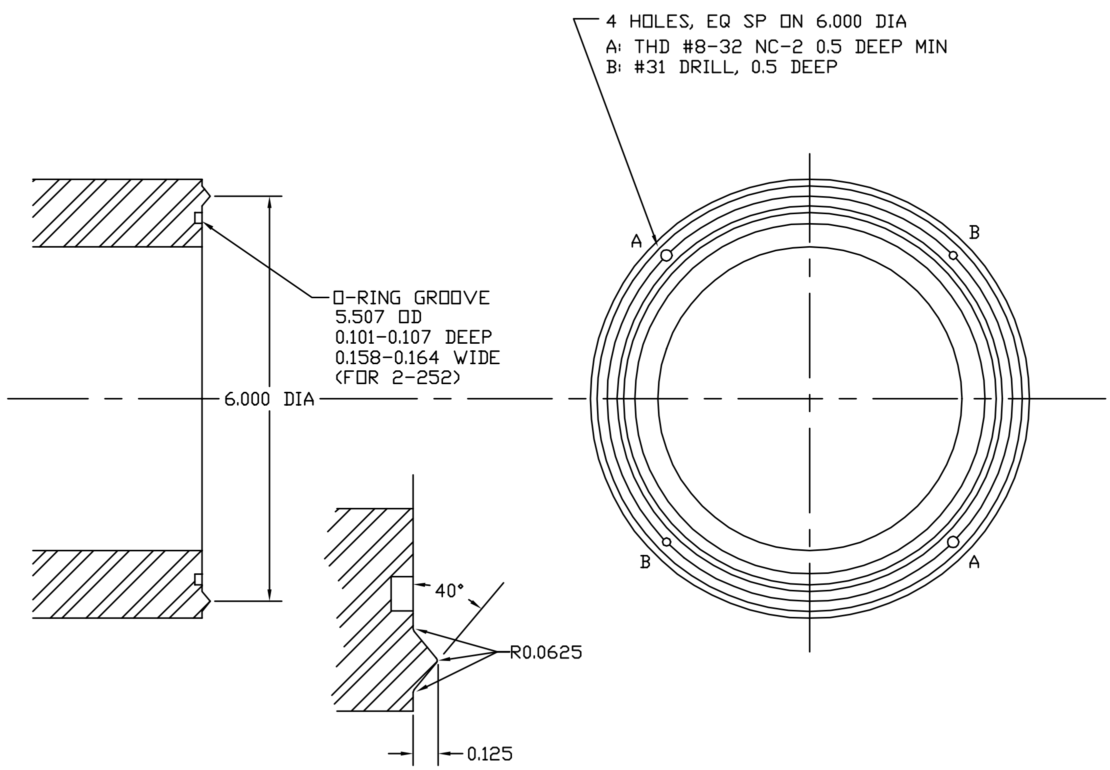
This appendix contains AUTOCAD drawings from the HYJET facility for reference purposes.


DWG CL-1
J. CHRISTOPHER KROK
20 FEB 1995
14.80
13.50
9.50
37/64 DRILL, 1.0 DEEP
TAP 5/8-18 NF-2
3/4 DEEP MIN
16 HOLES EQ SP ON 12.000 DIA
5.300
2.00
1.250
0.450
0.250 R
0.15 X 45° CHAMFER
0.125 R
0.1875 R
10.997-11.000 DIA
12.000 DIA
CLOSURE ADAPTER
MAT'L: 304 SS
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED



21/32 DRILL THRU
16 HOLES EQ SP ON 12.000 DIA
13.50
4.50
9.00
J. CHRISTOPHER KROK
2 MARCH 1995
DWG OE-1
29.375
1.250
GAS TIGHT
M
32
GAS TIGHT
M
32
1.250
7.00 DIA
OUTER EXTENSION
MAT'L: 304 SS
ALL DIMENSIONS INCHES ±0.005 UNLES NOTED

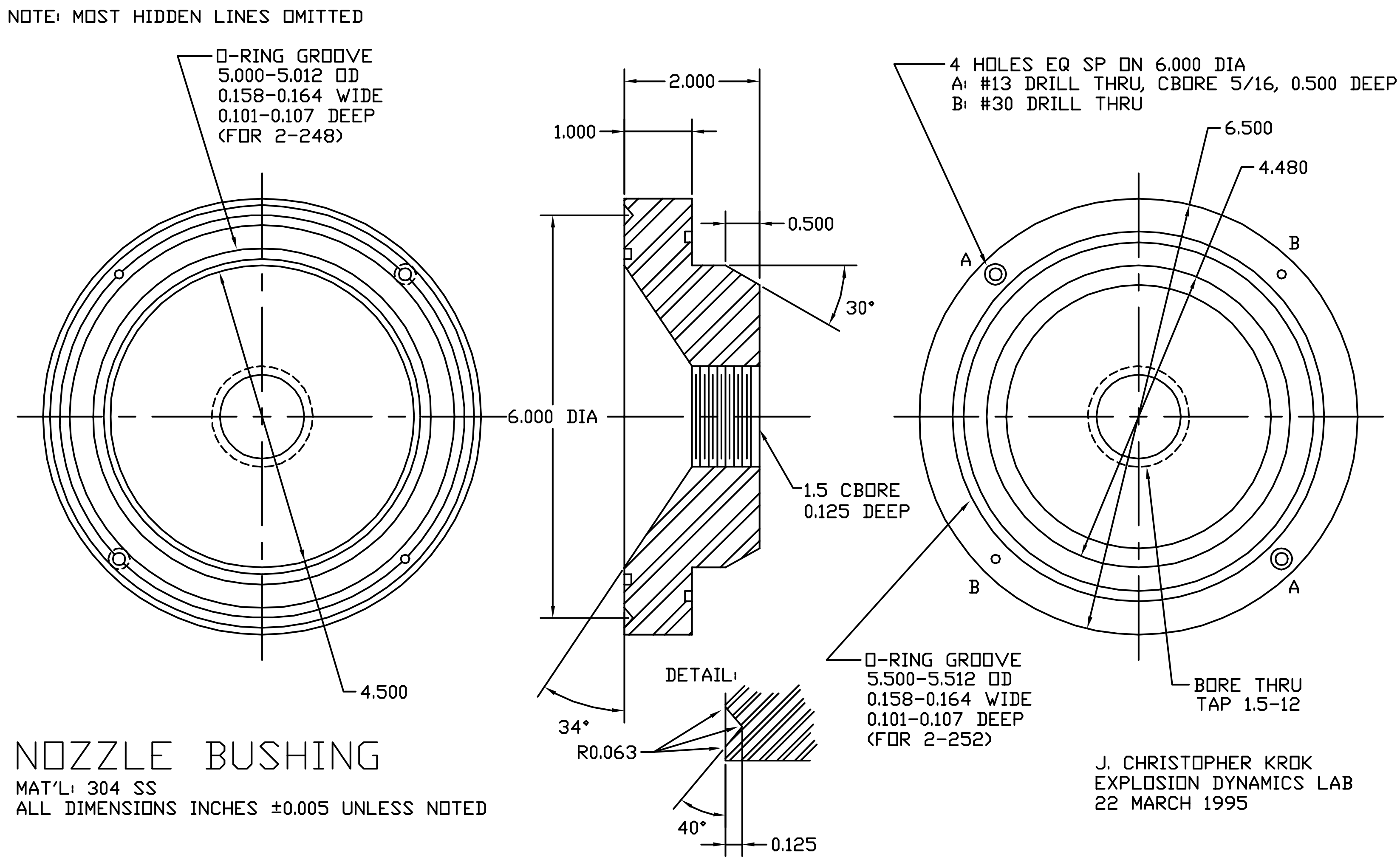

8.50
6.50
4.50
J. CHRISTOPHER KROK
8 MARCH 1995
DWG IE-1
NOTE: END DETAILS OMITTED
SEE DWG IE-2 FOR DETAILS
40.000
32.375
FABRICATE BUTTRESS AS NECESSARY TO PROVIDE ADEQUATE STRENGTH
4.000
0.250
0.750
32
8.005 +0.010 -0 DIA
DIA ON THIS LENGTH REDUCED TO 6.516
INNER EXTENSION
MAT'L: 304 SS
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED

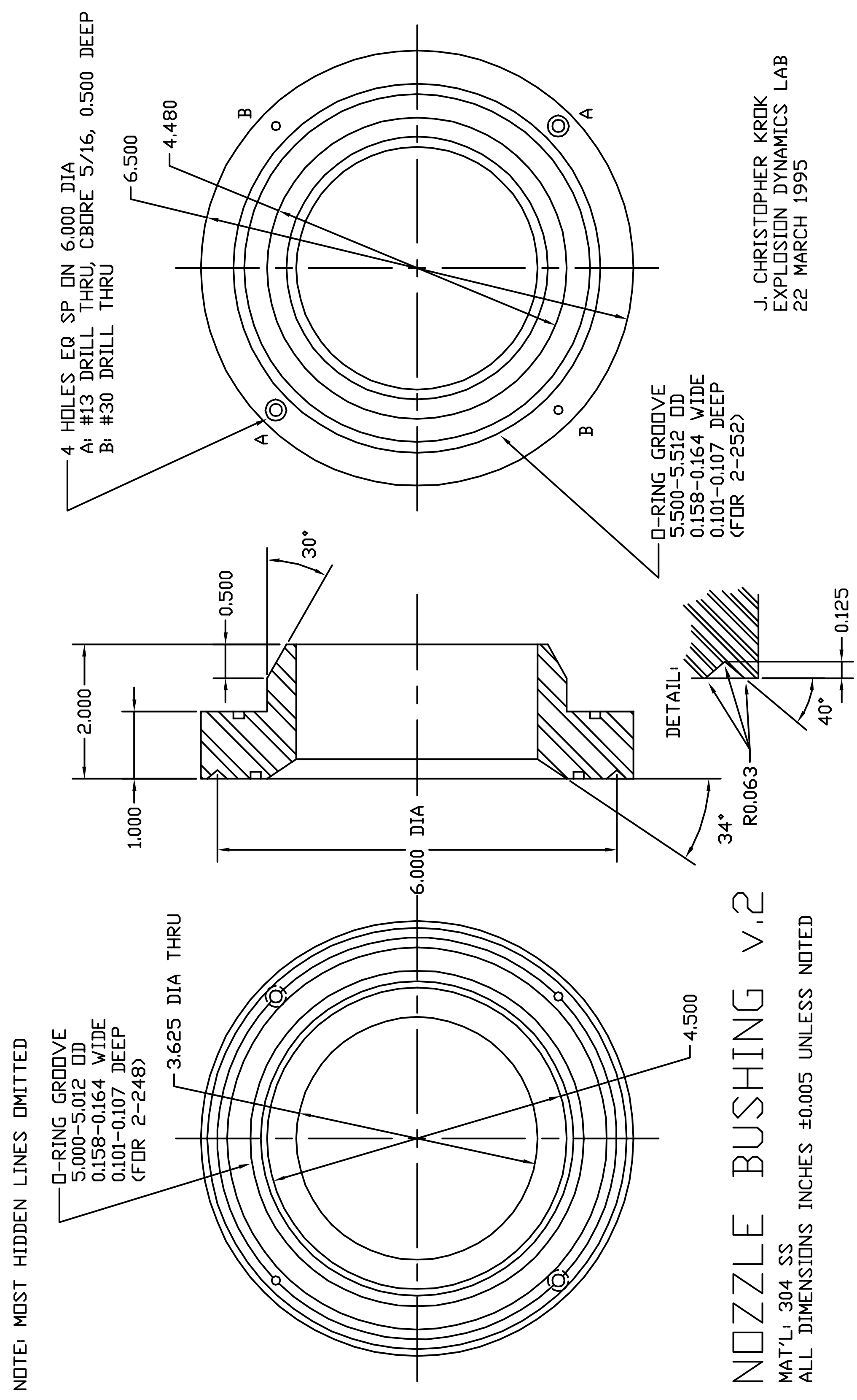


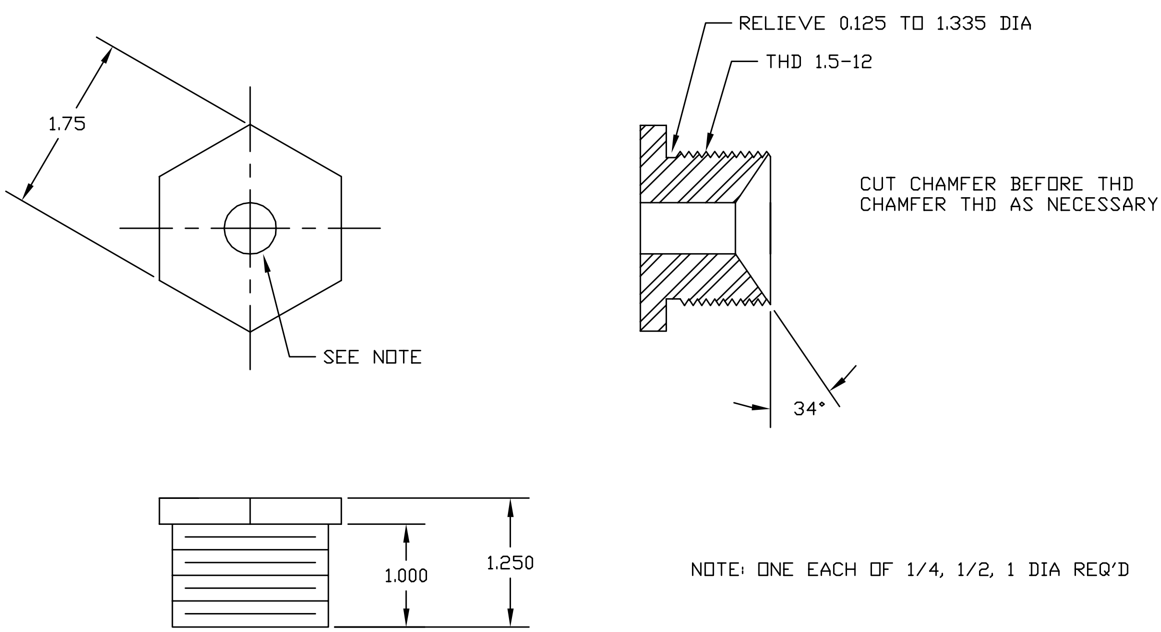
INNER EXTENSION END DETAIL

ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED
FINISH BOTTOM OF O-RING GROOVES TO 32

J. CHRISTOPHER KROK
7 MARCH 1995
DWG IE-2


NOTE: MOST HIDDEN LINES OMITTED
O-RING GROOVE
5.000-5.012 OD
0.158-0.164 WIDE
0.101-0.107 DEEP
(FOR 2-248)
4.500
2.000
1.000
0.500
30°
6.000 DIA
1.5 CBORE
0.125 DEEP
34°
DETAIL:
R0.063
40°
0.125
4 HOLES EQ SP ON 6.000 DIA
A: #13 DRILL THRU, CBORE 5/16, 0.500 DEEP
B: #30 DRILL THRU
6.500
4.480
A
B
B
A
O-RING GROOVE
5.500-5.512 OD
0.158-0.164 WIDE
0.101-0.107 DEEP
(FOR 2-252)
BORE THRU
TAP 1.5-12
NOZZLE BUSHING
MAT'L: 304 SS
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED
J. CHRISTOPHER KROK
EXPLOSION DYNAMICS LAB
22 MARCH 1995

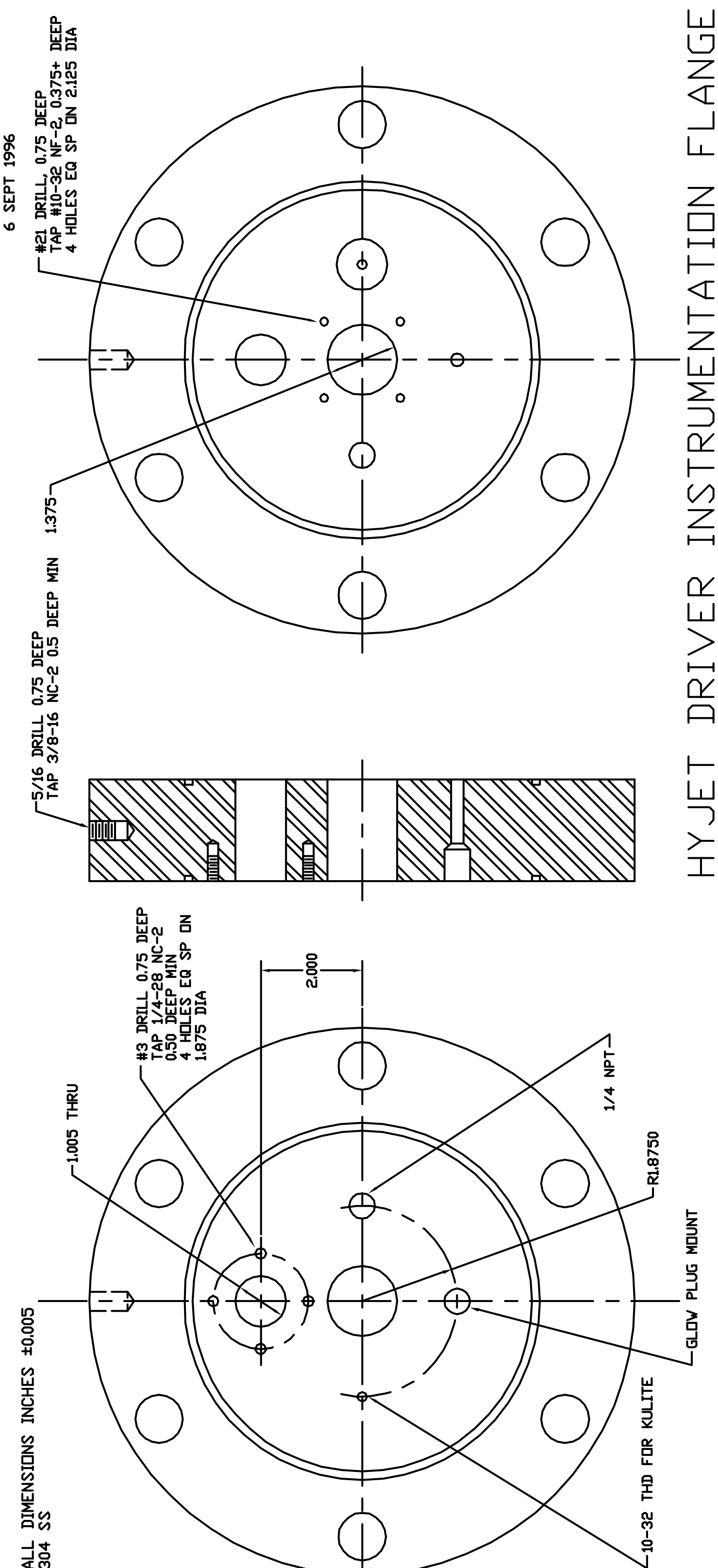

NOTE: MOST HIDDEN LINES OMITTED
O-RING GROOVE
5.000-5.012 OD
0.158-0.164 WIDE
0.101-0.107 DEEP
(FOR 2-248)
3.625 DIA THRU
4.500
6.000 DIA
1.000
2.000
0.500
30°
34°
R0.063
DETAIL:
40°
0.125
O-RING GROOVE
5.500-5.512 OD
0.158-0.164 WIDE
0.101-0.107 DEEP
(FOR 2-252)
4 HOLES EQ SP ON 6.000 DIA
A: #13 DRILL THRU, CBORE 5/16, 0.500 DEEP
B: #30 DRILL THRU
6.500
4.480
A
B
A
B
NOZZLE BUSHING v.2
MAT'L: 304 SS
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED
J. CHRISTOPHER KROK
EXPLOSION DYNAMICS LAB
22 MARCH 1995

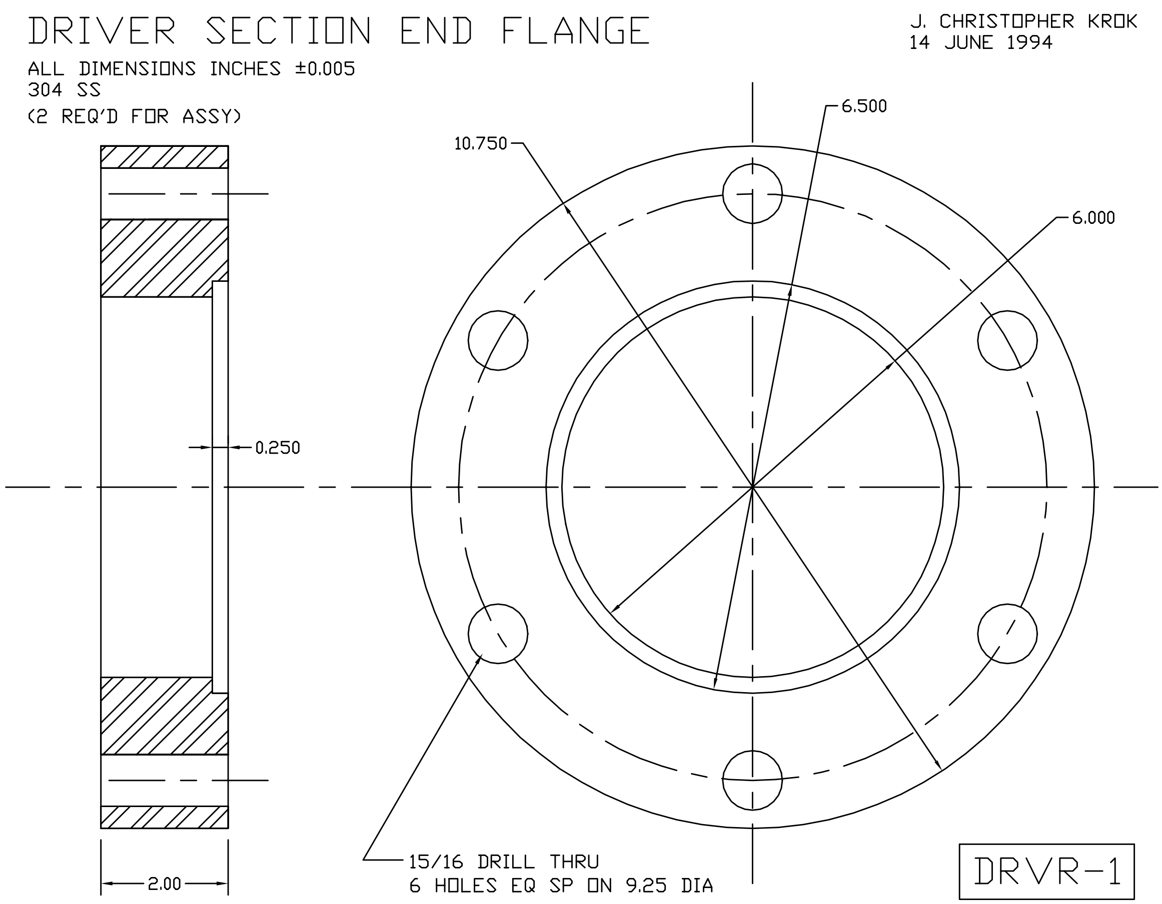


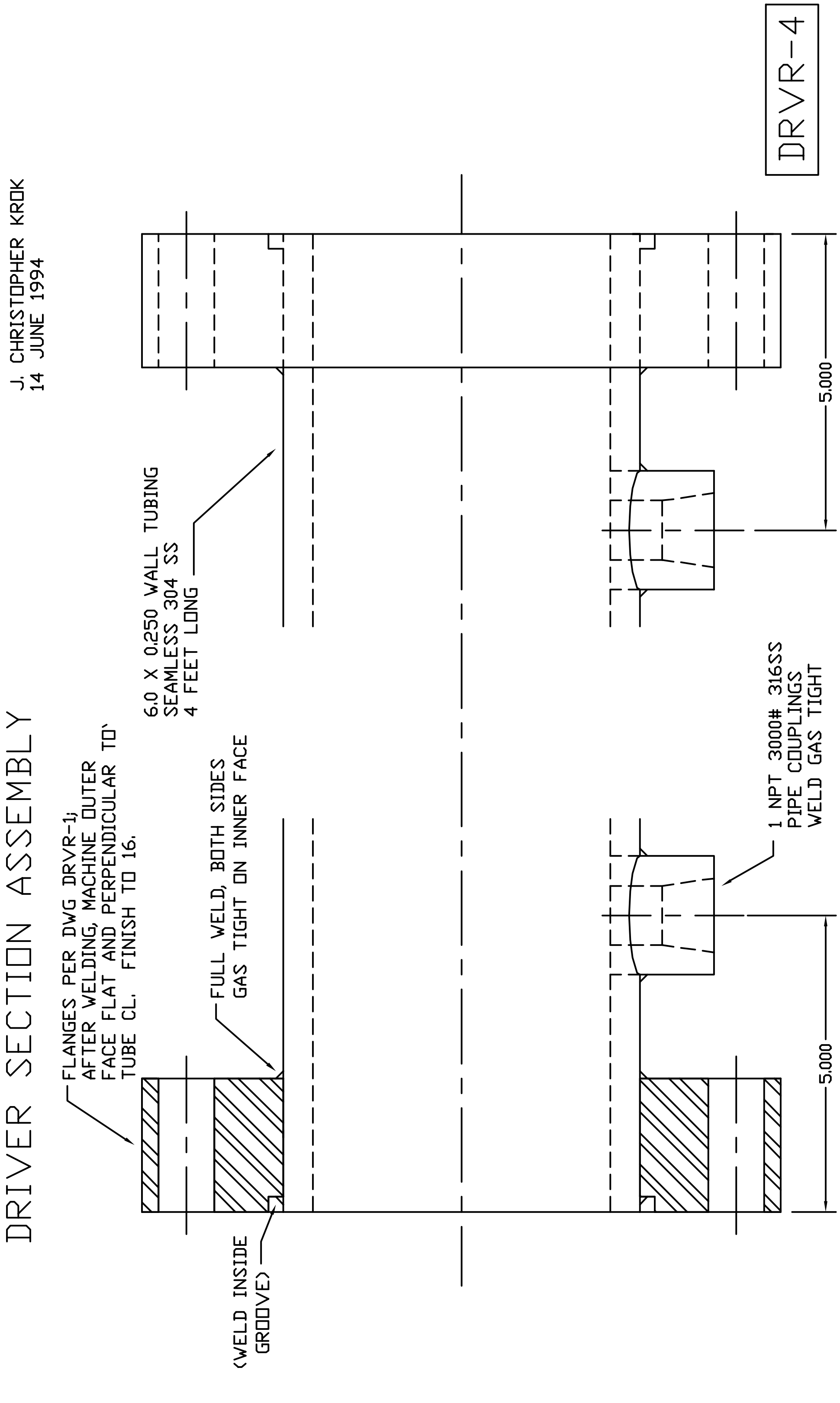
NOZZLE

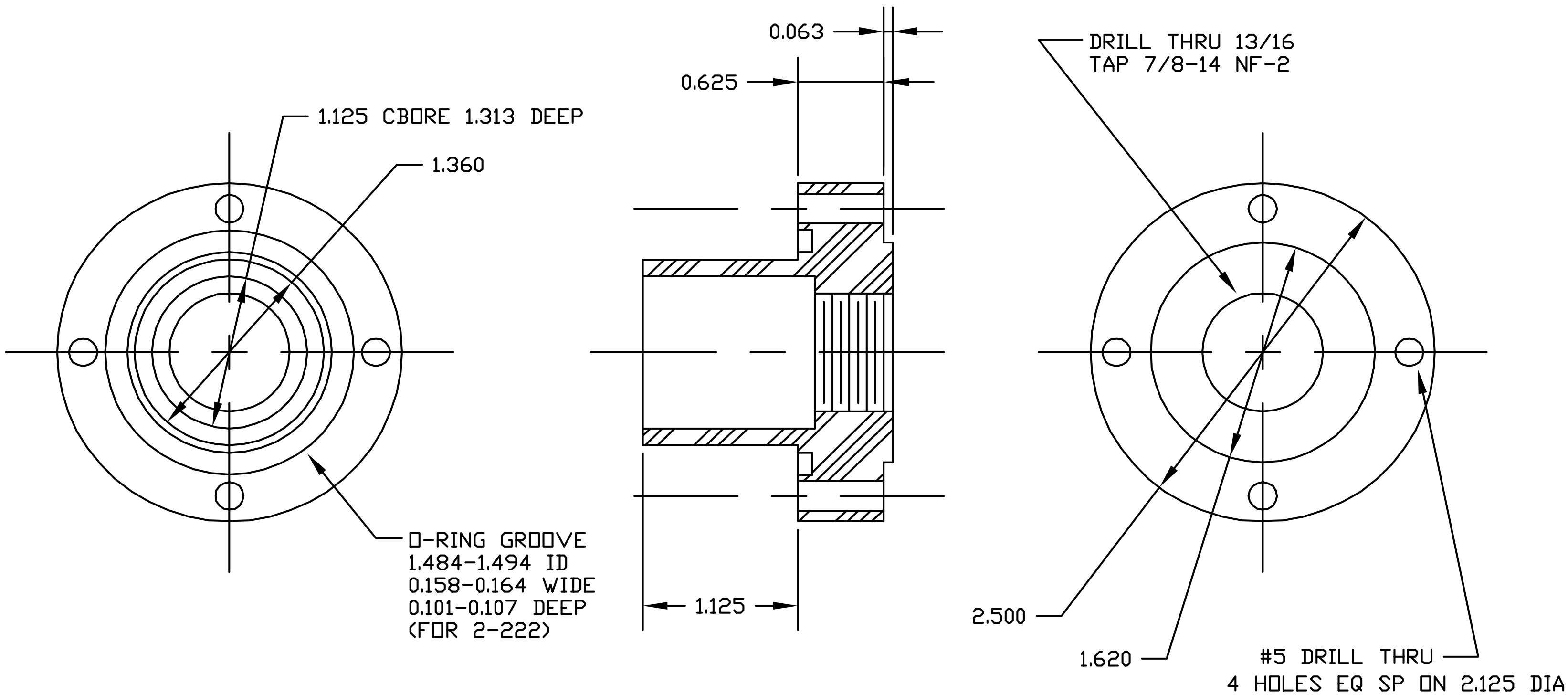
MAT'L: 304SS 1-3/4 HEX BAR
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED
USE 2-125 O-RING

J. CHRISTOPHER KROK
EXPLOSION DYNAMICS
23 MARCH 1995


ALL DIMENSIONS INCHES ±0.005
304 SS
1.005 THRU
#3 DRILL 0.75 DEEP
TAP 1/4-28 NC-2
0.50 DEEP MIN
4 HOLES EQ SP ON
1.875 DIA
2.000
1/4 NPT
R1.8750
GLOW PLUG MOUNT
10-32 THD FOR KULITE
5/16 DRILL 0.75 DEEP
TAP 3/8-16 NC-2 0.5 DEEP MIN
J. CHRISTOPHER KROK
6 SEPT 1996
#21 DRILL, 0.75 DEEP
TAP #10-32 NF-2, 0.375+ DEEP
4 HOLES EQ SP ON 2.125 DIA
1.375
HYJET DRIVER INSTRUMENTATION FLANGE


DRIVER SECTION END FLANGE
J. CHRISTOPHER KROK
14 JUNE 1994
ALL DIMENSIONS INCHES ±0.005
304 SS
(2 REQ'D FOR ASSY)
6.500
10.750
6.000
0.250
2.00
15/16 DRILL THRU
6 HOLES EQ SP ON 9.25 DIA
DRVR-1


DRIVER SECTION ASSEMBLY
J. CHRISTOPHER KROK
14 JUNE 1994
FLANGES PER DWG DRVR-1;
AFTER WELDING, MACHINE OUTER
FACE FLAT AND PERPENDICULAR TO
TUBE CL. FINISH TO 16.
FULL WELD, BOTH SIDES
GAS TIGHT ON INNER FACE
(WELD INSIDE
GROOVE)
6.0 X 0.250 WALL TUBING
SEAMLESS 304 SS
4 FEET LONG
1 NPT 3000# 316SS
PIPE COUPLINGS
WELD GAS TIGHT
5.000
5.000
DRVR-4

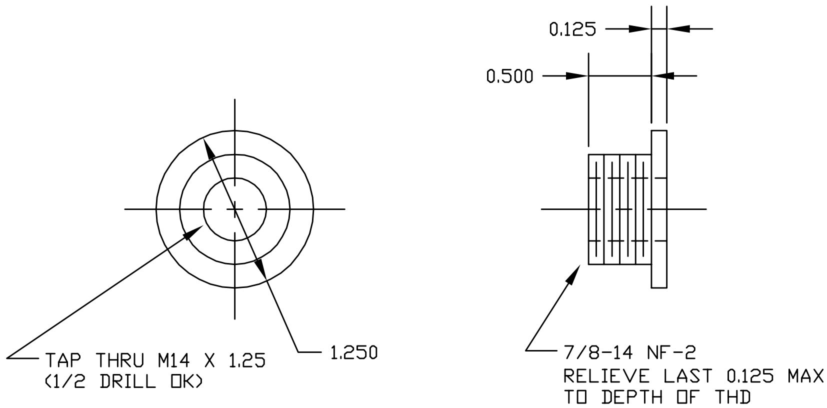


NOTE: HIDDEN LINES OMITTED

SPARK PLUG ISOLATOR

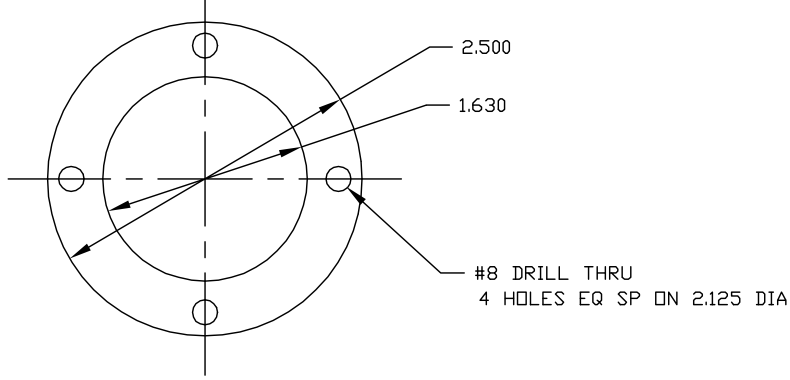
MAT'L: 2.5 DIA TFE BAR STOCK
ALL DIMENSIONS ±0.005 UNLESS NOTED

J. CHRISTOPHER KROK
EXPLOSION DYNAMICS LAB
20 MARCH 1995



SPARK PLUG BUSHING

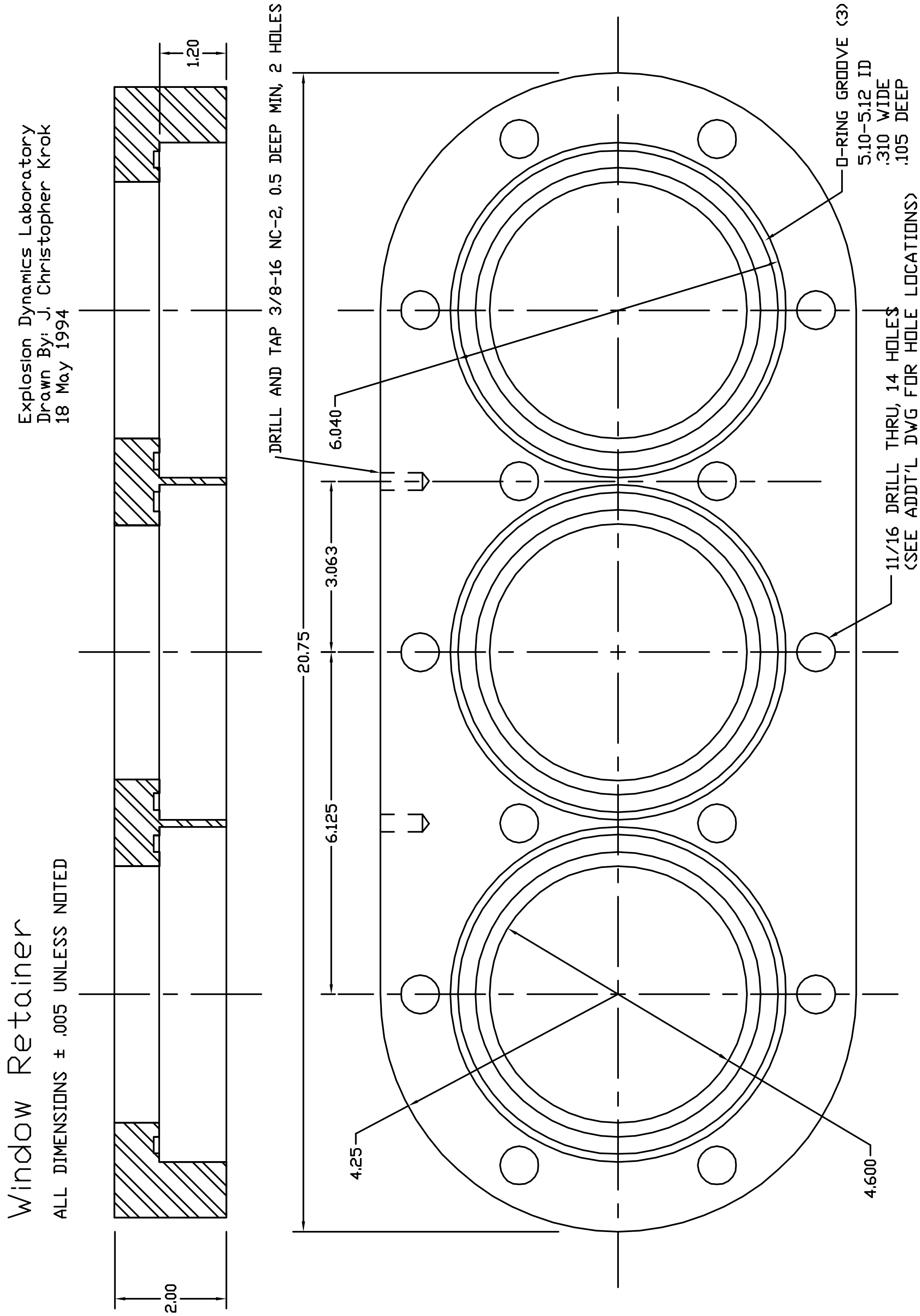
MAT'L: 1.25 DIA CRS BAR
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED

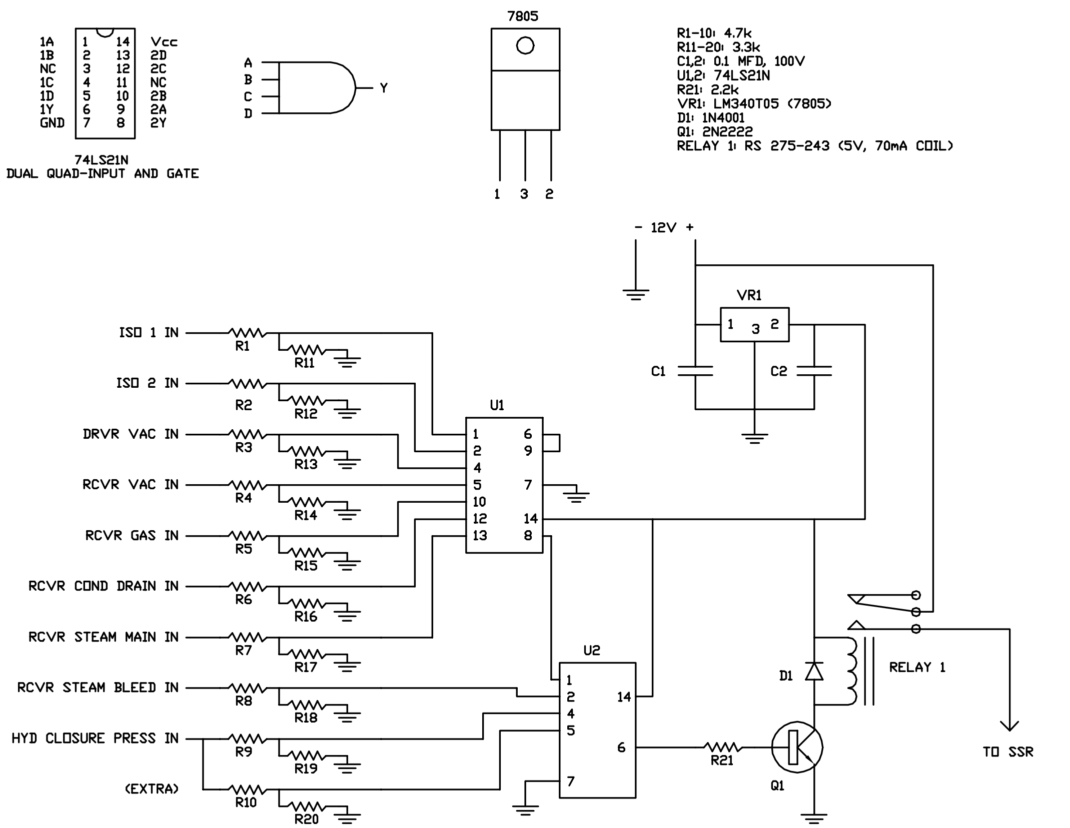


ISOLATOR RETAINING RING

MAT'L: 1/16 STEEL PLATE
ALL DIMENSIONS INCHES ±0.005 UNLESS NOTED

J. CHRISTOPHER KROK
EXPLOSION DYNAMICS LAB
20 MARCH 1995


Window Retainer
ALL DIMENSIONS ± .005 UNLESS NOTED
Explosion Dynamics Laboratory
Drawn By: J. Christopher Krok
18 May 1994
1.20
2.00
DRILL AND TAP 3/8-16 NC-2, 0.5 DEEP MIN, 2 HOLES
6.040
20.75
3.063
6.125
4.25
4.600
O-RING GROOVE (3)
5.10-5.12 ID
.310 WIDE
.105 DEEP
11/16 DRILL THRU, 14 HOLES
(SEE ADDT'L DWG FOR HOLE LOCATIONS)



HYJET LOGIC CONTROL SAFETY INTERLOCK CIRCUIT

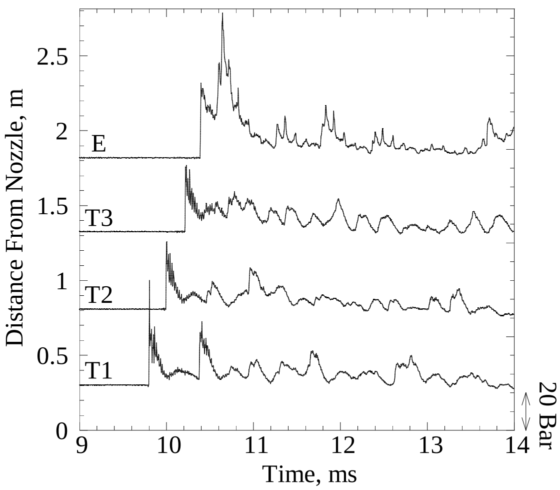
J. C. KROK 11 SEPT 1995

Appendix C

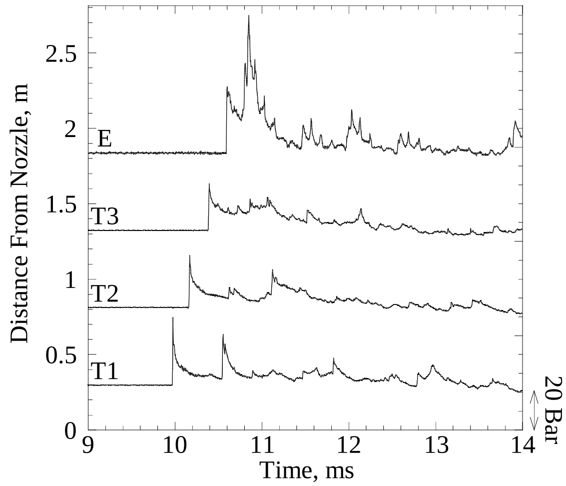
BETA Pressure Traces

This section contains plots of all pressure traces in the BETA series. They are organized in order of increasing β for each system.

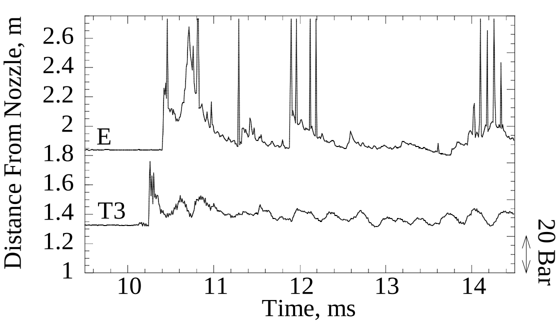
C.1 Nitrogen Dilution, 298 K



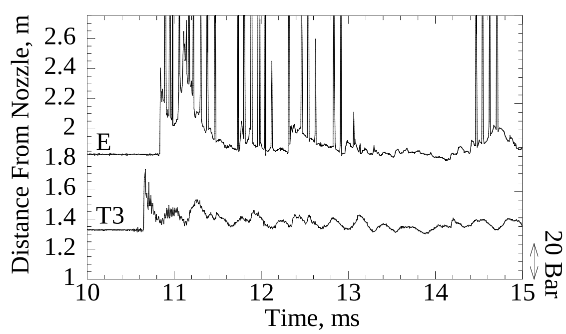
Run 343: β=2.6
92-mm nozzle



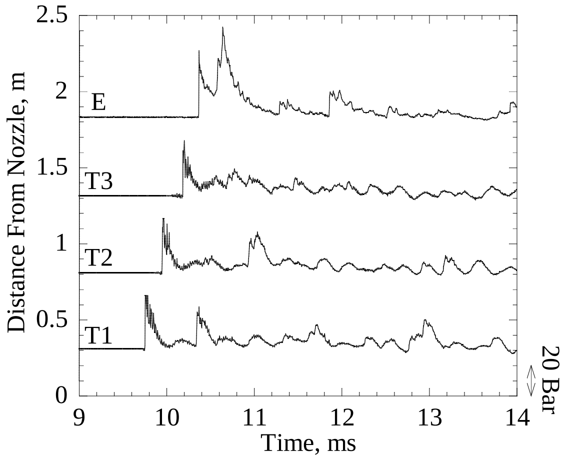
Run 356: β=2.6
92-mm nozzle



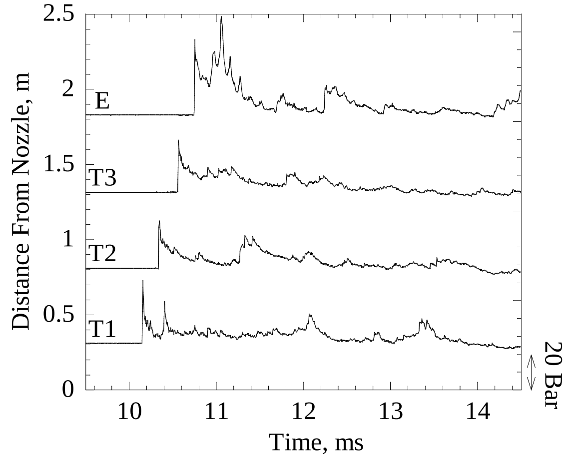
Run 312: β=3.76
92-mm nozzle



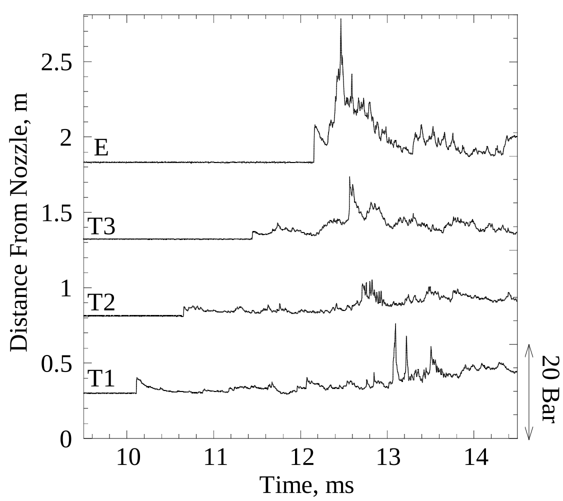
Run 313: β=4
92-mm nozzle



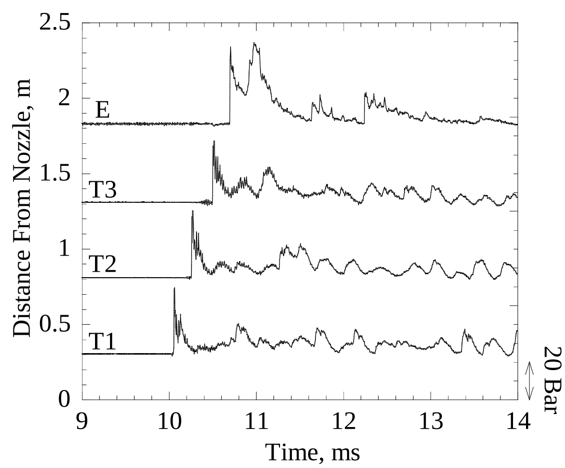
Run 340: β=4.2
92-mm nozzle



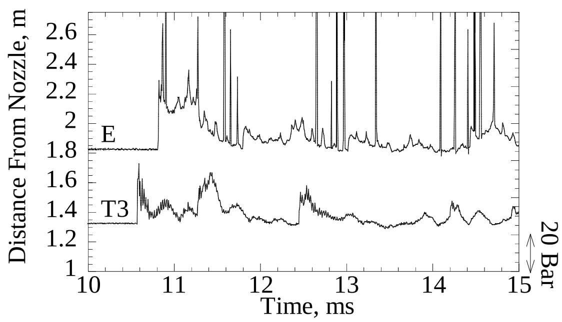
Run 355: β=4.2
92-mm nozzle



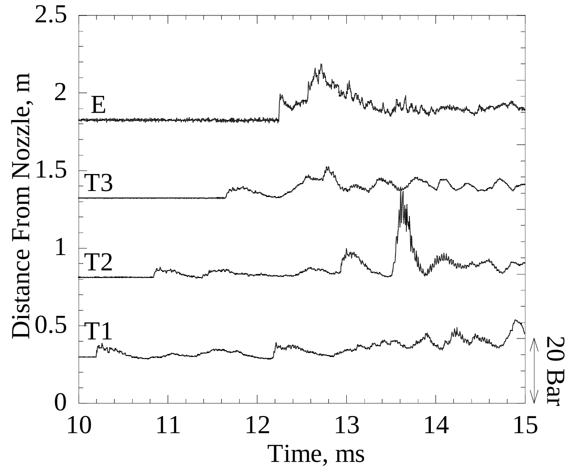
Run 354: β=4.3
92-mm nozzle



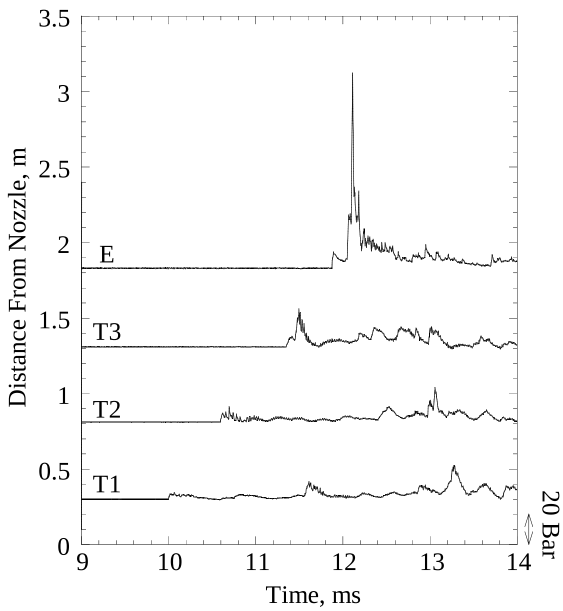
Run 338: β=4.3
92-mm nozzle



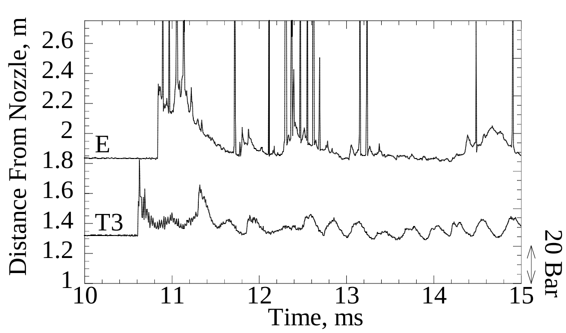
Run 317: β=4.3
92-mm nozzle



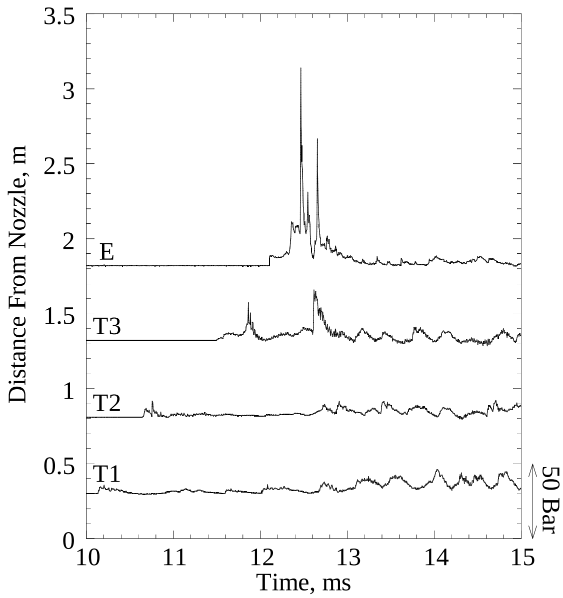
Run 337: β=4.4
92-mm nozzle



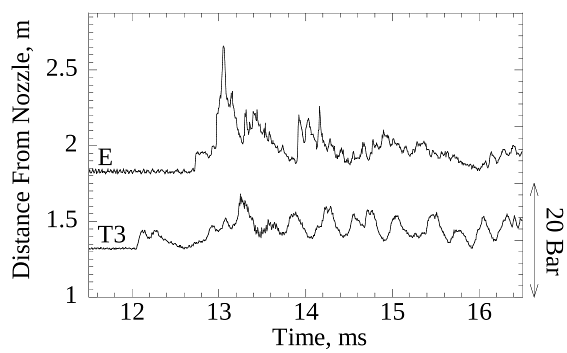
Run 339: β=4.4
92-mm nozzle



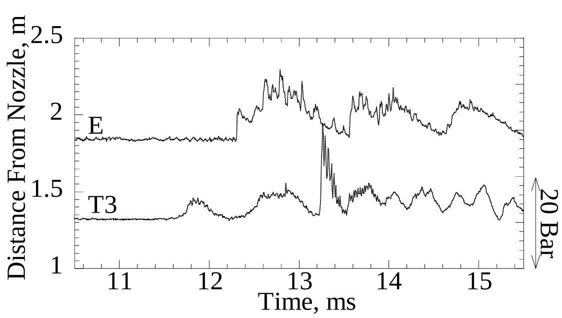
Run 315: β=4.4
92-mm nozzle



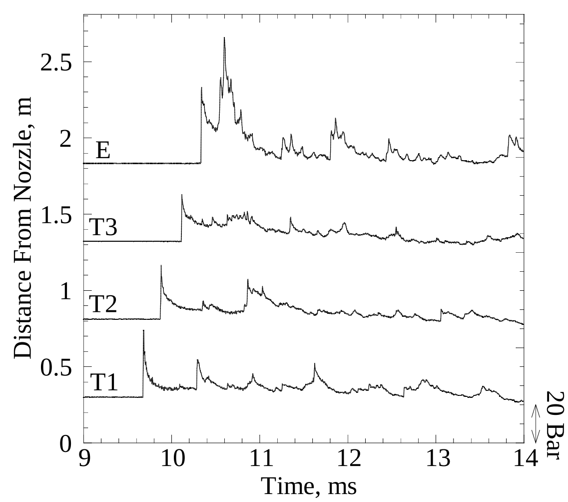
Run 336: β=4.5
92-mm nozzle



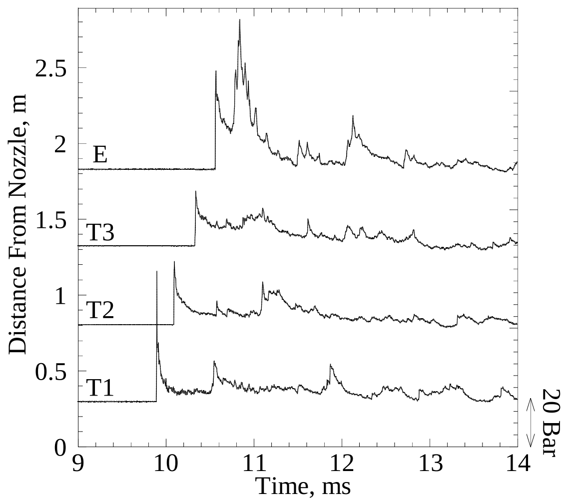
Run 314: β=4.5
92-mm nozzle



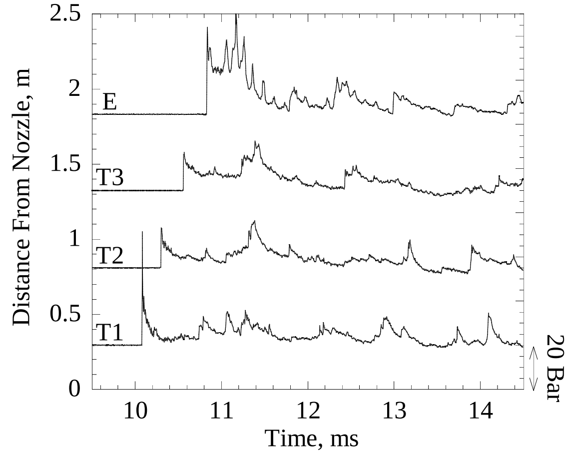
Run 316: β=4.6
92-mm nozzle



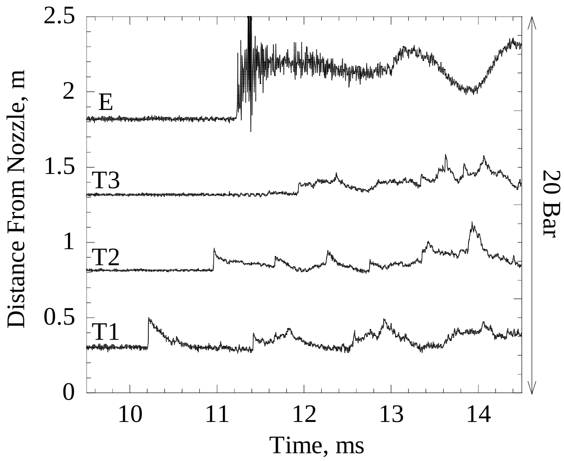
Run 357: β=3.76
64-mm nozzle



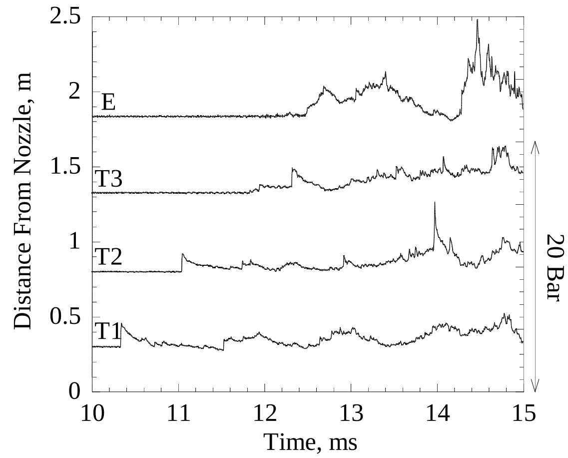
Run 360: β=4.1
64-mm nozzle



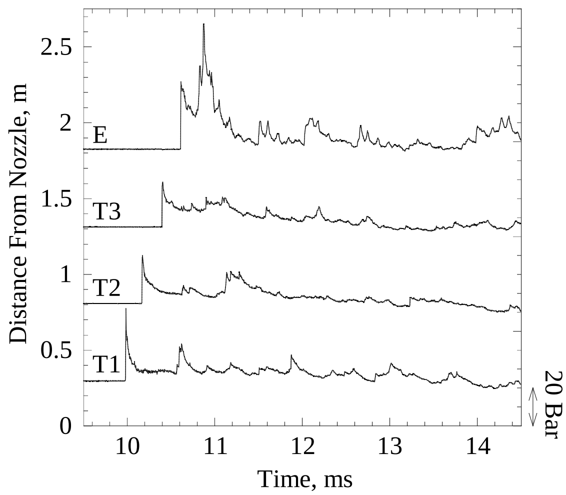
Run 358: β=4.2
64-mm nozzle



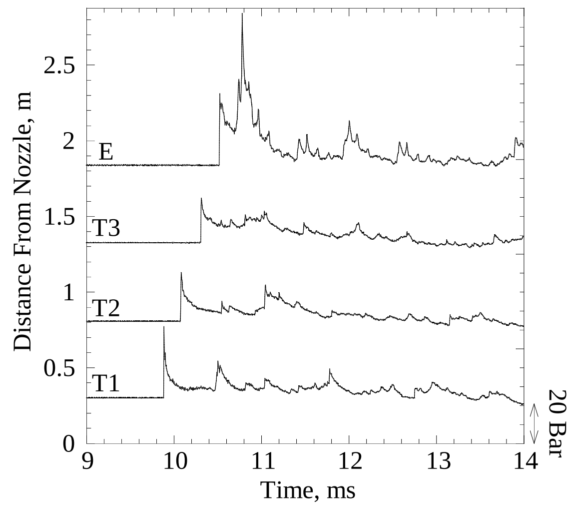
Run 359: β=4.3
64-mm nozzle



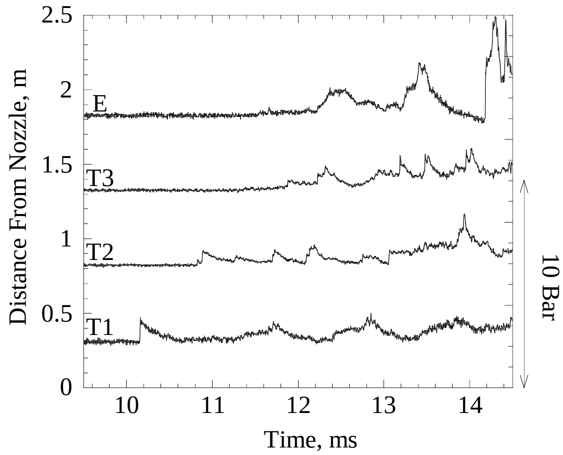
Run 379: β=4.5
64-mm nozzle



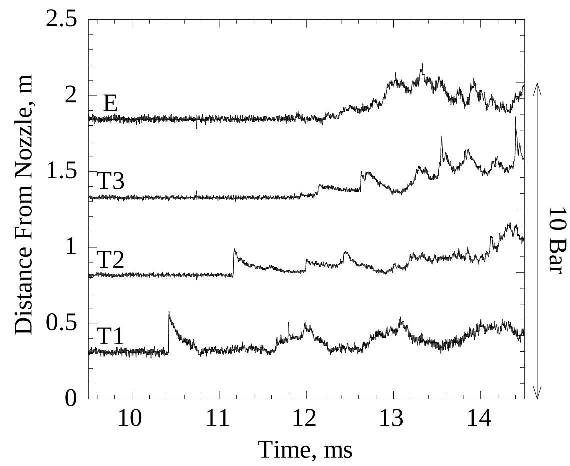
Run 366: β=2.9
38-mm nozzle



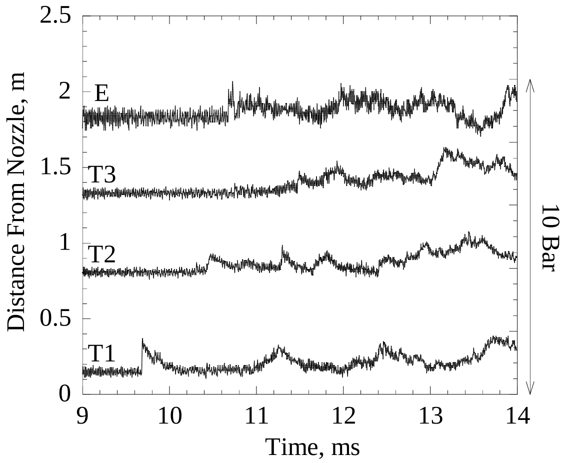
Run 362: β=3.0
38-mm nozzle



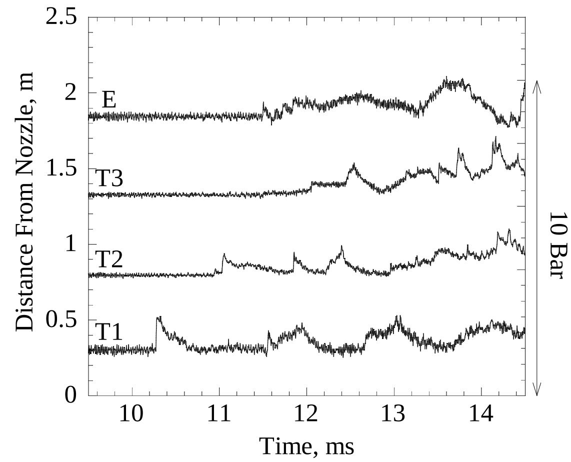
Run 365: β=3.1
38-mm nozzle



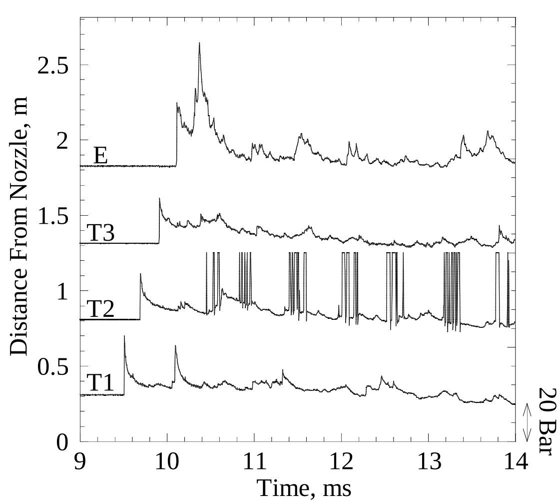
Run 364: β=3.2
38-mm nozzle



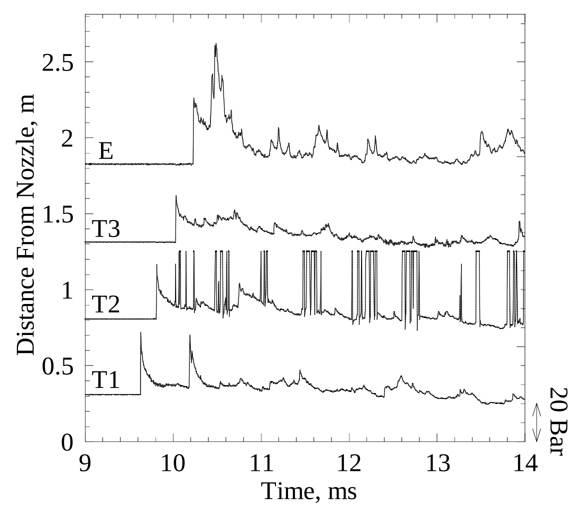
Run 363: β=3.4
38-mm nozzle



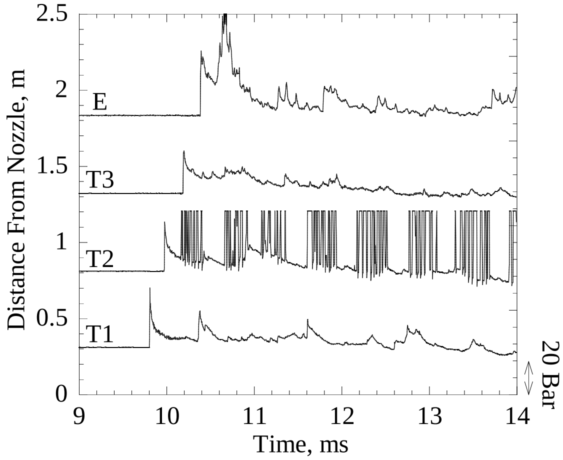
Run 361: β=3.76
38-mm nozzle



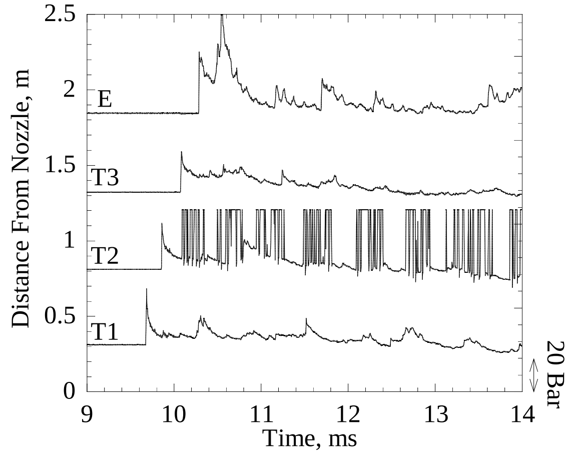
Run 424: β=2.4
25-mm nozzle w/c



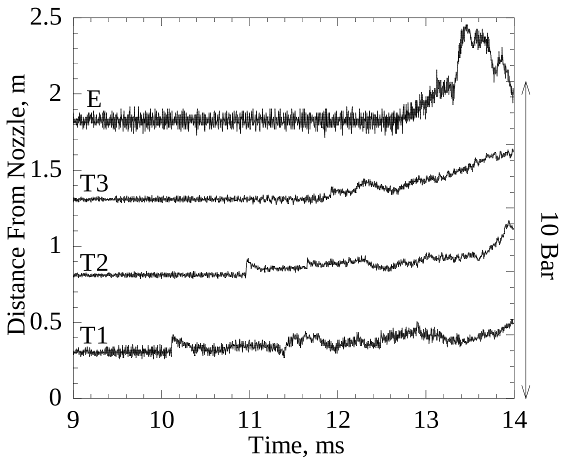
Run 430: β=2.4
25-mm nozzle w/c



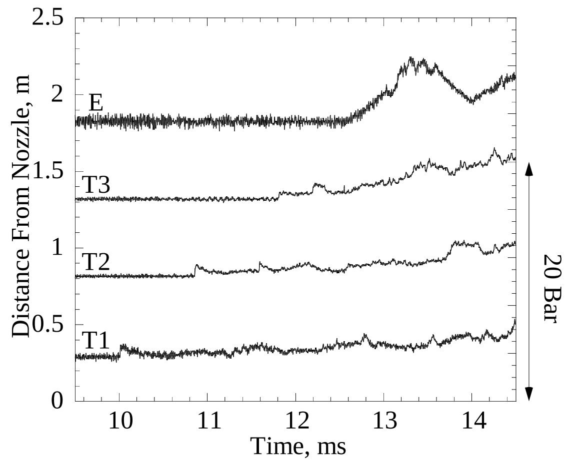
Run 407: β=2.6
25-mm nozzle w/c



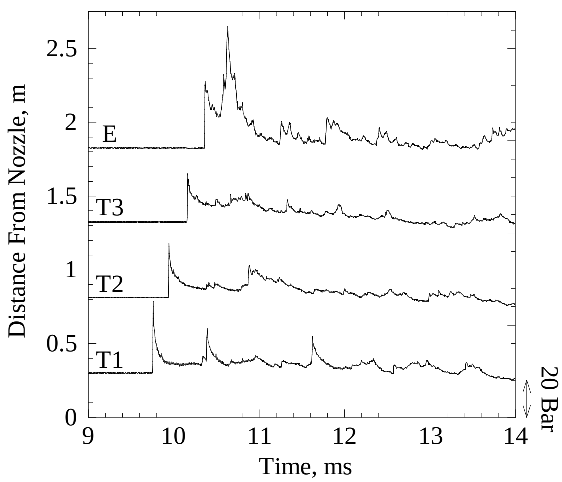
Run 408: β=2.6
25-mm nozzle w/c



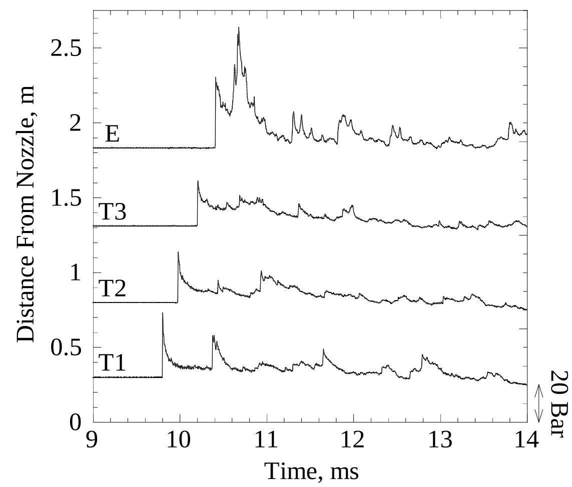
Run 420: β=2.6
25-mm nozzle w/c



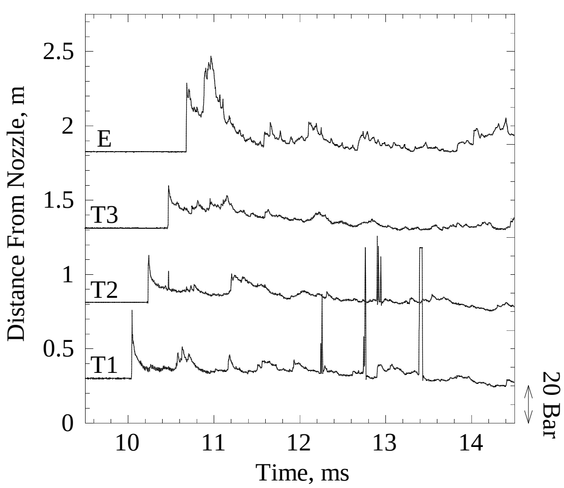
Run 429: β=2.6
25-mm nozzle w/c



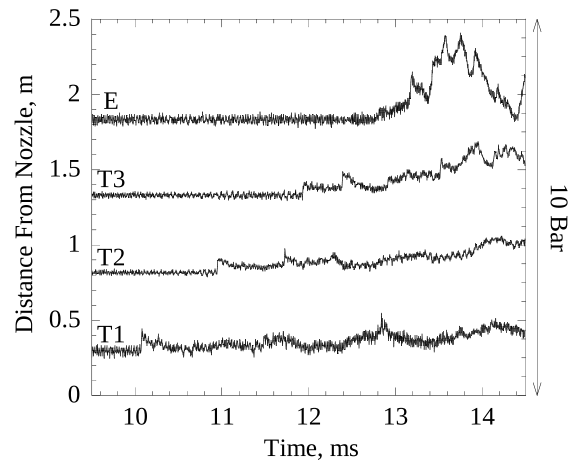
Run 367: β=2.8
25-mm nozzle w/c



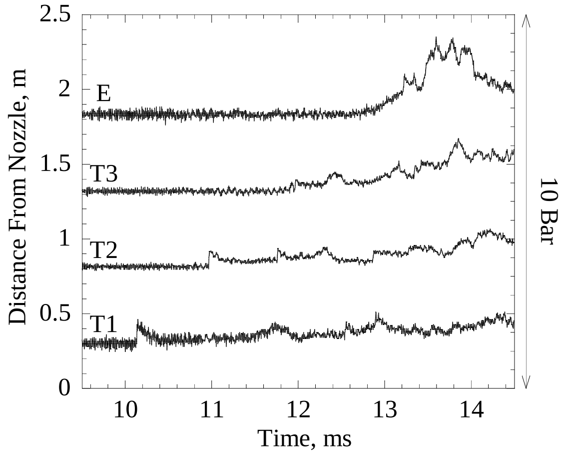
Run 369: β=2.9
25-mm nozzle w/c



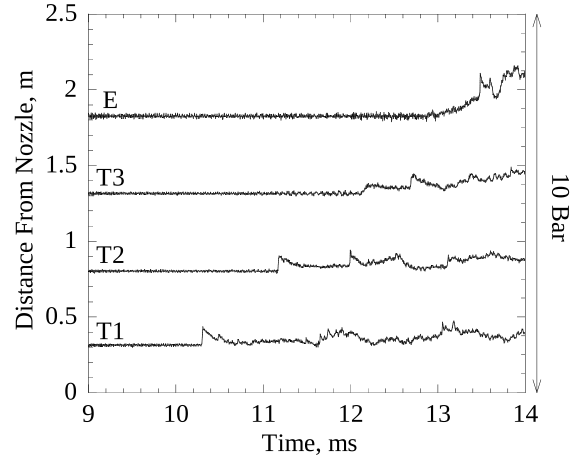
Run 377: β=2.9
25-mm nozzle w/c



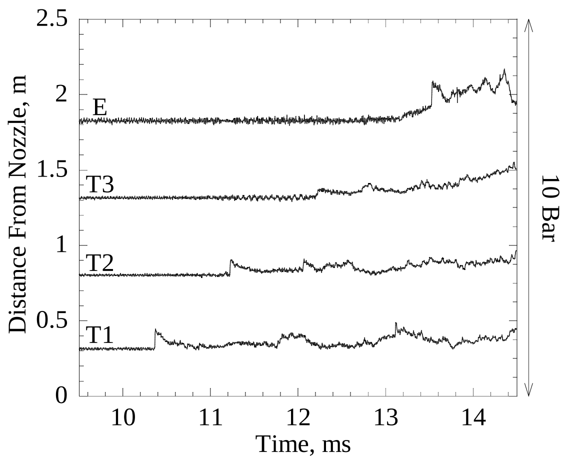
Run 368: β=3.0
25-mm nozzle w/c



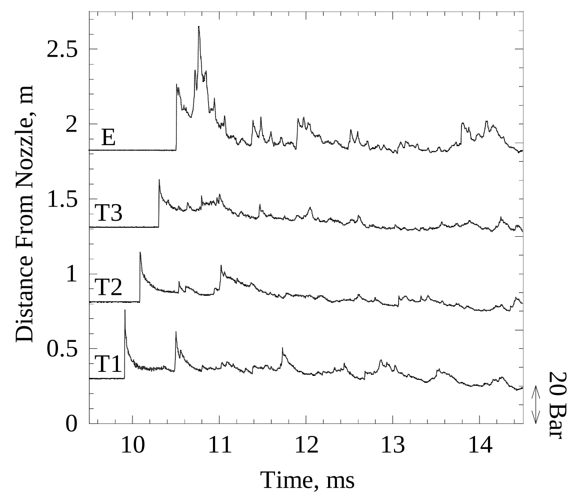
Run 378: β=3.1
25-mm nozzle w/c



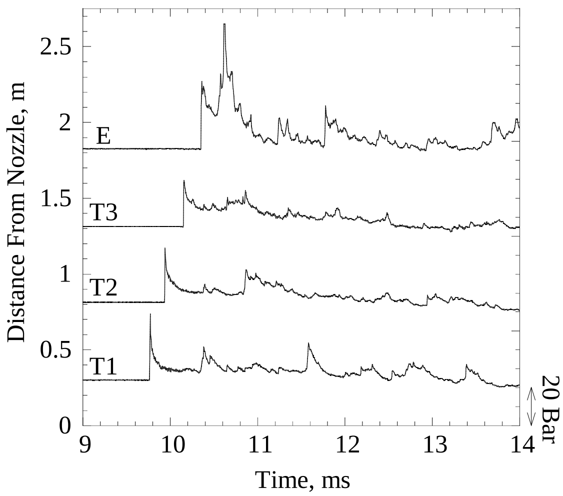
Run 416: β=3.76
25-mm nozzle w/c



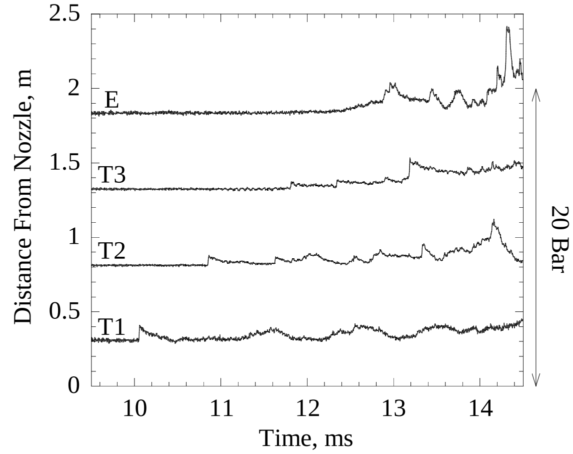
Run 419: β=3.76
25-mm nozzle w/c



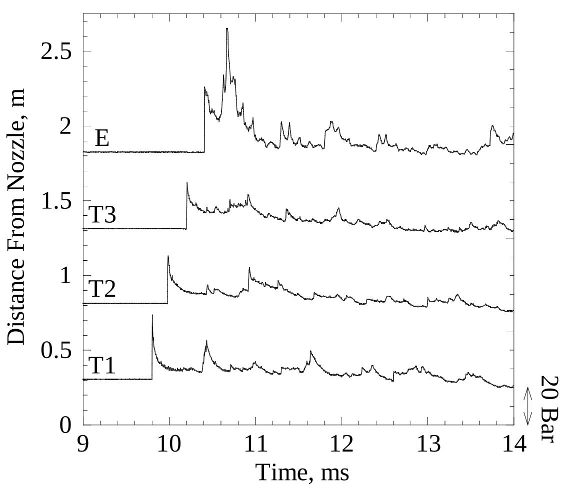
Run 375: β=2.4
25-mm nozzle n/c



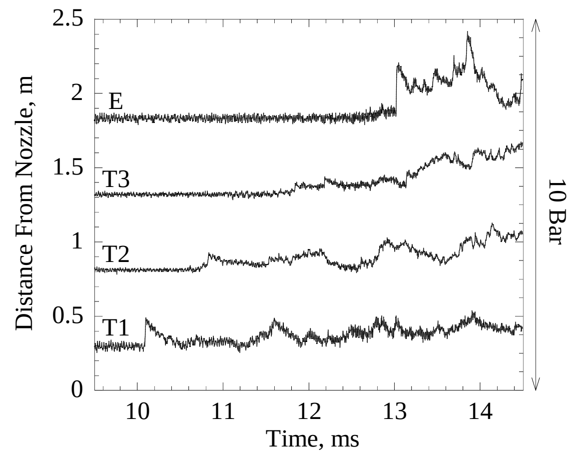
Run 376: β=2.5
25-mm nozzle n/c



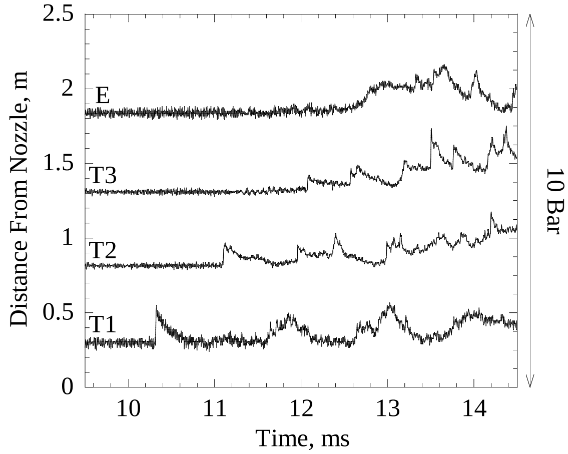
Run 374: β=2.5
25-mm nozzle n/c



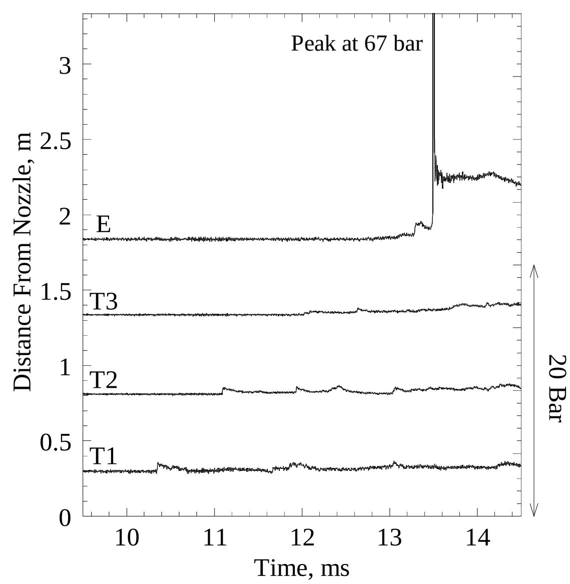
Run 372: β=2.6
25-mm nozzle n/c



Run 373: β=2.7
25-mm nozzle n/c

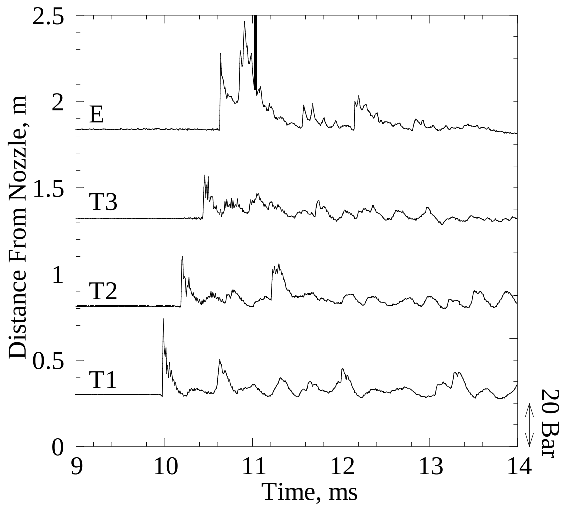


Run 371: β=2.8
25-mm nozzle n/c

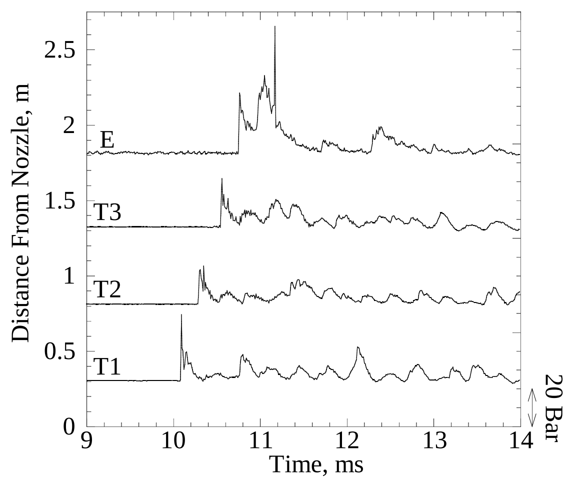


Run 370: β=2.9
25-mm nozzle n/c

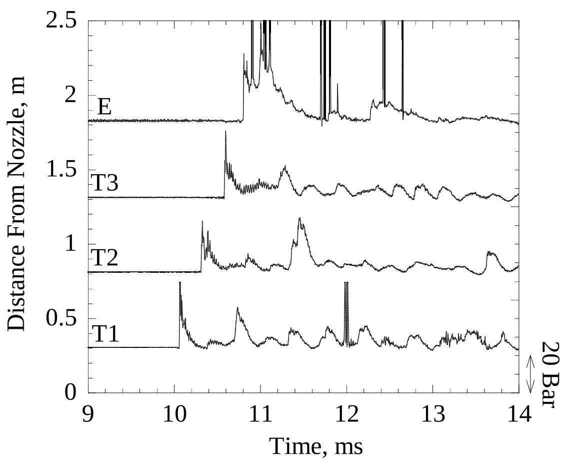
C.2 Nitrogen Dilution, 373 K



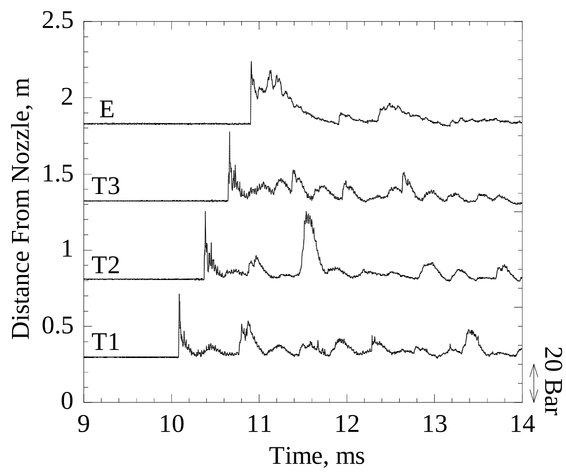
Run 321: β=4.6
92-mm nozzle



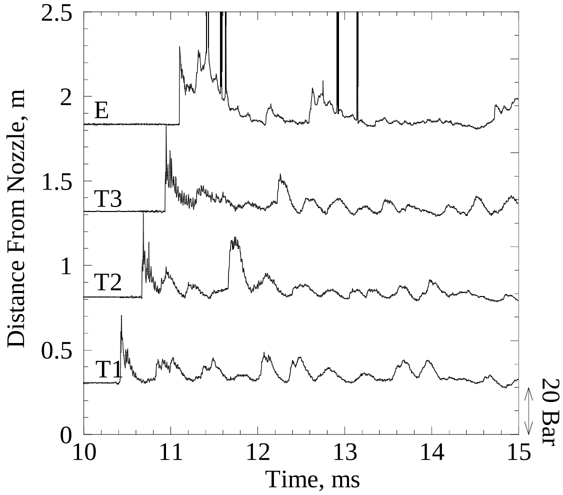
Run 322: β=4.8
92-mm nozzle



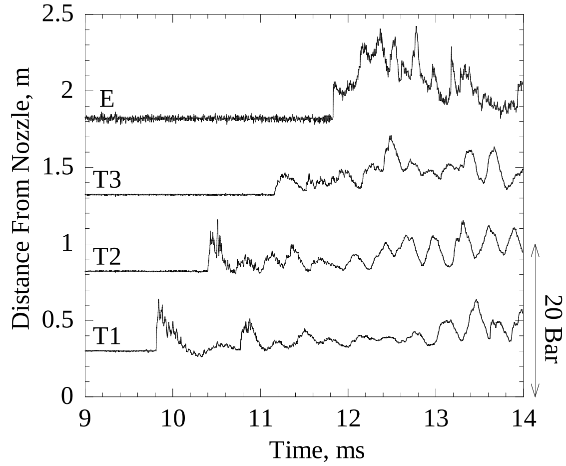
Run 329: β=5.1
92-mm nozzle



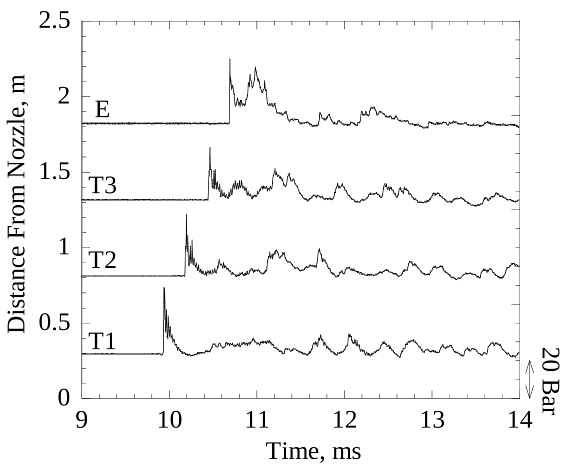
Run 344: β=5.1
92-mm nozzle



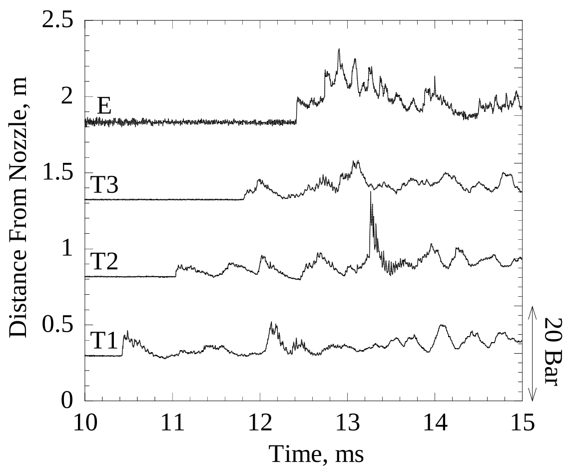
Run 324: β=5.2
92-mm nozzle



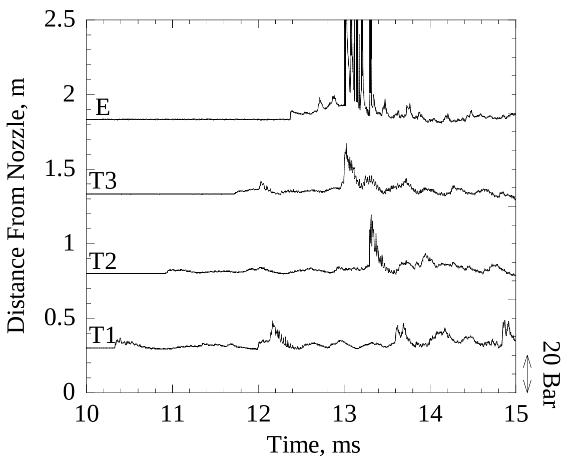
Run 328: β=5.2
92-mm nozzle



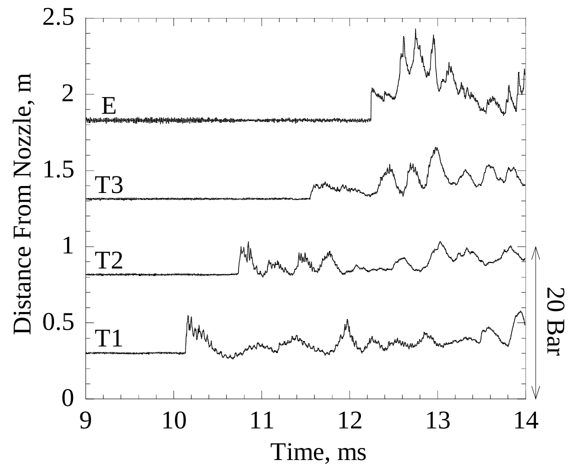
Run 341: β=5.2
92-mm nozzle



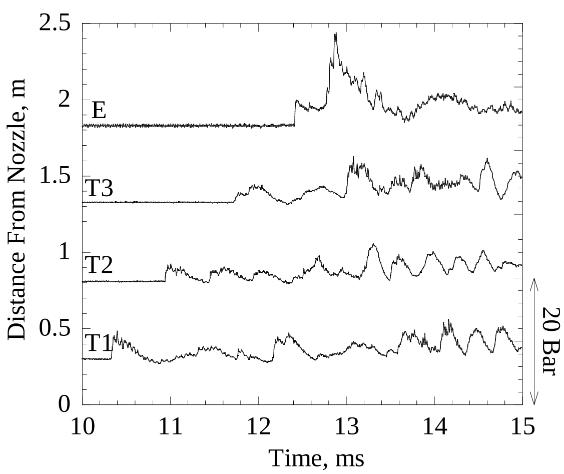
Run 325: β=5.3
92-mm nozzle



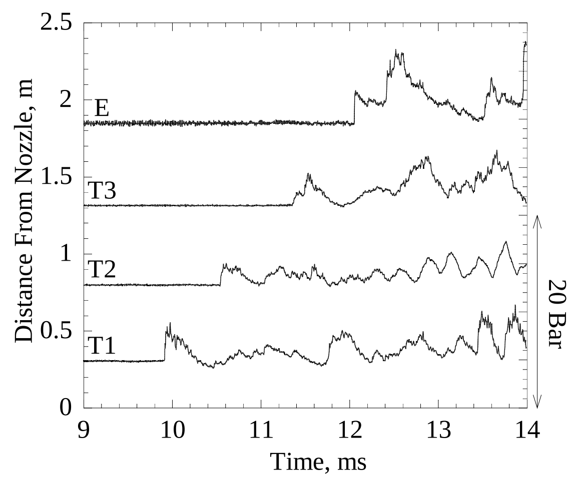
Run 327: β=5.3
92-mm nozzle



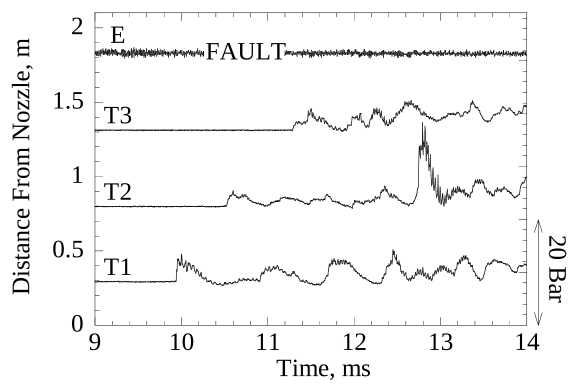
Run : β=5.3
92-mm nozzle



Run 326: β=5.4
92-mm nozzle

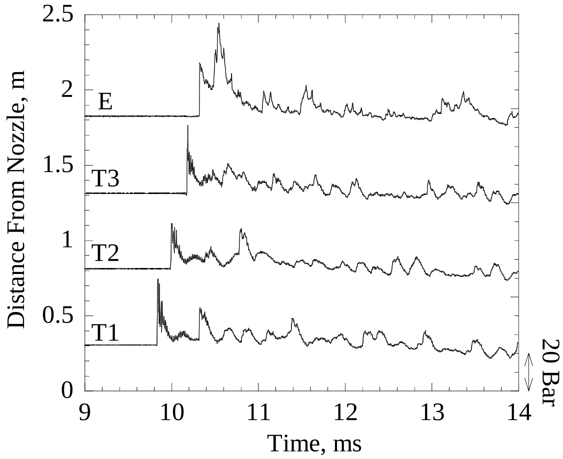


Run 342: β=5.4
92-mm nozzle

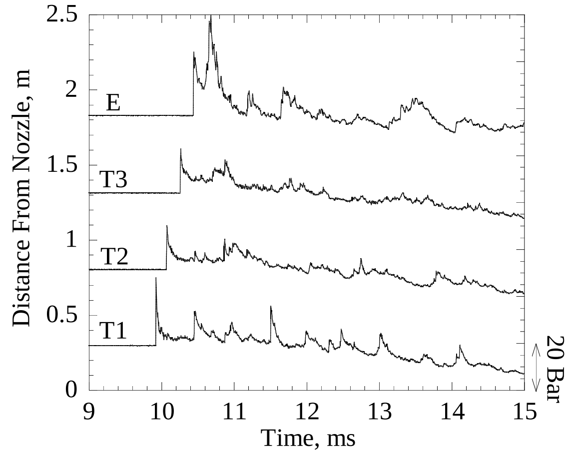


Run 323: β=5.5
92-mm nozzle

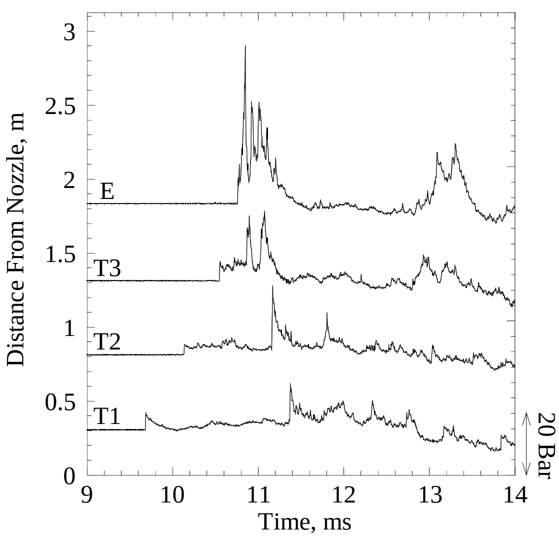
C.3 Water Vapor Dilution, 373 K



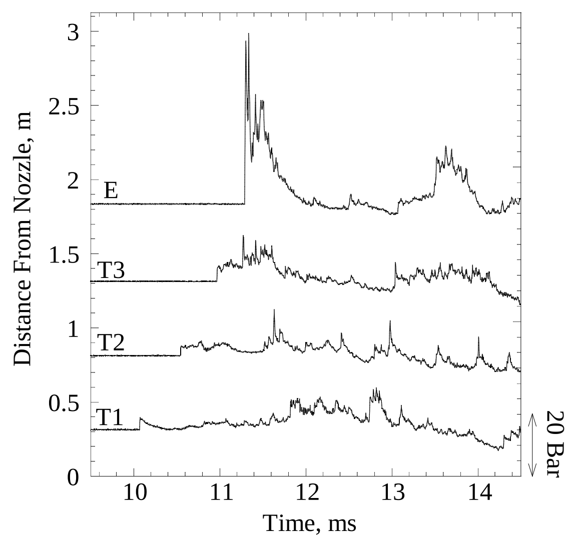
Run 352: β=1.0
92-mm nozzle



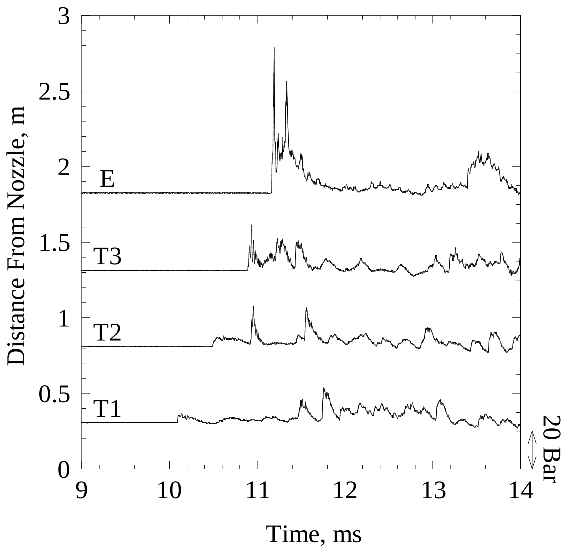
Run 380: β=1.1
92-mm nozzle



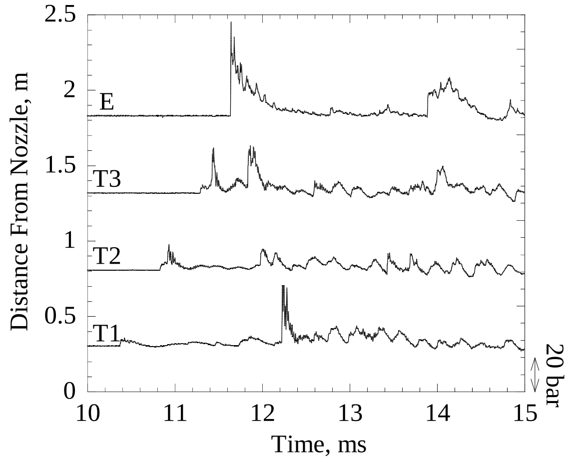
Run 382: β=1.2
92-mm nozzle



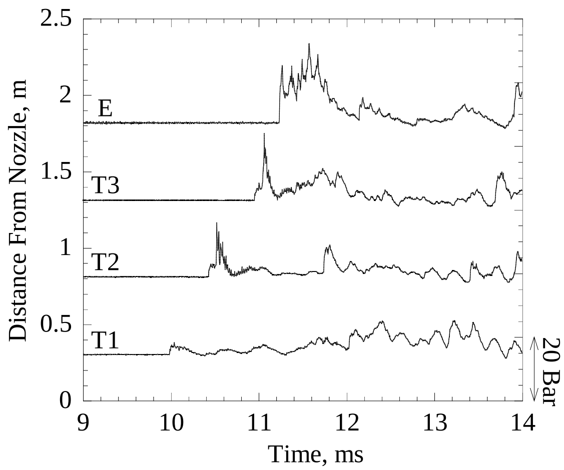
Run 381: β=1.3
92-mm nozzle



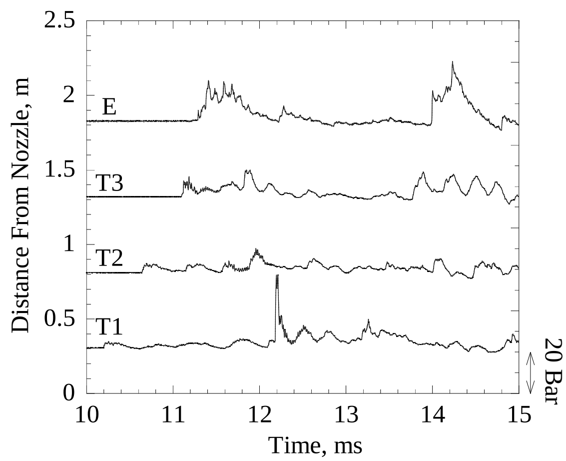
Run 350: β=1.4
92-mm nozzle



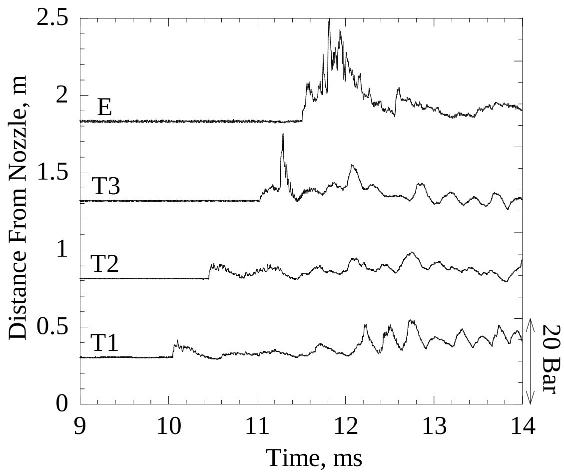
Run 351: β=1.6
92-mm nozzle



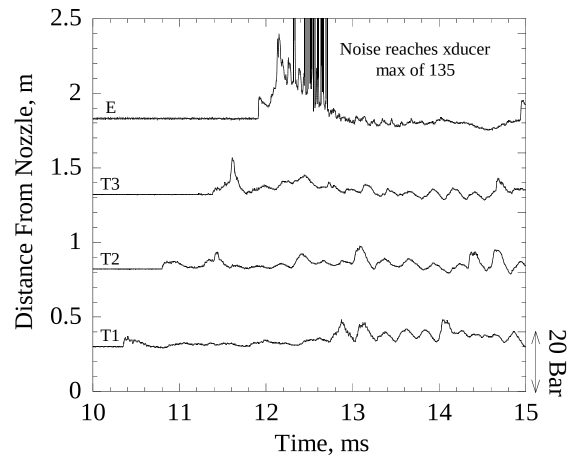
Run 349: β=1.8
92-mm nozzle



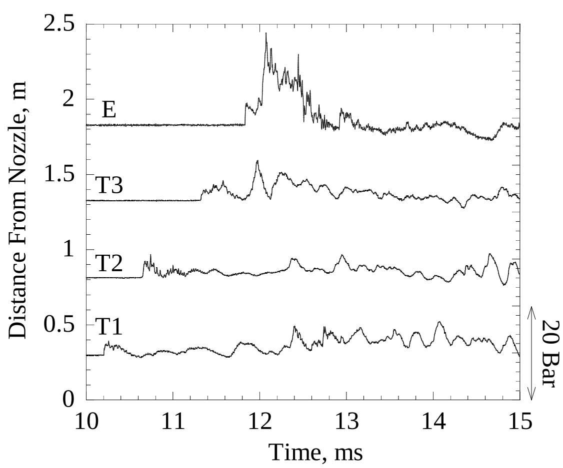
Run 348: β=2.0
92-mm nozzle



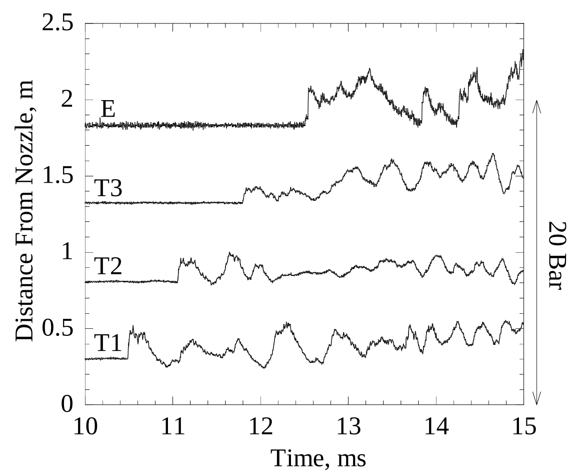
Run 347: β=2.6
92-mm nozzle



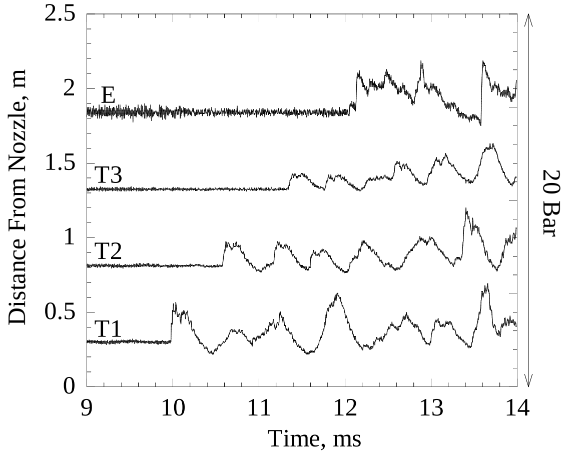
Run 332: β=3.0
92-mm nozzle



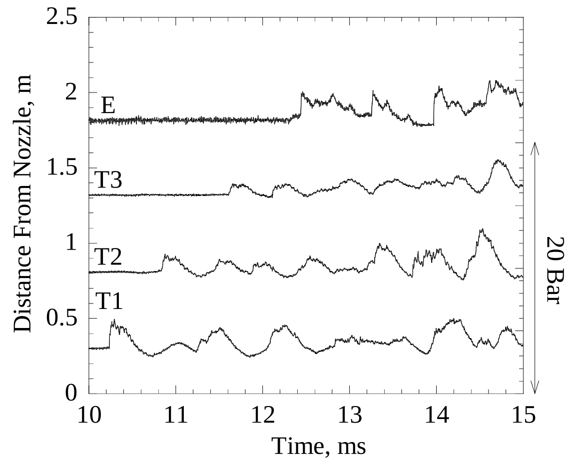
Run 346: β=3.0
92-mm nozzle



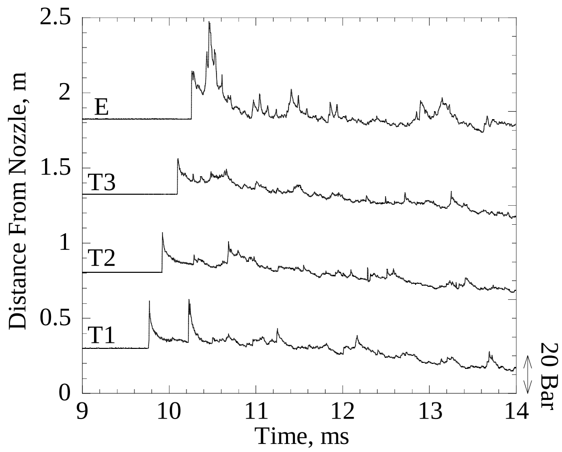
Run 345: β=3.5
92-mm nozzle



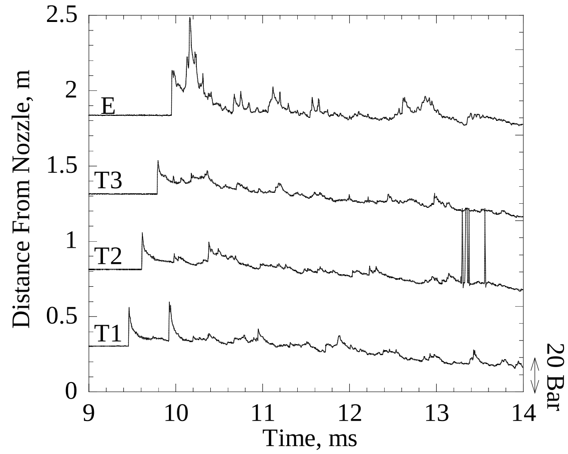
Run 331: β=4.0
92-mm nozzle



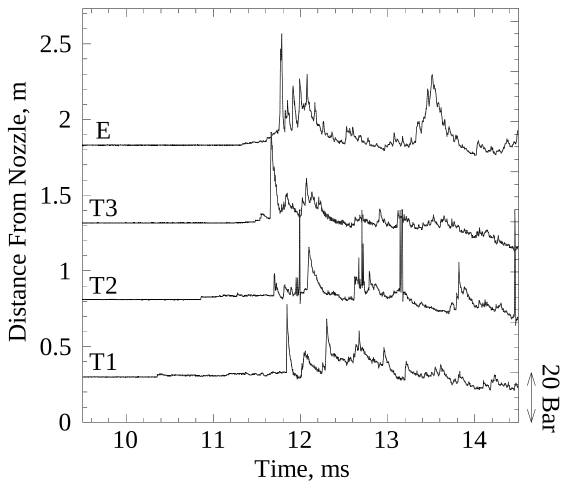
Run 330: β=5.0
92-mm nozzle



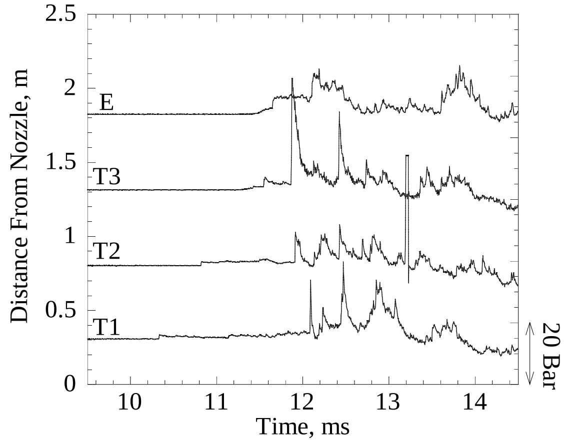
Run 388: β=0.5
38-mm nozzle



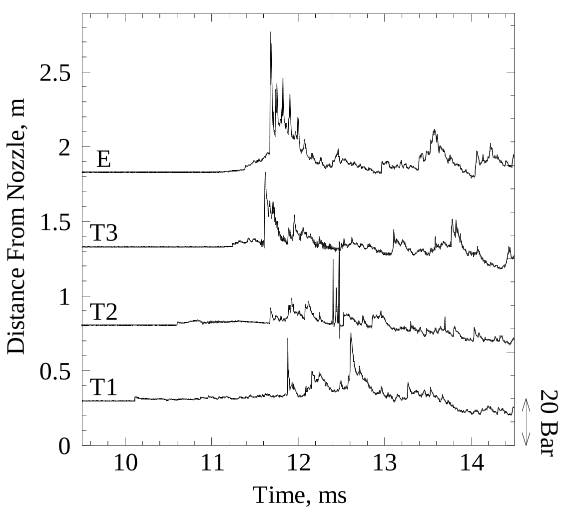
Run 389: β=0.55
38-mm nozzle



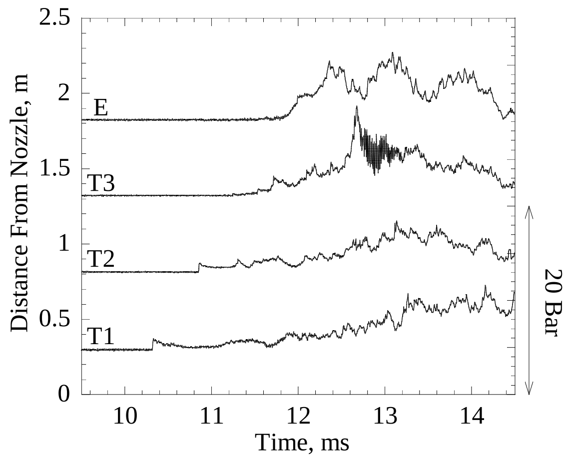
Run 390: β=0.6
38-mm nozzle



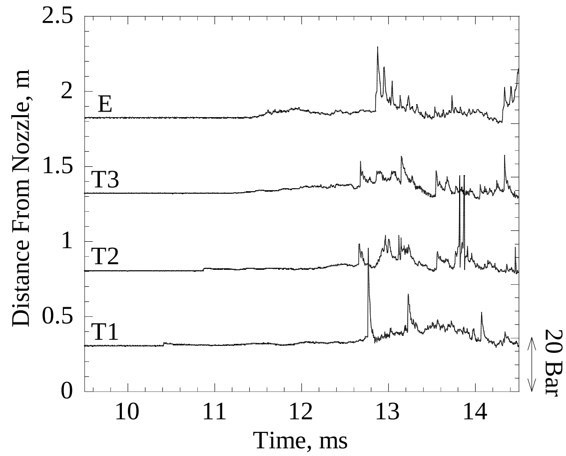
Run 386: β=0.66
38-mm nozzle



Run 385: β=0.7
38-mm nozzle

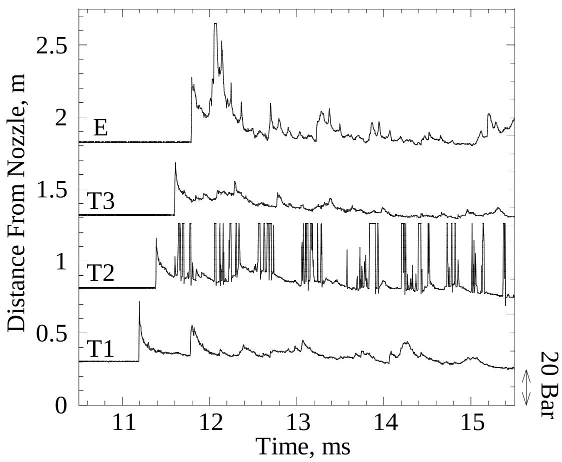


Run 391: β=0.8
38-mm nozzle

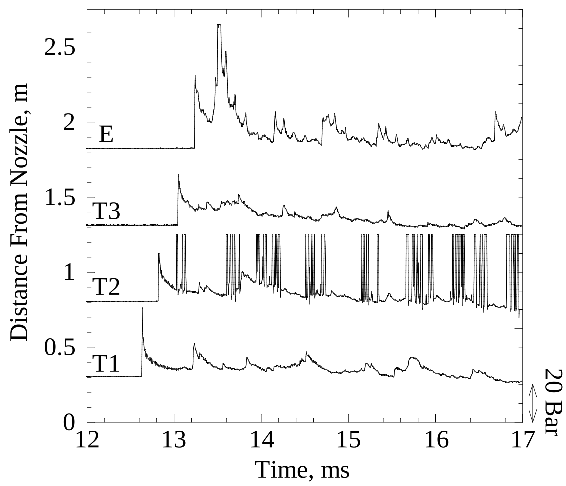


Run 384: β=0.86
38-mm nozzle

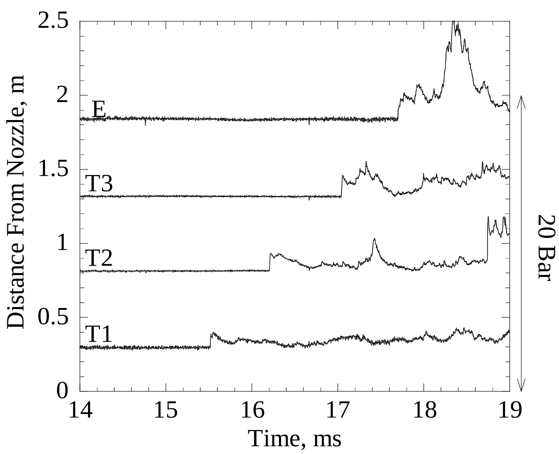
C.4 Nitrogen Dilution, 298 K, No Diaphragm



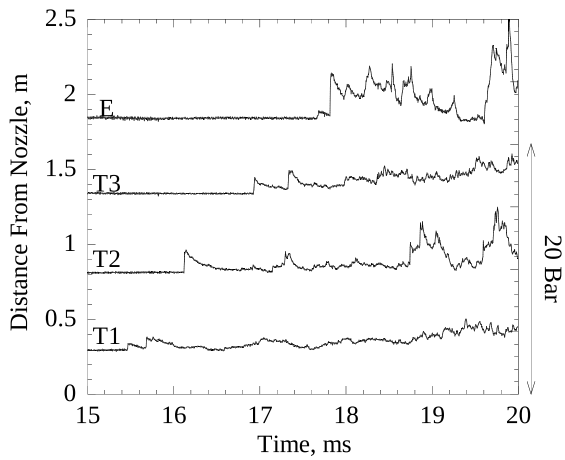
Run 393: β=3.0
92-mm nozzle



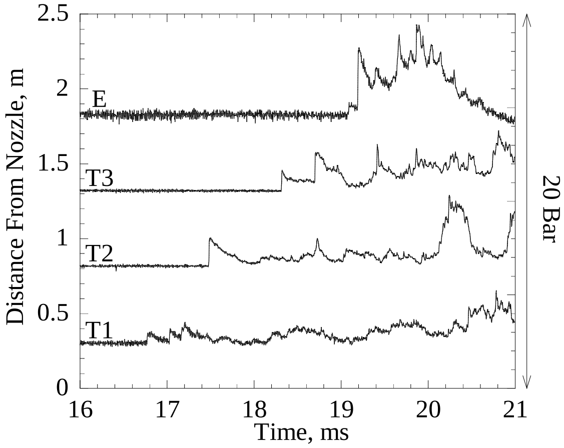
Run 394: β=3.3
92-mm nozzle



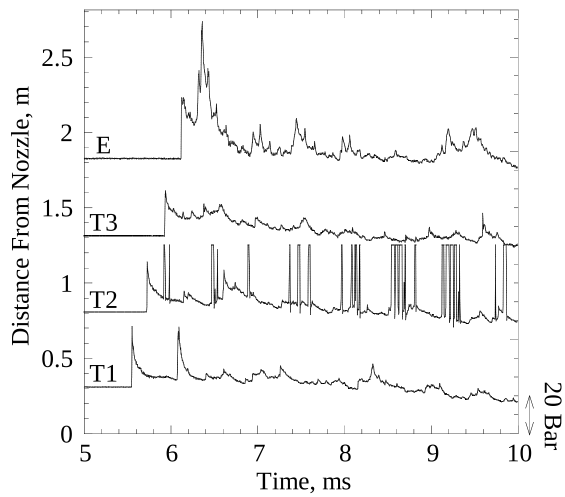
Run 392: β=3.76
92-mm nozzle



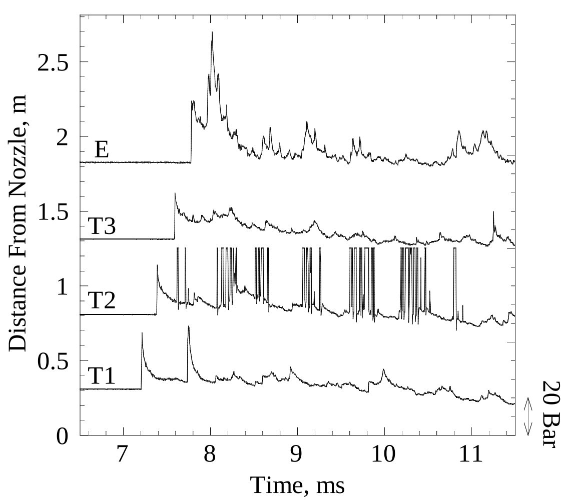
Run 396: β=3.76
92-mm nozzle



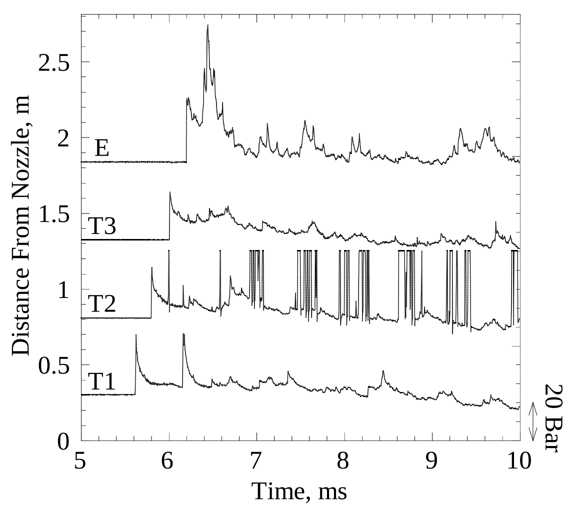
Run 395: β=4.0
92-mm nozzle



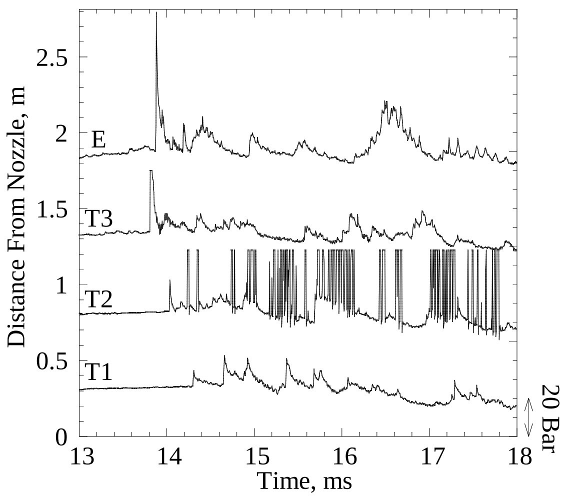
Run 423: β=1.5
25-mm nozzle w/c



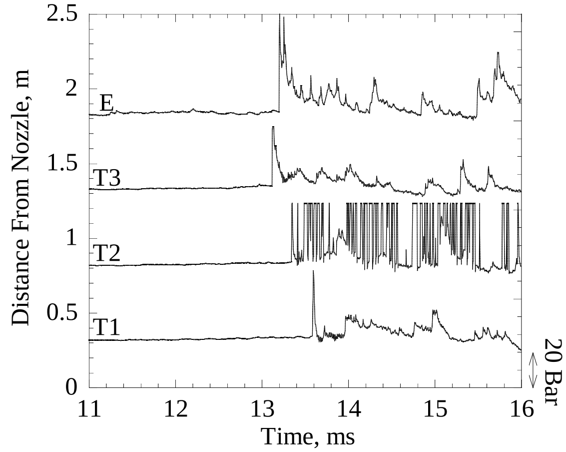
Run 431: β=1.5
25-mm nozzle w/c



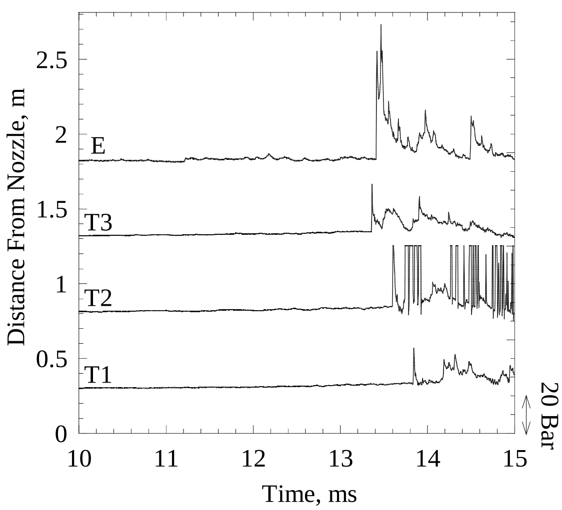
Run 411: β=1.7
25-mm nozzle w/c



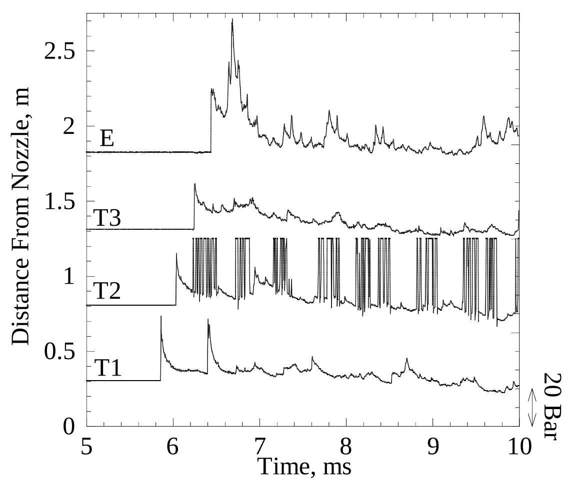
Run 422: β=1.7
25-mm nozzle w/c



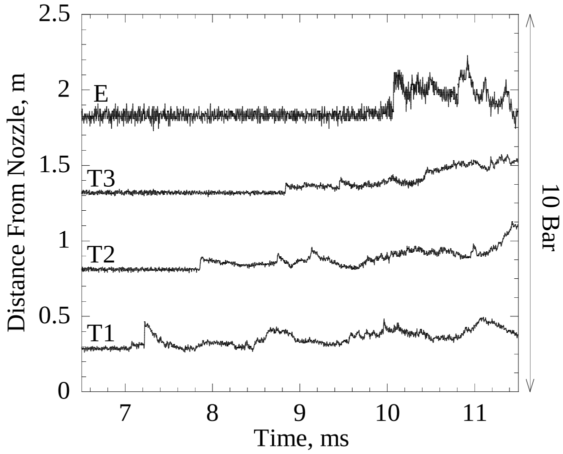
Run 409: β=1.8
25-mm nozzle w/c



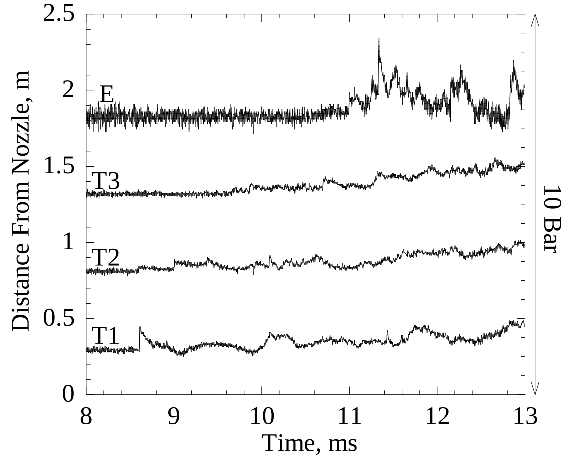
Run 410: β=1.8
25-mm nozzle w/c



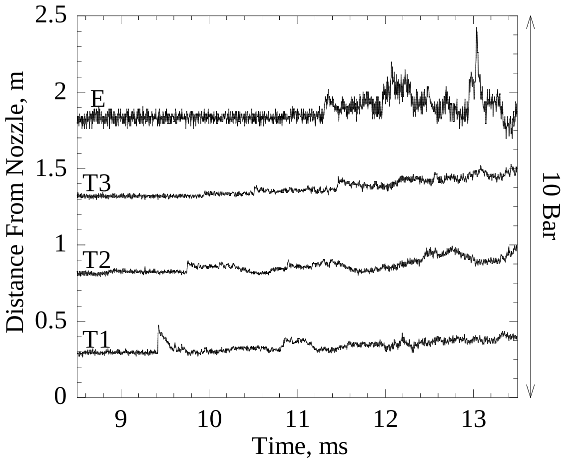
Run 401: β=1.8
25-mm nozzle w/c



Run 400: β=2.0
25-mm nozzle w/c



Run 399: β=2.4
25-mm nozzle w/c



Run 398: β=2.6
25-mm nozzle w/c

Appendix D

Run Summary

This appendix contains a table summarizing all of the runs performed in this research. The column headings are as follows:

1. **Run Number**: Sequential numbers used to identify each run, as a serial number.
2. **Date**
3. **Time**
4. **Series**: Indicates the series that each run was part of, as described in the text. The CHA and HHA series, not described in the text, are generic terms for Cold Hydrogen-Air (298 K) and Hot Hydrogen-Air (373 K), respectively. These were used as test runs. Other test runs are listed here as well.
5. **DRVR**: Gas mixture in driver, as percentages. A, air; H, hydrogen; N, nitrogen; O, oxygen; S, steam (gaseous H_2O).
6. **Nozz**: Nozzle diameter, in mm. Additional codes are: NC, no cutter (nozzle diameters 25 mm and smaller use a diaphragm cutter by default); CV, constant volume test (nozzle plugged); ND, no diaphragm.
7. **RCVR**: Gas mixture in receiver, format same as DRVR.
8. **T1, DR**: Initial temperature in driver, in °C.
9. **T1, RC**: Initial temperature in receiver, in °C.
10. **P_p, DR**: Peak pressure measured by driver Kulite, bars.
11. **P_p, RC**: Peak pressure measured by receiver Kulite, bars.
12. **P_p, T3**: Peak pressure measured by PCB in T3 position, bars.
13. **P_p, E**: Peak pressure measured by PCB in E position, bars.

14. **REC**: Receiver Event Code. Describes resulting event in receiver vessel. B, burn (deflagration); D, detonation (prompt initiation); T, transition to detonation (DDT); LE, late or secondary explosion. If blank, receiver was inert, a fault occurred, or run was a systems test.

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
18	2-Feb-96	1530	COMP	80H/20O	12.7	50N/50A	19.5	20.5	11.41	1.15			
19	2-Feb-96	1650	COMP	80H/20O	12.7	2H/49N/49/A	20.7	20.7	10.94	1.18			NB
20	5-Feb-96	1030	COMP	80H/20O	12.7	ABORT							
21	5-Feb-96	1150	COMP	80H/20O	12.7	4H/48N/48A	20.6	22.1	10.86	1.22			NB
22	5-Feb-96	1545	COMP	80H/20O	12.7	6H/47N/47A	21.2	22.6	10.63	1.89			B
23	6-Feb-96	0948	COMP	80H/20O	12.7	8H/46N/46A	19.5	21.9	10.98	3.39			B
24	6-Feb-96	1123	COMP	80H/20O	12.7	10H/45N/45A	20.8	22.4	10.78	3.92			B
25	6-Feb-96	1400	COMP	80H/20O	25	50N/50A	20.0	23.0	10.66	1.36			
26	6-Feb-96	1618	COMP	80H/20O	25	2H/49N/49A	21.7	22.8	10.39	1.39			NB
27	12-Feb-96	0918	COMP	80H/20O	25	4H/48N/48A	19.3	20.8	11.01	1.44			NB
28	13-Feb-96	1341	COMP	80H/20O	25	TRIG FAIL							
29	27-Feb-96	1605	COMP	80H/20O	25	CLIPPED							B
30	28-Feb-96	1042	COMP	80H/20O	25	CLIPPED							B
31	28-Feb-96	1305	COMP	80H/20O	25	6H/47N/47A	20.0	21.2	11.07	1.95			B
32	28-Feb-96	1436	COMP	80H/20O	25	6H/47N/47A	22.0	22.0	NR	2.06			B
33	1-Mar-96	1050	COMP	80H/20O	25	8H/46N/46A	19.2	20.0	10.91	3.33			B
34	1-Mar-96	1400	COMP	80H/20O	25	100N	19.7	21.6	10.35	1.18			
35	1-Mar-96	1645	COMP	80H/20O	25	100A	19.5	22.0	10.74	1.39			
36	7-Mar-96	1433	COMP	80H/20O	25	10H/45N/45A	20.0	20.0	10.51	4.56			B
37	7-Mar-96	1609	COMP	80H/20O	12.7	50N/50A	20.3	21.6	10.45	1.15			
38	8-Mar-96	1110	COMP	80H/20O	12.7	100A	19.0	20.6	10.28	1.15			
39	8-Mar-96	1203	COMP	80H/20O	12.7	100A	21.3	21.2	11.65	1.16			
40	13-Mar-96	1530	COMP	80H/20O	12.7	100N	19.3	20.6	10.06	1.05			
41	13-Mar-96	1633	COMP	80H/20O	12.7	100N	20.7	21.2	11.25	1.08			
42	13-Mar-96	1730	COMP	80H/20O	25	100A	21.4	21.2	11.09	1.37			
43	14-Mar-96		COMP	80H/20O	25	100N	18.9	20.4	10.79	1.18			
44	14-Mar-96	1135	COMP	80H/20O	12.7	50N/50A	20.3	20.4	NR	NR			
45	14-Mar-96	1435	COMP	80H/20O	12.7	2H/49N/49A	20.3	20.6	10.16	1.17			NB
46	29-Mar-96	1524	COMP	80H/20O	12.7	6H/47N/47A	19.6	20.4	10.23	1.79			B
47	29-Mar-96	1658	COMP	80H/20O	12.7	8H/46N/46A	20.9	21.1	10.35	3.28			B
48	1-Apr-96	1511	COMP	80H/20O	6.4	10H/45N/45A	19.5	20.2	10.84	3.92			B
49	1-Apr-96	1729	COMP	80H/20O	6.4	CLOG							B
50	2-Apr-96	1340	COMP	80H/20O	6.4	CLOG							B
51	2-Apr-96	1455	COMP	80H/20O	6.4	CLOG TEST							
52	15-Apr-96		S	80H/20O	12.7	ABORT							B
53	16-Apr-96	1523	S	80H/20O	12.7	10H/45S/45A	23.6	98.0	10.59	2.95			B
54	16-Apr-96	1648	S	80H/20O	12.7	8H/46S/46A	23.8	97.7	9.68	2.01			B
55	16-Apr-96	1818	S	80H/20O	12.7	6H/47S/47A	24.7	96.6	10.52	1.16			NB
56	16-Apr-96	1938	S	80H/20O	12.7	4H/48S/48A	25.4	95.8	10.22	1.09			NB

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
57	17-Apr-96	1038	S	80H/20O	12.7	2H/49S/49A	22.2	102.9	10.58	1.17			NB
58	17-Apr-96	1206	S	80H/20O	12.7	50S/50A	23.6	102.2	10.32	1.09			
59	17-Apr-96	1334	S	80H/20O	25	8H/46S/46A	24.0	101.0	10.09	1.99			B
60	17-Apr-96	1521	S	80H/20O	25	8H/46S/46A	24.2	100.4	10.22	1.93			B
61	21-Apr-96	1504	COMP	80H/20O	25	10H/45N/45A	22.4	24.3	10.77	4.33			B
62	22-Apr-96	1605	COMP	80H/20O	12.7	10H/45N/45A	22.0	26.0	10.35	4.07			B
63	23-Apr-96	1610	COMP	80H/20O	12.7	10H/45N/45A	23.3	20.4	10.41	4.08			B
64	24-Apr-96		SA	80H/20O	12.7	ABORT							B
65	24-Apr-96	1344	SA	80H/20O	12.7	60S/8H/32A	24.2	102.8	10.21	1.13			NB
66	24-Apr-96	1502	SA	80H/20O	12.7	50S/10H/40A	24.0	102.0	NR	2.58			B
67	24-Apr-96	1648	SA	80H/20O	12.7	40S/12H/48A	25.3	100.2	10.26	3.39			B
68	25-Apr-96	0914	SA	80H/20O	12.7	60S/8H/32A	23.4	103.7	10.59	1.45			B
69	25-Apr-96	1017	SA	80H/20O	12.7	50S/10H/40A	24.0	103.0	NR	2.74			B
70	25-Apr-96	1306	SA	80H/20O	12.7	40S/12H/48A	24.4	102.6	10.75	3.56			B
71	29-Apr-96	0900	SA	80H/20O	12.7	30S/14H/56A	23.9	102.2	10.46	4.3			B
72	29-Apr-96	0959	SA	80H/20O	12.7	20S/16H/64A	25.2	103.6	10.24	4.49			B
73	29-Apr-96	1110	SA	80H/20O	12.7	10S/18H/72A	25.7	102.8	10.21	5.03			B
74	29-Apr-96	1230	SA	80H/20O	12.7	0S/20H/80A	26.1	103.6	10.20	5.53			B
75	29-Apr-96	1413	SA	80H/20O	25	0S/20H/80A	25.0	103.0	10.08	5.59			B
76	29-Apr-96	1606	SA	80H/20O	12.7	60S/8H/32A	25.6	104.8	10.15	1.16			NB
77	30-Apr-96	1036	Kg20H		CV	20H/80A							B
78	30-Apr-96	1319	SA	80H/20O	12.7	55S/9H/36A	23.8	103.4	10.07	2.16			B
79	30-Apr-96	1516	SA	80H/20O	12.7	GAINS OFF	24.9	106.2	9.78	1.3			B
80	30-Apr-96	1625	SA	80H/20O	25	60S/8H/32A	25.7	106.1	10.07	1.37			NB
81	30-Apr-96	1802	SA	80H/20O	25	CLIPPED	25.5	105.8	10.10	CLIP			B
82	30-Apr-96	1900	SA	80H/20O	25	50S/10H/40A	26.4	106.0	10.01	3.05			B
83	30-Apr-96	2045	SA	80H/20O	25	40S/12H/48A	25.8	107.7	10.00	3.76			B
84	30-Apr-96	2145	SA	80H/20O	25	30S/14H/56A	26.6	108.3	9.67	4.04			B
85	1-May-96	0945	SA	80H/20O	25	20S/16H/64A	23.7	102.3	10.19	4.52			B
86	1-May-96	1051	SA	80H/20O	25	10S/18H/72A	25.1	103.7	9.94	5.15			B
87	1-May-96	1158	SA	80H/20O	92	60S/8H/32A	26.1	104.6	7.74	2.08			B
88	1-May-96	1316	SA	80H/20O	92	30S/14H/56A	26.3	103.6	7.58	4.64			B
89	1-May-96	1423	SA	80H/20O	92	20H/80A	26.8	103.6	7.60	6.19			B
90	1-May-96	1520	SA	80H/20O	92	100A	27.6	106.0	7.25	2.21			
91	1-May-96	1601	SA	80H/20O	92	100N	28.2	105.6	7.56	1.92			
92	2-May-96	1530	SA	80H/20O	92	100A	23.2	57.3					
93	3-May-96	1152	SA	80H/20O	92	50S/10H/40A	23.7	100.8	7.87	3.2			B
94	3-May-96	1515	SA	80H/20O	92	40S/12H/48A	24.1	106.8	7.58	4.26			B
95	4-May-96	0920	SA	80H/20O	92	20S/16H/64A	23.5	104.1	7.01	5.34			B

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
96	4-May-96	1115	SA	80H/20O	92	10S/18H/72A	25.6	103.8	6.94	5.76			B
97	4-May-96	1225	SA	80H/20O	25	60S/8H/32A	26.1	105.5	9.68	1.34			NB
98	10-May-96	1020	HHA	80H/20O	92	22H/78A	23.6	99.3	7.82	7.06			B
99	10-May-96	1425	HHA	80H/20O	92	24H/76A	23.4	99.4	NTRIG				
100	10-May-96	1615	HHA	80H/20O	92	24H/76A	25.2	101.8	8.61	7.05			B
101	10-May-96	1735	HHA	80H/20O	92	26H/74A	26.2	103.6	8.56	7.48			B
102	29-May-96	1120	HHA	80H/20O	92	28H/72A	23.8	95.2	8.34	8.87			B
103	29-May-96	1355	HHA	80H/20O	92	30H/70A	24.7	96.4	8.60	9.05			D?
104	30-May-96	0940	HHA	80H/20O	92	26H/74A	22.0	100.0	8.60	8.6		12.35 M	B
105	30-May-96	1100	HHA	80H/20O	92	28H/72A	25.3	100.5	8.43	8.95		12.35 M	D?
106	21-Jun-96	1300	CAM TEST										
107	21-Jun-96		CAM TEST										
108	21-Jun-96		CAM TEST										
109	21-Jun-96		CAM TEST										
110	21-Jun-96		CAM TEST										
111	22-Jun-96		CAM TEST										
112	22-Jun-96		CAM TEST										
113	24-Jun-96	1400	CHA	80H/20O	6.4	10H/90A	23.3	24.0	9.88	4.15			B
114	24-Jun-96		1N2O	80H/20O	92	8H/8N2O/84A			8.22	4.8			B
115	24-Jun-96		2N2O	80H/20O	92	50N2O/50A			8.14	2.69			
116	25-Jun-96	1045	COMP	80H/20O	92	100A	25.0	25.0	8.74	2.65			
117	25-Jun-96	1200	3N2O	80H/20O	92	4H/48N2O/48A	24.7	25.2	8.18	3.72			
118	26-Jun-96		COMP	80H/20O	6.4	100A	23.2	24.8	9.48	1.04			
119	26-Jun-96		COMP	80H/20O	6.4	100N	24.3	25.1					
120	15-Jul-96	1645	CAM TEST										
121	18-Jul-96	1020	NITRO	80H/20O	92	24H/76A	24.4	24.0	8.58	8.3	12.47	14.4	B
122	18-Jul-96	1145	NITRO	80H/20O	92	26H/74A	25.7	26.8	9.02	8.57	9.89	20	
123	18-Jul-96		NITRO	80H/20O	92	24H/76A	26.1	29.3	8.47	8.33	16.43	20.93	LE
124	18-Jul-96	1500	NITRO	80H/20O	92	26H/74A	26.2	31.1	8.43	9.28	36.92 M	36.62 M	D
125	18-Jul-96		NITRO	80H/20O	92	26H/74A	26.3	33.0	8.36	8.96	37.41	61.28	D
126	19-Jul-96	0845	NITRO	80H/20O	92	100A	23.1	28.7	8.44	2.49	2.79	5.63	
127	19-Jul-96	1030	NITRO	80H/20O	92	25H/75A	24.6	28.3	8.61	8.48	13.09	24.01	LE
128	19-Jul-96	1325	NITRO	80H/20O	92	23H/77A	24.4	30.1	8.42	8.08	10.4	17.53	LE
129	19-Jul-96	1445	NITRO	80H/20O	92	27H/73A	25.7	32.1	8.37	9.28	37.59	61.98	D
130	22-Jul-96	1035	NITRO	10N/72H/18O	92	23H/77A	23.1	24.2	8.81	8.65	41.19	25.22	LE
131	22-Jul-96	1145	NITRO	10N/72H/18O	92	24H/76A	25.2	27.1	8.77	8.69	9.87	35.84	LE
132	22-Jul-96	1315	NITRO	10N/72H/18O	92	25H/75A	25.7	29.3	8.66	9.2	40.49	72.25 M	D
133	22-Jul-96	1440	NITRO	10N/72H/18O	92	26H/74A	26.0	31.4	8.73	8.94	47.77	55.4	D
134	22-Jul-96	1625	NITRO	10N/72H/18O	92	27H/73A	25.7	33.0	8.68	9.35	39.5	72.75 M	D

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
135	22-Jul-96	1805	NITRO	20N/64H/16O	92	24H/76A	25.7	34.6	10.19	8.34	8.92	26.23	LE
136	23-Jul-96	1010	NITRO	20N/64H/16O	92	25H/75A	23.4	28.9	10.04	8.4	19.59	22.16	LE
137	23-Jul-96	1225	NITRO	20N/64H/16O	92	26H/74A	24.4	30.9	10.11	9.42	47.75	72.75 M	D
138	23-Jul-96	1445	NITRO	50N/40H/10O	92	25H/75A	25.2	32.5	BURN	TOO	SLOW		B
139	23-Jul-96	1600	NITRO	50N/40H/10O	92	25H/75A	25.9	34.6	8.63	8.04	7.5	17.11	LE
140	24-Jul-96	0940	NITRO	30N/56H/14O	92	CONTAMINATED							D
141	24-Jul-96	1100	NITRO	30N/56H/14O	92	25H/75A	25.3	31.4	8.70	8.45	12.81	21.01	LE
142	24-Jul-96	1520	NITRO	30N/56H/14O	92	24H/76A	25.2	31.8	8.48	8.11	11.36	20.49	LE
143	24-Jul-96	1650	NITRO	30N/56H/14O	92	26H/74A	25.7	33.8	8.94	8.33	14.54	12.31	B
144	25-Jul-96	1035	NITRO	30N/56H/14O	92	27H/73A	23.9	28.4	9.13	8.4	8.88	10.31	B
145	25-Jul-96	1215	NITRO	30N/56H/14O	92	28H/72A	24.8	31.2	9.03	8.76	30.73	13.36	LE
146	25-Jul-96	1355	NITRO	30N/56H/14O	92	30H/70A	25.4	33.3					LE
147	25-Jul-96	1555	NITRO	25N/60H/15O	92	30H/70A	25.2	34.9	10.30	9.41	42.18	85.66	D
148	25-Jul-96	1655	NITRO	25N/60H/15O	92	28H/72A	26.3	37.4	10.35	9.27	38.33	83.23	D
149	26-Jul-96	0940	NITRO	25N/60H/15O	92	26H/74A	23.5	29.8	10.86	9.4	42.29	80.62	D
150	26-Jul-96	1105	NITRO	25N/60H/15O	92	24H/76A	25.0	32.4	10.37	8.88	32.39	64.26	D
151	26-Jul-96	1310	NITRO	25N/60H/15O	92	22H/78A	25.1	33.7	10.56	9.02	34.41	101.67	LE
152	26-Jul-96	1425	NITRO	25N/60H/15O	92	23H/77A	25.8	35.3	10.26	11.05	25.25	100.98	LE
153	26-Jul-96	1605	NITRO	25N/60H/15O	92	100A	27.1	37.2	10.31	1.9	3.19	6.66	
154	29-Jul-96	1335	NITRO	25N/60H/15O	92	23H/77A	23.3	24.4	10.13	8.79	9.8	48.86	LE
155	29-Jul-96	1450	NITRO	80H/20O	92	23H/77A	24.9	27.2	8.35	8.12	14.82	25.62	LE
156	30-Jul-96	1000	NITRO	80H/20O	CV	N/A	23.3		10.03				
157	30-Jul-96	1305	NITRO	5N/76H/19O	CV	N/A	24.2		10.45				
158	30-Jul-96	1335	NITRO	10N/72H/18O	CV	N/A	26.5		10.93				
159	30-Jul-96	1435	NITRO	15N/68H/17O	CV	N/A	30.0		11.10				
160	30-Jul-96	1542	NITRO	20N/64H/16O	CV	N/A	29.1		12.66				
161	30-Jul-96	1633	NITRO	25N/60H/15O	CV	N/A	29.1		12.96				
162	31-Jul-96	1037	NITRO	30N/56H/14O	CV	N/A	23.9		12.80				
163	31-Jul-96	1115	NITRO	35N/52H/13O	CV	N/A	26.2		12.85				
164	31-Jul-96	1235	NITRO	40N/48H/12O	CV	N/A	28.7		11.93				
165	31-Jul-96	1315	NITRO	45N/44H/11O	CV	N/A	29.1		8.36				
166	31-Jul-96	1503	NITRO	50N/40H/10O	CV	N/A	27.1		8.20				
167	31-Jul-96	1540	NITRO	55N/36H/9O	CV	N/A	28.3		7.19				
168	5-Aug-96	1610	NITRO	20N/64H/16O	92	27H/73A	23.5	23.7	9.47	9.65	50.39	97.32	D
169	6-Aug-96	1033	NITRO	20N/64H/16O	92	25H/75A	23.2	24.7	9.86	9.23	23.94	72.96	LE
170	6-Aug-96	1145	NITRO	25N/60H/15O	92	25H/75A	25.3	27.8	10.51	8.87	45.67	51.99	D
171	6-Aug-96	1440	NITRO	67H/33O	92	100A	24.6	29.7	3.20	2.4	2.77	9.46	
172	7-Aug-96	1015	NITRO	25N/60H/15O	92	21H/79A	23.4	25.7	10.53	7.98	11.25	51.03	LE
173	7-Aug-96	1145	NITRO	25N/60H/15O	92	20H/80A	25.1	28.2	10.18	7.87	12.21	20.93	LE

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
174	7-Aug-96	1255	NITRO	25N/60H/15O	92	19H/81A	25.8	30.1	10.15	7.47	9.2	20	LE
175	8-Aug-96	1345	NITRO	10N/72H/18O	92	100A	22.2	25.9	8.60	2.24	3.26	5.56	
176	8-Aug-96	1520	NITRO	20N/64H/16O	92	100A	23.3	26.0	9.43	2.11	2.77	4.76	
177	8-Aug-96		NITRO	30N/56H/14O	92	100A	23.6	25.8	7.47	1.92	2.87	6.05	
178	11-Aug-96	1310	NITRO	25N/60H/15O	92	10H/90A	21.6	22.5	9.96	2.93	5.6	9.94	B
179	11-Aug-96	1420	NITRO	25N/60H/15O	92	15H/85A	23.4	24.0	10.17	6.51	10.9	18.85	LE
180	12-Aug-96	1120	NITRO	20N/64H/16O	92	10H/90A	21.6	23.2					B
181	12-Aug-96	1255	NITRO	20N/64H/16O	92	10H/90A	23.3	24.7	9.40	6.62	7.68	20.94	LE
182	12-Aug-96	1433	NITRO	20N/64H/16O	92	10H/90A	23.9	25.7	9.27	5.83	10.15	17.36	LE
183	12-Aug-96	1545	NITRO	20N/64H/16O	92	15H/85A	24.5	26.7	9.25	6.63	9.56	16.28	LE
184	4-Sep-96	1320	NITRO	45N/44H/11O	CV	N/A	21.8		11.95				
185	4-Sep-96	1400	NITRO	50N/40H/10O	CV	N/A	23.3		10.74				
186	4-Sep-96	1520	NITRO	40N/48H/12O	CV	N/A	23.3		11.79				
187	5-Sep-96	1105	NITRO	45N/44H/11O	CV	N/A	21.7		7.94				
188	5-Sep-96	1140	NITRO	45N/44H/11O	CV	N/A	22.9		8.75				
189	5-Sep-96	1400	NITRO	50N/40H/10O	CV	N/A	23.1		10.07				
190	5-Sep-96	1443	NITRO	45N/44H/11O	CV	N/A	23.8		8.41				
191	6-Sep-96	1215	NITRO	45N/44H/11O	CV	N/A	22.3		11.01				
192	6-Sep-96	1405	NITRO	45N/44H/11O	CV	N/A	22.9		7.90				
193	27-Sep-96	1020	NITRO	35H/65A	92	100 A	22.2	23.7	5.84	2.92	2.1		
194	27-Sep-96	1515	NITRO	35H/65A	92	100 A	22.3	23.9	6.15	2.65	1.99		
195	27-Sep-96	1635	NITRO	25N/60H/15O	92	100 A	22.8	23.8	13.62	3.02	2.73		
196	18-Oct-96	1600	NITRO	30H/70A	92	10H/90A	20.8	21.2	BAD	TRIG			
206	11-Nov-96	1350	SHOCK-4	30H/70A	92	100A	22.4	23.4					
207	11-Nov-96	1415	SHOCK-4	30H/70A	92	100A							
208	11-Nov-96	1445	SHOCK-4	30H/70A	92	100A	24.3	23.9	6.02	1.6	2.09	2.64	
209	11-Nov-96	1540	SHOCK-5	30H/70A	92	100A	24.3	23.8	5.77	1.52	1.91	3.55	
210	11-Nov-96	1607	SHOCK-6	30H/70A	92	100A	24.7	24.1	5.50	1.61	2.33	2.62	
211	11-Nov-96	1655	SHOCK-7	30H/70A	92	100A	24.6	23.8	4.91	1.65	1.89	3.89	
212	11-Nov-96	1717	SHOCK-8	30H/70A	92	100A	24.9	24.4	1.62	5.71	2.02	5.17	
213	12-Nov-96	1115	SHOCK-9	30H/70A	92	100A	22.3	23.5	5.31	1.61	1.95	3.99	
214	12-Nov-96	1148	SHOCK-10	30H/70A	92	100A	23.3	23.6	6.14	1.58	1.93	3.27	
215	12-Nov-96	1222	SHOCK-11	30H/70A	92	100A	23.9	23.8	7.47	1.7	2.45	4.03	
216	12-Nov-96	1733	SHOCK-12	30H/70A	92	100A	22.9	23.7	5.15	1.68	2.11	3.13	
217	12-Nov-96	1802	SHOCK-13	30H/70A	92	100A	23.6	24.0	4.85	1.62	1.95	4.24	
218	14-Nov-96	1350	SHOCK-14	30H/70A	92	100A	22.7	23.4	5.57	1.62	2.11	3.91	
219	14-Nov-96	1427	SHOCK-15	30H/70A	92	100A	23.4	23.6	6.24	1.61	2.66	3.9	
220	14-Nov-96	1515	SHOCK-16	30H/70A	92	100A	23.9	23.5	6.99	1.7	2.41	4.19	
221	14-Nov-96	1540	SHOCK-17	30H/70A	92	100A	24.3	23.7	6.37	1.57	2.3	4.17	

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
222	14-Nov-96	1622	SHOCK-18	30H/70A	92	100A	24.8	23.8	5.13	1.69	2.14	3.76	
223	14-Nov-96	1650	SHOCK-19	30H/70A	92	100A	25.1	23.9	5.37	1.69	1.99	3.1	
224	15-Nov-96	1144	SHOCK-4	30H/70A	92	100A	22.5	23.4	4.92	1.79	2.2	3.43	
225	15-Nov-96	1220	DAS TEST	10H/90A	92	10H/90A	23.4	23.4	3.88	4.1			
226	20-Nov-96	1445	SHOCK-10	100A	92	100A					1.2	1.42	
227	20-Nov-96		SHOCK-10	100A	92	100A					1.29	1.77	
228	3-Dec-96	1710	DAS TEST	10H/90A	92	80H/20O	22.7	22.7	9.43	5.19	12.98	17.55	
229	4-Dec-96	1135	NITRO	80H/20O	92	28H/72O	22.8	23.5	8.85	8.8	34.16	72.72M	D
230	5-Dec-96	1105	SA	80H/20O	12.7	50S/10H/40A	22.7	96.3	11.68	2.7			B
231	11-Dec-96	1110	CHA	80H/20O	12.7	12H/88A	22.6	22.8	13.30	4.67			B
309	3-Feb-97	1440	BETA	β=7.6	CV		22.0		4.19				
311	6-Feb-97	1421	CHA	β=7.6	92	30H/70A	22.6	26.4	4.03				
312	8-Feb-97	1223	BETA-N2	β=2.6	92	β=3.76	21.9	23.6	10.04	8.7	35.82	72.27M	D
313	8-Feb-97	1326	BETA-N2	β=2.6	92	β=4	24.1	26.9	11.23	8.41	35.72	102.31M	D
314	8-Feb-97	1430	BETA-N2	β=2.6	92	β=4.5	25.2	29.9	10.82	7.85	13.69	23.19	LE
315	8-Feb-97	1700	BETA-N2	β=2.6	92	β=4.4	23.9	30.6	11.75	8.03	41.19	102.14	D
316	9-Feb-97	1230	BETA-N2	β=2.6	92	β=4.6	21.9	25.8	11.00	8.12	21.79	16.14	LE
317	9-Feb-97	1336	BETA-N2	β=2.6	92	β=4.3	24.1	28.9	11.05	8.37	33.28	102.48M	D
318	9-Feb-97	1417	BETA-N2	β=2.6	CV		25.7		15.03				
319	10-Feb-97	1722	BETA-N2	β=2.6	92	100A	22.0		9.09	1.6	2.62	4.21	
320	10-Feb-97	1852	BETA-N2	β=2.6	92	100A	23.2	24.8	8.06	1.6	2.54	4.42	
321	11-Feb-97	1157	BETA-N2	β=2.6	92	β=4.6	22.6	99.1	11.09	6.89	21.01	135.03	D
322	11-Feb-97	1337	BETA-N2	β=2.6	92	β=4.8	23.7	99.1	11.44	6.89	26.74	68.44	D
323	11-Feb-97	1432	BETA-N2	β=2.6	92	β=5.5	24.9	100.8	9.03	6.33	10.58	FAULT	LE
324	11-Feb-97	1554	BETA-N2	β=2.6	92	β=5.2	24.4	102.0	10.05	6.8	37.18	135.03M	D
325	11-Feb-97	1751	BETA-N2	β=2.6	92	β=5.3	24.0	102.0	10.45	6.57	9.25	16.71	N
326	11-Feb-97	1856	BETA-N2	β=2.6	92	β=5.4	24.7	100.3	11.39	6.26	9.36	15.73	N
327	11-Feb-97	1945	BETA-N2	β=2.6	92	β=5.3	25.3	102.5	11.23	7.36	28.17	135.03M	LE
328	11-Feb-97	2035	BETA-N2	β=2.6	92	β=5.2	25.8	104.5	8.76	6.29	8.78	13.28	N
329	11-Feb-97	2149	BETA-N2	β=2.6	92	β=5.1	24.0	102.0	11.17	6.66	36.86	193.51M	D
330	12-Feb-97	1007	BETA-H2O	β=2.6	92	β=5.0			10.61	5.37	6.29	5.19	N
331	12-Feb-97	1420	BETA-H2O	β=2.6	92	β=4.0	23.2	103.2	9.13	5.63	7.93	5.78	N
332	12-Feb-97	1521	BETA-H2O	β=2.6	92	β=3.0	25.1	104.7	11.43	KILLED	13.43		N
333	13-Feb-97	1606	NITRO	25N/	92	23H/77A	23.8	43.5	10.24	8.52	23.1	135	LE
334	14-Feb-97	1056	NITRO	25N/	92	23H/77A	22.4	31.4	9.06	9.01	31.47	131.32M	LE
335	20-Feb-97	1354	NITRO	25N/	92	30H/70A	24.7	26.2	9.16	8.44	37.18	55.95	D
336	21-Feb-97	1038	BETA-N2	β=2.6	92	β=4.5	22.1	24.7	10.22	9.1	34.76	132.94M	LE

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
337	21-Feb-97	1220	BETA-N2	β=2.6	92	β=4.4	23.6	27.6	10.36	8.3	10.9	18.56	N
338	21-Feb-97	1422	BETA-N2	β=2.6	92	β=4.3	23.6	29.6	11.76	7.99	33.54	44.51	D
339	22-Feb-97	1318	BETA-N2	β=2.6	92	β=4.4	22.1	25.7	9.42	9.22	26.12	130.29	LE
340	22-Feb-97	1432	BETA-N2	β=2.6	92	β=4.2	23.8	28.8	9.73	8.49	3718	60.23	D
341	23-Feb-97	1247	BETA-N2	β=2.6	92	β=5.2	21.9	100.2	9.96	6.56	28.7	35.35	D
342	23-Feb-97	1346	BETA-N2	β=2.6	92	β=5.4	23.7	101.7	8.79	6.4	21.31		N
343	23-Feb-97	1452	BETA-N2	β=2.6	92	β=5.3	24.0	104.0	10.50	6.32	7.82	13.05	N
344	23-Feb-97	1859	BETA-N2	β=2.6	92	β=5.1	22.6	103.4	11.32	6.57	37.18	33.87	D
345	24-Feb-97	1022	BETA-H2O	β=2.6	92	β=3.5	21.7	102.8	11.10	6.12	4.29	7.96	N
346	24-Feb-97	1137	BETA-H2O	β=2.6	92	β=3.0	23.6	102.4	10.70	KILLED	9.61	20.72	N
347	24-Feb-97	1254	BETA-H2O	β=2.6	92	β=2.6	24.5	103.8	9.64		16.73	25.04	LE
348	24-Feb-97	1605	BETA-H2O	β=2.6	92	β=2.0	22.9	103.8	10.97		13.92	30	LE
349	24-Feb-97	1735	BETA-H2O	β=2.6	92	β=1.8	24.1	102.8	9.56		22.02	26.01	T
350	24-Feb-97	1840	BETA-H2O	β=2.6	92	β=1.4	25.3	102.6	10.57		25.15	78.15	T
351	24-Feb-97	1944	BETA-H2O	β=2.6	92	β=1.6	25.9	102.1	10.04		28.66	55.66	T
352	24-Feb-97	2043	BETA-H2O	β=2.6	92	β=1.0	26.5	102.3	10.38		37.18	50.5	D
353	1-Mar-97	1136	BETA-N2	β=2.6	92	β=2.6	20.4	21.3	10.44		36.49	78.54	D
354	18-Mar-97	1234	BETA-N2	β=2.6	92	β=4.3	24.4	26.4					LE
355	18-Mar-97	1549	BETA-N2	β=2.6	92	β=4.2	23.4	27.8	11.46		30.06	56.08	D
356	18-Mar-97	1756	BETA-N2	β=2.6	92	β=2.6	23.8	29.8	11.50		25.75	74.15	D
357	19-Mar-97	0926	BETA-N2	β=2.6	64	β=3.76	22.4	26.4	11.12		25.62	66.97M	D
358	19-Mar-97	1036	BETA-N2	β=2.6	64	β=4.2	24.3	29.6	12.80		23.48	48.63	D
359	19-Mar-97	1325	BETA-N2	β=2.6	64	β=4.3	23.6	30.5	11.43				B
360	19-Mar-97	1922	BETA-N2	β=2.6	64	β=4.1	22.5	29.3	12.08			64.23	D
361	20-Mar-97	0818	BETA-N2	β=2.6	38	β=3.76	22.0	26.3	12.86				B
362	20-Mar-97	1243	BETA-N2	β=2.6	38	β=3.0	22.8	27.8	13.62		24.69	81.31	D
363	20-Mar-97	1624	BETA-N2	β=2.6	38	β=3.4	22.8	28.9	11.94			3.13	B
364	21-Mar-97	0936	BETA-N2	β=2.6	38	β=3.2	22.5	25.7	13.78				B
365	21-Mar-97	1301	BETA-N2	β=2.6	38	β=3.1	22.5	27.5	12.33				B
366	21-Mar-97	1718	BETA-N2	β=2.6	38	β=2.9	22.1	28.3	13.90		24.63	66.97M	D
367	21-Mar-97	2102	BETA-N2	β=2.6	25	β=2.8	22.1	28.7	13.05		27.11	66.97M	D
368	22-Mar-97	0910	BETA-N2	β=2.6	25	β=3.0	21.4	26.2	13.76				B
369	22-Mar-97	1811	BETA-N2	β=2.6	25	β=2.9	21.9	26.2	13.41		25.11	65.68	D
370	23-Mar-97	1241	BETA-N2	β=2.6	25NC	β=2.9	22.6	26.8	12.67			67	LE
371	23-Mar-97	1458	BETA-N2	β=2.6	25NC	β=2.8	22.0	29.0	13.69				B
372	23-Mar-97	1705	BETA-N2	β=2.6	25NC	β=2.6	22.4	30.4	13.85		25.85	66.97M	D
373	24-Mar-97	0829	BETA-N2	β=2.6	25NC	β=2.7	22.2	26.5	13.41				B

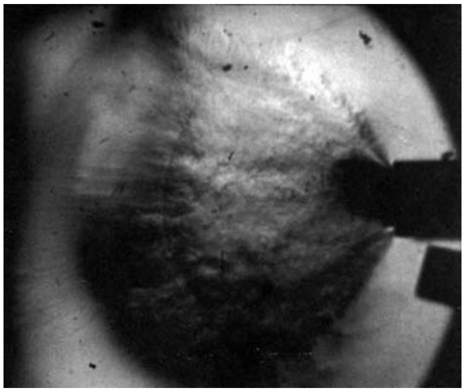
Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
374	24-Mar-97	1157	BETA-N2	β=2.6	25NC	β=2.5	22.1	27.9	13.04				B
375	24-Mar-97	1410	BETA-N2	β=2.6	25NC	β=2.4	22.6	30.1	14.14		26.36	66.97M	D
376	24-Mar-97	1907	BETA-N2	β=2.6	25NC	β=2.5	21.4	28.8	13.04			66.97M	D
377	25-Mar-97	1055	BETA-N2	β=2.6	25	β=2.9	22.2	25.9	14.32			52.53	D
378	25-Mar-97	1338	BETA-N2	β=2.6	25	β=3.1	22.5	28.3	13.53				B
379	25-Mar-97	1729	BETA-N2	β=2.6	64	β=4.5	22.0	28.8	12.42			8.78	B
380	26-Mar-97	0913	BETA-H2O	β=2.6	92	β=1.1	24.2	100.7	10.45		19.88	43.93	D
381	26-Mar-97	1030	BETA-H2O	β=2.6	92	β=1.3	25.8	100.8					T
382	26-Mar-97	1202	BETA-H2O	β=2.6	92	β=1.2	26.3	102.2					T
383	26-Mar-97	1316	BETA-H2O	β=2.6	38	β=1.0	26.9	101.2	12.58				B
384	26-Mar-97	1431	BETA-H2O	β=2.6	38	β=0.86	27.1	103.6					LE
385	26-Mar-97	1549	BETA-H2O	β=2.6	38	β=0.7	26.9	100.4	12.96			61.2	T
386	26-Mar-97	1709	BETA-H2O	β=2.6	38	β=0.66	26.9	103.7	12.63			16.89	T
387	26-Mar-97	1805	MISFILL	β=2.6	38	β=??	27.4	102.6	13.11				T
388	27-Mar-97	0845	BETA-H2O	β=2.6	38	β=0.5	21.7	104.6	13.27		19.91	52.88	D
389	27-Mar-97	0941	BETA-H2O	β=2.6	38	β=0.55	24.6	104.5	12.89		20.62	58.27	D
390	27-Mar-97	1040	BETA-H2O	β=2.6	38	β=0.6	26.2	104.2	12.91			45.57	T
391	27-Mar-97	1212	BETA-H2O	β=2.6	38	β=0.8	26.1	104.2	13.23				B
392	28-Mar-97	1330	BETA-N2	β=3.76	92ND	β=3.76		34.0					B
393	28-Mar-97	1440	BETA-N2	β=3.0	92ND	β=3.0	22.8	35.9	9.45		30.01	66.97M	D
394	28-Mar-97	1663	BETA-N2	β=3.3	92ND	β=3.3	23.1	37.4	9.25		28.08	66.97M	D
395	29-Mar-97	1016	BETA-N2	β=4.0	92ND	β=4.0	21.1	27.6	9.48			12.92	B
396	29-Mar-97	1107	BETA-N2	β=3.76	92ND	β=3.76	23.2	31.2	9.44				B
397	29-Mar-97	1550	BETA-N2	β=2.9	25ND	β=2.9	21.7	29.1	14.34				B
398	29-Mar-97	1850	BETA-N2	β=2.6	25ND	β=2.6	21.9	30.0	13.60				B
399	30-Mar-97	1146	BETA-N2	β=2.4	25ND	β=2.4	21.2	26.6					B
400	30-Mar-97	1400	BETA-N2	β=2.0	25ND	β=2.0	22.2	29.1	12.22			10.73	B
401	30-Mar-97	2100	BETA-N2	β=1.8	25ND	β=1.8	21.4	28.9	11.73		25.37	72.22	D
402	31-Mar-97	1629	CAM TEST	β=2.6	25	100A	20.8	25.5	14.11				
403	31-Mar-97	1800	CAM TEST	β=2.6	25	100A	21.9	25.6					
404	31-Mar-97	1916	CAM TEST	β=2.6	25	100A	22.4	25.4					
405	1-Apr-97	0900	CAM TEST	β=2.6	25	100A	22.0		13.68		1.26	1.93	
406	1-Apr-97	1045	CAM TEST	β=2.6	25	100A							
407	1-Apr-97	1332	BETA-N2	β=2.6	25	β=2.6	21.6	23.6	13.85			63.1	D
408	1-Apr-97	1737	BETA-N2	β=2.6	25	β=2.6			14.09		25.27	66.74	D
409	1-Apr-97	1927	BETA-N2	β=1.8	25ND	β=1.8	22.4	29.7					T
410	2-Apr-97	1112	BETA-N2	β=1.8	25ND	β=1.8	21.1	26.6					T

Run #	Date	Time	Series	DRVR	Nozz	RCVR	T1, DR	T1, RC	Pp, DR	Pp, RC	Pp, T3	Pp, E	REC
411	2-Apr-97	1538	BETA-N2	β=1.7	25ND	β=1.7	21.3	28.9	11.97		26.19	73.51	D
412	2-Apr-97	1655	BETA-N2	β=3.76	25ND	β=3.76	22.8	32.9					B
413	3-Apr-97	0835	BETA-N2	β=3.76	25ND	β=3.76	20.8	27.1					B
414	3-Apr-97	1113	BETA-N2	β=3.76	25ND	β=3.76							B
415	4-Apr-97	1740	BETA-N2	β=2.6	25	100A	21.4	24.3					
416	4-Apr-97	1935	BETA-N2	β=2.6	25	β=3.76	22.0	27.0	14.05				B
417	4-Apr-97	2035	BETA-N2	β=3.76	25ND	β=3.76	23.1	27.4	11.45				B
418	5-Apr-97	1055	BETA-N2	β=3.76	25ND	β=3.76	22.2	29.2					B
419	5-Apr-97	1150	BETA-N2	β=2.6	25	β=3.76	23.3	32.2					B
420	5-Apr-97	1308	BETA-N2	β=2.6	25	β=2.6	21.1	27.4					B
421	5-Apr-97	1413	BETA-N2	β=2.6	25	β=2.6	22.4	31.4	13.74				B
422	5-Apr-97	1528	BETA-N2	β=1.7	25ND	β=1.7	23.5	34.2					T
423	5-Apr-97	1737	BETA-N2	β=1.5	25ND	β=1.5							D
424	5-Apr-97	1850	BETA-N2	β=2.6	25	β=2.4	24.1	39.8	13.42		25.11	66.55	D
425	5-Apr-97	2311	BETA-N2	β=2.6	25	β=3.76	22.3	35.3					
426	6-Apr-97	0021	BETA-N2	β=3.76	25ND	β=3.76	23.3	37.7	9.17				
427	6-Apr-97	0130	BETA-N2	β=2.6	92	100A	23.6	40.3					
428	6-Apr-97	1205	BETA-N2	β=2.6	92	15H/85A	21.3	29.9					
429	6-Apr-97	1607	BETA-N2	β=2.6	25	β=2.6	21.4	28.8	13.69				NG
430	6-Apr-97	1722	BETA-N2	β=2.6	25	β=2.4	22.8	32.3	13.89		25.52	64.68	D
431	6-Apr-97	1831	BETA-N2	β=1.5	25ND	β=1.5	23.6	35.4	11.66		25.59	71	D
432	9-Apr-97	2045	BETA-N2	β=1.9	25ND	β=1.9	20.0	21.3					T
433	16-Apr-97	1813	BETA-N2	β=2.6	92	β=2.6	21.4	24.7			25.5		D

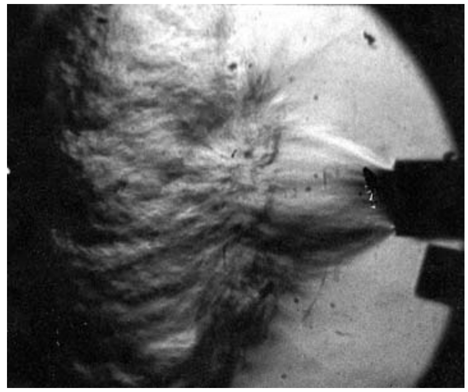
Appendix E

RPI Jet Visualization

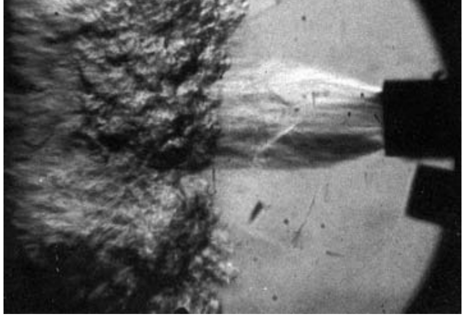
This Appendix contains photographs of jet startup from the final tests in the RPI facility. In the photographs, the diameter of the jet tube is 0.5" (12.7 mm). The initial driver mixture is 80% H_2-20% O_2. The receiver mixtures are listed in the captions.



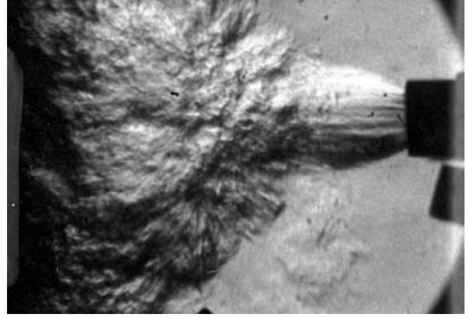
1 (t=0)



2 (0.074 ms)

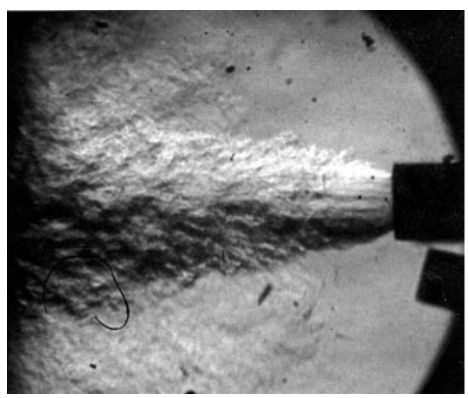


4 (0.223 ms)



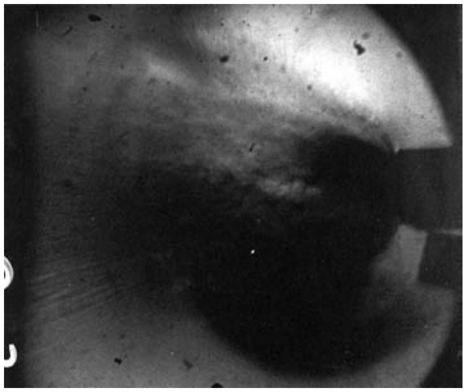
37 (2.678 ms)

61 (4.464 ms)

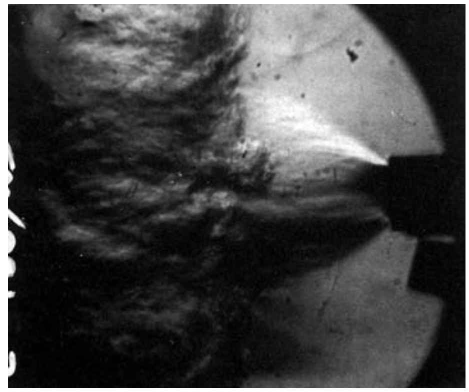


144 (10.639 ms)

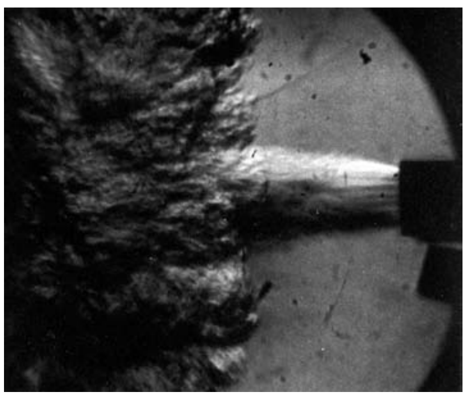
Figure E.1: Jet startup, venting into 100% N_2. Note lead shocks and large, turbulent vortex head which convects downstream. Framing rate is 13.44 kfps. RPI run 128.



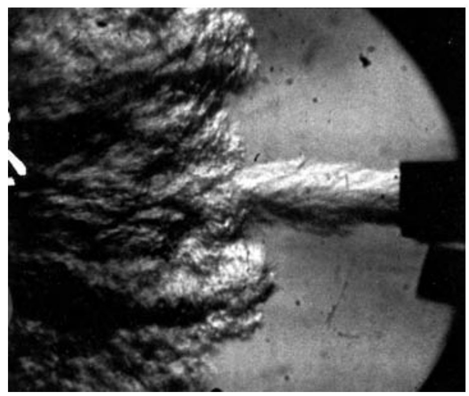
1 (t=0)



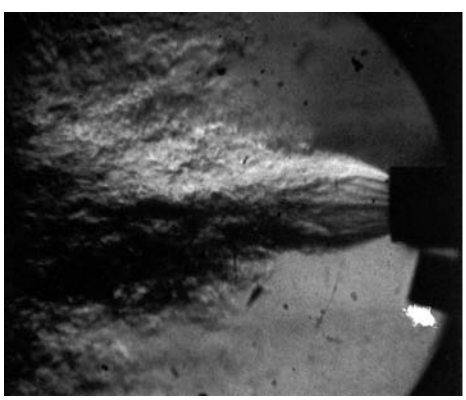
2 (0.149 ms)



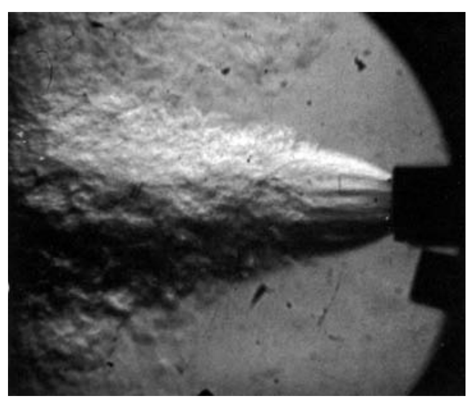
3 (0.298 ms)



4 (0.447 ms)

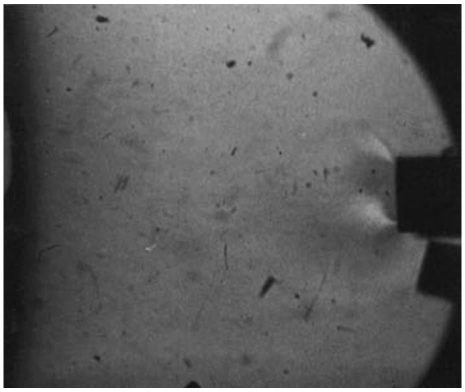


33 (4.768 ms)

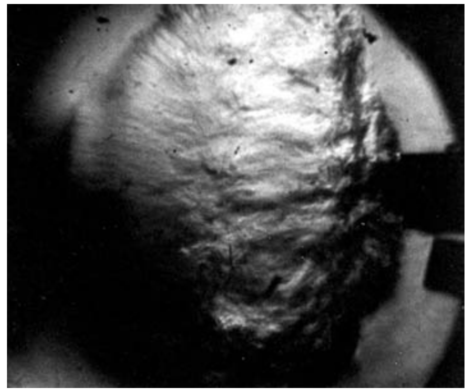


53 (7.748 ms)

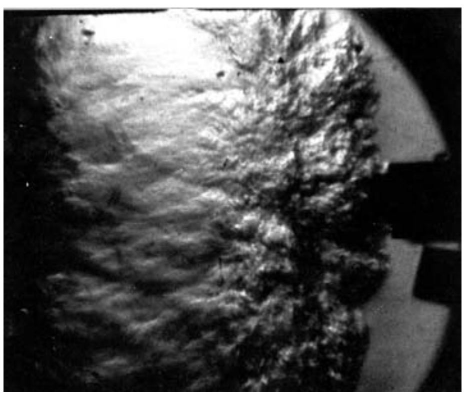
Figure E.2: Jet startup, venting into 100% air. The jet is expected to burn as a diffusion flame under these conditions, but no difference is visible between these photos and those of Figure E.1. Reduced flow in frame 4 is due to diaphragm clogging (diaphragm later cleared). Framing rate is 6.72 kfps. RPI run 124.



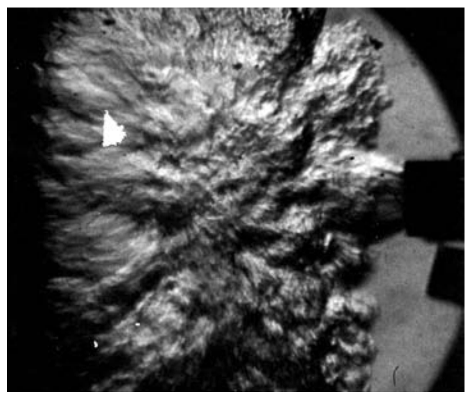
1 (t=0)



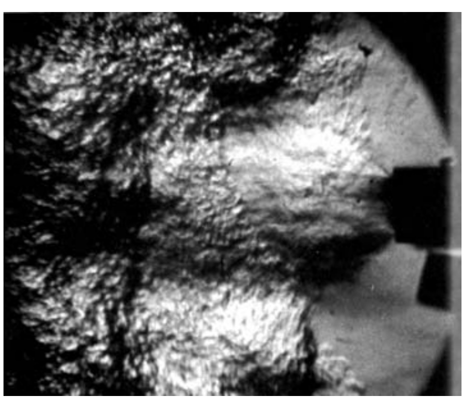
2 (0.072 ms)



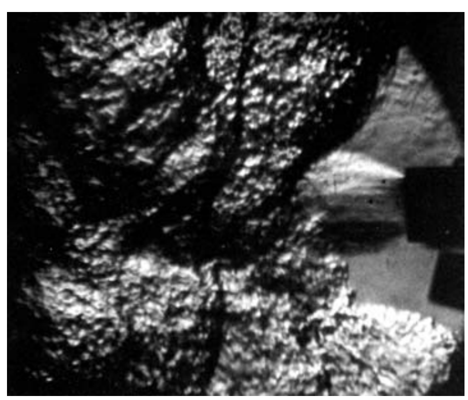
3 (0.142 ms)



4 (0.215 ms)



74 (5.220 ms)



124 (8.790 ms)

Figure E.3: Jet initiation of deflagration in 1:1 air:N_2, with 10% H_2. Framing rate is 13.44 kfps. RPI run 127.