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Operator's Guide for the Combustion Driven Shock Tunnel in the T5 Laboratory at GALCIT

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Introduction

The combustion driven shock tunnel was designed and built at GALCIT to supply the hypersonic facility T5 with "hot" hydrogen for hypervelocity mixing and combustion experiments. This "hot" fuel is needed to reproduce the environment encountered by a scramjet engine in real flight where the fuel is used first to cool down the skin of the airplane before being injected into the engine. The combustion driven shock tunnel was chosen over other options for better flexibility and for safety reasons.

This operator's guide is only intended for future users of the combustion driven shock tunnel and will not cover material already presented in the GALCIT thesis " Studies of Mixing and Combustion in Hypervelocity Flows with Hot Hydrogen Injection" by Jacques Bélanger. It is mandatory to carefully study chapter 3 of that thesis before getting into the details of the system operation presented here.

The manual is divided into two parts, the first part describes the different components and how they are assembled, the second part describes the firing procedure itself. A major effort is made in this guide to incorporate the hands-on experience learned over the years with the system. Hopefully, these "hints" will save time and trouble to future users.

1 - Components

The drawings of all the components of the combustion driven shock tunnel are in the T5 laboratory in a drawer next to all the T5 drawings. Almost all the drawings have been updated to the design currently used, but at the same time older versions of the system are kept in that drawer and have been designated "old version", so be careful to use the latest version of the drawings. In the last few years some drawings have been put in Autocad mostly for assembly representations. A list of these drawings is presented here and can be found in the directory home/hyper/T5/cast.

-burst_sys.dwg	: burst system assembly shown in fig. 1 of this report.
-burst_sys_zoom.dwg	: zoom of the burst system assembly shown in fig. 2.
-cast.dwg	: filling and purging lines of the system shown in fig. 7.
-cast_end.dwg	: shock tunnel assembly in the test section of T5 (fig. 3).
-plate.dwg	: flat plate used for first combustion experiments in T5.
-injectors.dwg	: 2 of the injectors used with the flat plate experiments.
-support.dwg	: driven section support system shown in fig. 4.

Some of the components of the system are "permanently" attached to the dump tank of T5 and stay there even if the combustion driven system is not used. The rest of the components are kept under a working area in the north-west corner of the T5 lab. The electrical parts and all the small items are kept in a drawer in that same area next to the large components.

1.1 - Driver Section

Taking into account the holes in the tube and the sudden loading of the system due to the combustion, the maximum pressure in the driver section should not exceed 35 MPa. If another "safety" margin is added to take into account user filling errors or mechanical problems, it is recommended not to exceed 25 MPa. Tests at 20 MPa have been successfully fired, but one of the problem with these high pressure tests is an accelerated wear of the diaphragm bursting wire and the spring inside the driver section.

A second pressure gauge, next to the 300 psi high precision one, was installed so that these high pressure tests could be performed. A mixture pressure of 400 to 500 psi, depending on the hydrogen concentration, is needed to get 20 MPa after combustion. During such tests, the gauge valve on the 300 psi gauge must be closed before the end of the filling process to prevent any damage to the gauge. This second pressure gauge is not very accurate so if many high pressure shots are planed, it could be a good idea to buy a better gauge.

The mixture is ignited by twelve regular automotive-type spark plugs, the only special thing about these spark plugs is that they are for "high performance" cars, with 3/4 in. of thread instead of the regular 1/2 in. (the thread is the S.A.E. Standard threads M-14 for spark plugs). Champion, Autolite and Bosch spark plugs were tested. The best results came from the Bosch ones (they can be found at Pep Boys for about $2.99 each or at almost any car supplier). The Champion ones also worked very well but they turned out to be difficult to find in local stores. The important advice here is simple, stay away from the cheaper ones -Autolite and such-, they are not well built and some of the ones tested slowly develop *leaks* through their core making repeatable tests almost impossible.

It is difficult to give a life expectancy for these spark plugs. The rule is that if there is any question about them, change them. As a matter of reference, in the first 250 shots, the spark plugs were changed at least 6 times. Some of the changes were probably not necessary and some of these changes were due to leaks or deposit on the electrodes after bad combustion. It is possible to foresee, with everything that has been learned with the system today, that a set of spark plugs should last for more than a hundred shots.

It is very simple to check if all the spark plugs work properly. The procedure consists of connecting the 9 volt trigger battery directly to the electrical circuit box with the system *on*, and to leave the driver section open. It is then possible to trigger the box and have the spark plugs firing. The coils can be recharged in less than a second so the system can be fired rapidly for as many times as needed. Looking inside the tube will show whether all the spark plugs are firing. The visibility of the sparks is usually very good but it could append that a spark from one or two of the spark plugs be blocked by the arm of the electrode itself, so the use of a mirror or some other technique may be needed. Before firing the spark plugs with the driver section open, *make sure* that there is no combustible gas in the tube, it would probably ignite (it appended before!).

Each spark plug has its own automotive-type 20 kV capacitor and its own electrical circuit. A red light on top of one of the two boxes shows if the system power is *on*. The system is ready as soon as it is turned *on*. To fire the system, the trigger signal is simultaneously sent to the twelve independent circuits. The circuits have been designed by Allan Goudy and he should be able to help if there is a problem. The power supply needed is a regular 120V AC and the system triggers with a signal of about 2.5V DC at the BNC connector on the side of the "east" box. A delay of a few milliseconds can be expected between the trigger signal and the actual sparks in the tube.

To get better sparks and consequently better combustion for filling pressures over 2 MPa (300 psi), the gap between the electrodes of the spark plug were reduced from 2 to 1 mm. The problem is that the spark plugs with 1 mm gap don't do as well when used at low pressure, so the smaller gap is not recommended in those conditions.

If, for some reason, all 12 spark plugs are not used during a test, it is then necessary to disconnect the electrical circuit of the unused spark plugs inside the boxes. If the circuits are not disconnected, capacitors in the electrical circuit will be destroyed. The same damage would occur if a spark plug cable is not correctly connected. Make sure everything is connected properly before firing the system.

The two gas mixtures commonly used are 14% hydrogen, 7% oxygen and 79% helium and 16% - 8% - 76%, respectively. Lower concentrations of hydrogen were tested, but the slow combustion and low speed of sound of the resulting driver gas makes such a concentration unsuitable for the "hot" hydrogen injection experiments. Higher concentrations of fuel were also tested, but strong waves occurred in the tube after combustion, and the high temperature reached in the tube caused damage to the diaphragm rupture device. In almost all filling pressures used, the ratio of pressure after and before combustion (P_4'/P_4) was 5.5 when 14% hydrogen mixture was used and 7.0 when the 16% hydrogen mixture was used. To make sure that the driver gas is well mixed, the mixture is left in the tube to settle for at least 30 minutes before the test. When the system is used with T5, the driver section is filled with the mixture before the firing procedure of T5 is started (disconnecting the support trolley). If there is a place where money could be well spent in improving the system, it is here. A small pump recirculating the mixture for a few minutes or a regulator controlling the fraction of each of the three gases could make sure that the gases are each time perfectly mixed.

1.2 - Diaphragm and Diaphragm Bursting System

The 5000 μF, 250 V capacitor is discharged into the diaphragm using the probe design shown in Figure 1. The O'rings needed to seal the system are not shown in this figure for clarity. The electronic circuit was designed and put together by Allan Goudy and once again, he should be able to help if something does not appear to be working properly. The power supply is 120V AC, and a signal of about 2.5V DC at the BNC connector on the top of the box is needed to trigger the system. A delay of about 0.12 ms can be expected between the trigger signal and the actual breaking of the diaphragm. A light on top of the box turns red when the capacitor is charged to 200 V, and later turns yellow when it reaches its maximum voltage of 250 V. Once the switch on the box is turned *on*, it takes about 5 to 10 minutes before the capacitor is fully charged and ready to be fired.

Be extremely careful with this system, small pieces of screw driver have been melted by its electrical discharge and nobody really wants to know what it could do to a person. To make the system safer, a circuit to slowly discharge the capacitor when the system is turned *off* has been added. So if you need to work in the area close to the system or if a shot is aborted, just turn off the system before doing anything else near it.

Even if the probe is made of a very good conductor like copper, the tip of the probe touching the diaphragm gets very hot and the surface becomes very rough after a few shots. It is necessary to file the tip very regularly and to use sand paper to make the surface as smooth as possible so that the probe tip does not break or damage the diaphragm prematurely.

A copper cylinder threaded at one end is screwed to the probe with its other end soldered to the wire coming from the system capacitor. Figures 1 and 2 show how the wire is fed through the wall of the driver section but stays insulated from it. An O'Ring is used to seal the space between the nylon insulator and the hole in the driver tube, and high temperature epoxy is used to seal the space between the insulator and the wire. If the operation of sealing the space between the wire and the insulator is not done with extreme care, a small leak could occur, making the insulator-wire unusable and unfixable. To reduce the possibility of a leak, the part of the multi-grain wire inside the insulator was first filled with solder. In normal utilization the wire and the epoxy wear out slowly and the piece has to be changed once in a while. High temperature shots (18% H_2) have damaged the wire inside the driver section and a new wire with insulator and copper cylinder had to be made.

The spring between the probe and its support inside the driver section is there to make sure that the probe constantly touches the diaphragm even after the combustion when the diaphragm buckles away from the probe. Too strong a spring could push too hard on the probe indenting the diaphragm and possibly causing premature rupture. Too weak a spring will not allow the probe to follow the diaphragm during combustion, making the system unusable at the time when it is needed. There seem to be side forces applied to the probe during combustion. These side forces must be proportional to the pressure inside the driver, so to compensate them and to make sure that the probe follows the diaphragm at all time, stronger springs are used for higher pressure shots. The possible damage to the diaphragm due to these stronger springs is compensated by the fact that thicker diaphragms are used for higher expected burst pressure. The three types of springs used are kept in the drawer with all the electrical parts and they are labeled -Ludwieg tube-, -low pressure- and -high pressure-. Other types of spring are also kept in the drawer for further experimentations with the system.

To dismantle the firing mechanism, it is necessary to undo the nut holding the insulator in place inside the bolt (see figure 2). The bolt can then be undone slowly with the insulator staying fixed relative to the tube. Once the bolt is undone, it is possible to push the insulator inside the driven section. The probe with its support can then be pulled out of the tube and the copper cylinder unscrewed from the probe. At this point the wire with the insulator can be pulled out of the tube through the hole on the side of the driver and the probe and spring can be serviced. To reassemble the system, the same procedure is done in reverse.

It is possible to do combustion and diaphragm bursting tests without having the whole driven section mounted in the test section of T5. This allows the user to test the system even when somebody else has his model in the test section of T5. The idea is to use only the short segment of the driven section mounted directly to the driver section of the system. An end plate with a pressure transducer hole and space to connect the flexible hose of the filling system was made for that purpose.

When the system was converted to a Ludwieg tube for the experiments presented in chapter 6 of the thesis, the pressures used were very low (300 kPa and lower with no combustion). For these experiments, thin aluminum diaphragms with a weak spring were used (the -Ludwieg tube- springs).

1.3 - Driven Section

In the configuration to be used with T5, the driven section is made of two parts. The first one connects the driver section of the tube to the test section of T5, the second one, inside the test section of T5, brings the driven section of the combustion shock tunnel to the test model. Figure 3 presents the assembled parts of the section inside the test section T5 with also the position of the secondary diaphragm (made of mylar).

The system can be opened by undoing the nut just below the test section of T5 and the one just downstream of the main diaphragm. Once these two are undone, the long piece of the driven section can be moved away. The small part of the driven section inside the test section of T5 can then be removed by unscrewing it from the model and pulling it down. Work on the diaphragm bursting system inside the driver can also be performed then. Figure 4 shows a sketch of the support system needed when the long piece of the driven section is disconnected from the rest of the system. Figures 5 and 6 are pictures taken of the system and give a good overall view of the different parts.

The model to be used in the test section of T5 should be made in such a way that it can easily be adjusted in order to be able to align the short part of the driven section with the hole in the T5 test section plate. A small misalignment makes it impossible to remove the short part of the driven section inside the test section of T5.

1.4 - Data Acquisition System

For a regular shot with T5, one of the trigger channels of the data acquisition system is connected to the output of one of the pressure transducers in the compression tube of T5. This signal is used to trigger the combustion about 20 ms before test time. Because the trigger voltage step increment is too large to fine tune the delay on the data acquisition system, an amplifier from the data acquisition system is used to amplify the signal from the transducer before it is sent to the trigger channel. Using an amplification of only 10 is sufficient to fine tune the combustion trigger to within a 1 or 2 ms margin.

Another trigger channel is connected to the pressure transducer at station #4 along the shock tube of T5. This signal is used to trigger the diaphragm bursting system; it does not need to be amplified. The trigger level can be adjusted low enough so that it triggers as the initial shock passes by. For very low temperature tests (low shock speed) or for tests with lower speed of sound test gases, it may be necessary to move the trigger signal to the pressure transducer station #3 of T5. This would give enough time for the combustion driven shock tunnel to stabilize its pressure at the end of the driven section during the actual test time of T5.

4 to 6 channels of the data acquisition system are needed to monitor the combustion driven shock tunnel. 2 pressure transducers in the driver section and 2 in the driven section are necessary to determine the pressures, driver gas temperature, the shock speed and, most importantly, the pressure at the end of the driven section (stagnation pressure). If some channels of the data acquisition system are available, it is also good to keep track of the trigger signals. These traces may be useful in determining what when wrong in a missed shot.

When the combustion driven shock tunnel needs to be tested without T5 (that is, very often), a delay box is used to send the second signal. The regular 5 V signal used to test the data acquisition system is used here to trigger the combustion and also to feed the delay box. The output of the box is a 5 V signal delayed by a predetermined time between 4 and 40 ms. This delayed signal is also usually used to trigger the data acquisition system. The delay box is kept in the drawer with all the other electrical parts.

The data of all the shots without T5 were taken out of the system but a copy of all the files is kept on tape in the T5 lab. Plots of most of the pressure traces from these tests are also available for consultation in a binder with the rest of the T5 data.

2 - Firing Procedures

Pages 12 and 13 reproduce the firing procedures written to help the user go through a firing sequence. A schematic of the system is shown in figure 7 to identify most of the components used during the firing procedures. The following comments further clarify some of the points in the checklist:

Step 4 : Never turn OFF the spark plug assembly when the driver is filled with a combustible mixture. The system discharges the coils when it is turned off, making it ignite the mixture in the driver.

Step 6 : The pressure gauge on the system cannot give good measurements of the vacuum level in the system, but an extra line that connects the system to the vacuum gauge of the dump tank of T5 has been installed. With a quick look at the extra line (not shown in figure 5), it is easy to see how to isolate the dump tank from its pressure gauge and have the gauge measure the pressure inside the combustion driven tunnel system by opening the appropriate extra valve.

Step 10 : Filling first with 50% of the He needed seems to be a good compromise between having enough He in the tube to mix with the H_2 and O_2 when these gases are added and the need to stir the whole mixture with the remaining 50% of He at the end.

Step 12 and 15 : It is very important that the filling be done energetically, meaning that strong jets must be created at the entrance of the driver section to enhance the mixing of the gases. To do so, the valves must be operated to create as large a flow rate as possible.

Step 24 : A settling time of 30 minutes seems adequate. Some tests have been conducted successfully with settling times of only 20 minutes but to stay on the safe side, longer is better (if no leaks are present).

Step 34 : Always arm the data acquisition system before turning the diaphragm bursting system on, it will save you a lot of missed shots.

CAST Firing Procedures   Shot No: 15-268   09/24/92

(version 4 - 11/17/93)

1 - Change diaphragms
    main diaphragm: 0.008 S.S. [✓]
    small diaphragm: Mylar [✓]
2 - Close shock tube .... [✓]
3 - Make sure all valves are in the right position:

- flexible hose valve:	open	[✓]	- driven section valve:	open	[✓]
- pressure gauge valve:	open	[✓]	- vacuum pump valve:	open	[✓]
- driver section valve:	open	[✓]	- purge valve:	close	[✓]
- gas bottle valves:	open	[✓]	- H_2, O_2, He, N_2 valves:	close	[✓]
- regulators:	close	[✓]			

4 - Turn on spark plug assembly .... [✓]
5 - Start the vacuum pump .... [✓]
6 - Wait for acceptable vacuum .... [✓]
7 - Close flexible hose valve .... [✓]
8 - Close vacuum pump valve .... [✓]
9 - Open He regulator (2 X times needed pressure) .... [✓]

10 - Fill the driver section with 50% of the He needed (76 % of total pressure)

total pressure 265 (psi) (38 %) 100.7 (psi)

vacuum pressure 29 /2.042 (in Hg) - 14.2 (psi)

filling gauge pressure 86.5 (psi) [✓]

11 - Open H_2 regulator (2 X times needed pressure) .... [✓]

12 - Fill the driver section with H_2 (16 % of total pressure)

total pressure 265 (psi) (16 %) 42.4 (psi)

He gauge pressure + 86.5 (psi)

filling gauge pressure 128.9 (psi) [✓]

13 - Close H_2 regulator .... [✓]
14 - Open O_2 regulator (2 X times needed pressure) .... [✓]

15 - Fill the driver section with O_2 (8 % of total pressure)

total pressure 265 (psi) (8 %) 21.2 (psi)

previous gauge pressure + 128.9 (psi)

filling gauge pressure 150.1 (psi) [✓]

16 - Close O_2 regulator (2 X times needed pressure) .... [✓]

17- Fill the driver section with 50% of the He needed (76 % of total pressure)

total pressure 265 (psi) (38%) 100.7 (psi)

previous gauge pressure + 150.1 (psi)

filling gauge pressure 250.8 (psi) [✓]

18- Close driver section valve .... [✓]
19- Close He regulator .... [✓]
20- Open vacuum pump valve .... [✓]
21- Open H_2, O_2, He, N_2 valves .... [✓]
22- Open flexible hose valve .... [✓]
23- Wait for acceptable vacuum .... [✓]
24- Wait for mixture settling .... [✓]
25- Close the vacuum pump valve .... [✓]
26- Open H_2 regulator (2 X times needed pressure) .... [✓]

27- Fill the driven section: total pressure 100 (psi)

vacuum pressure 29 /2.042 (in Hg) - 14.2 (psi)

gauge pressure 85.8 (psi) [✓]

28- Close the driven section valve .... [✓]
29- Close H_2 regulator .... [✓]
30- Open vacuum pump valve .... [✓]
31- Open H_2 valve .... [✓]
32- Close flexible hose valve .... [✓]
33- Arm the data acquisition system .... [✓]
34- Turn on diaphragm bursting system .... [✓]

35- FIRE [✓]

36- Turn off diaphragm bursting system .... [✓]
37- Open driver section valve .... [✓]
38- Open flexible hose valve .... [✓]
39- Open driven section valve .... [✓]
40- Open vacuum pump valve .... [✓]
41- Wait at least 15 minutes .... [✓]
42- Vent the hole system .... [✓]
43- Turn off vacuum pump .... [✓]
44- Turn off spark plug assembly .... [✓]
45- Open shock tube .... [✓]

Signature : Jacques B. Sauget

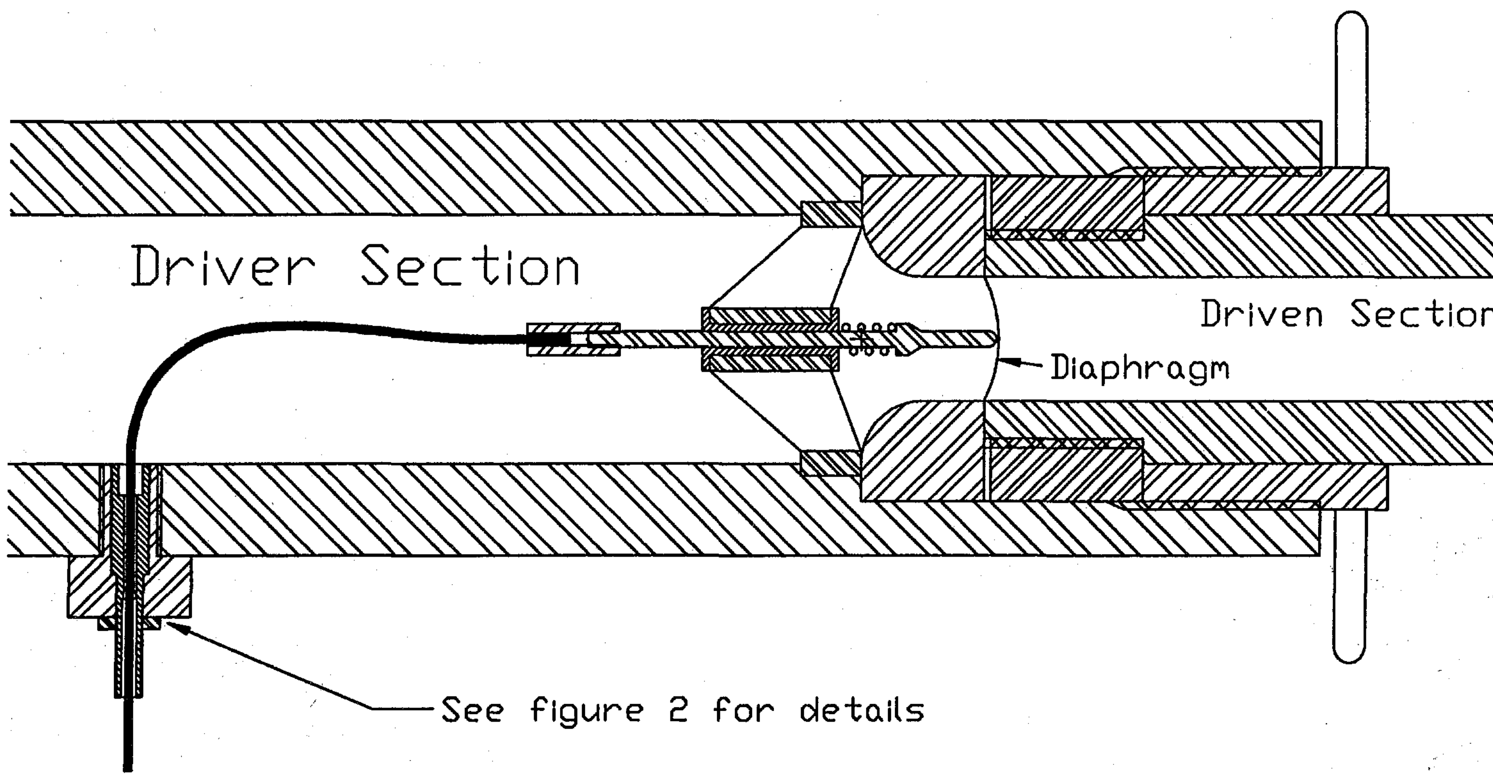

Figure 1. View of the diaphragm bursting system inside the driver section.

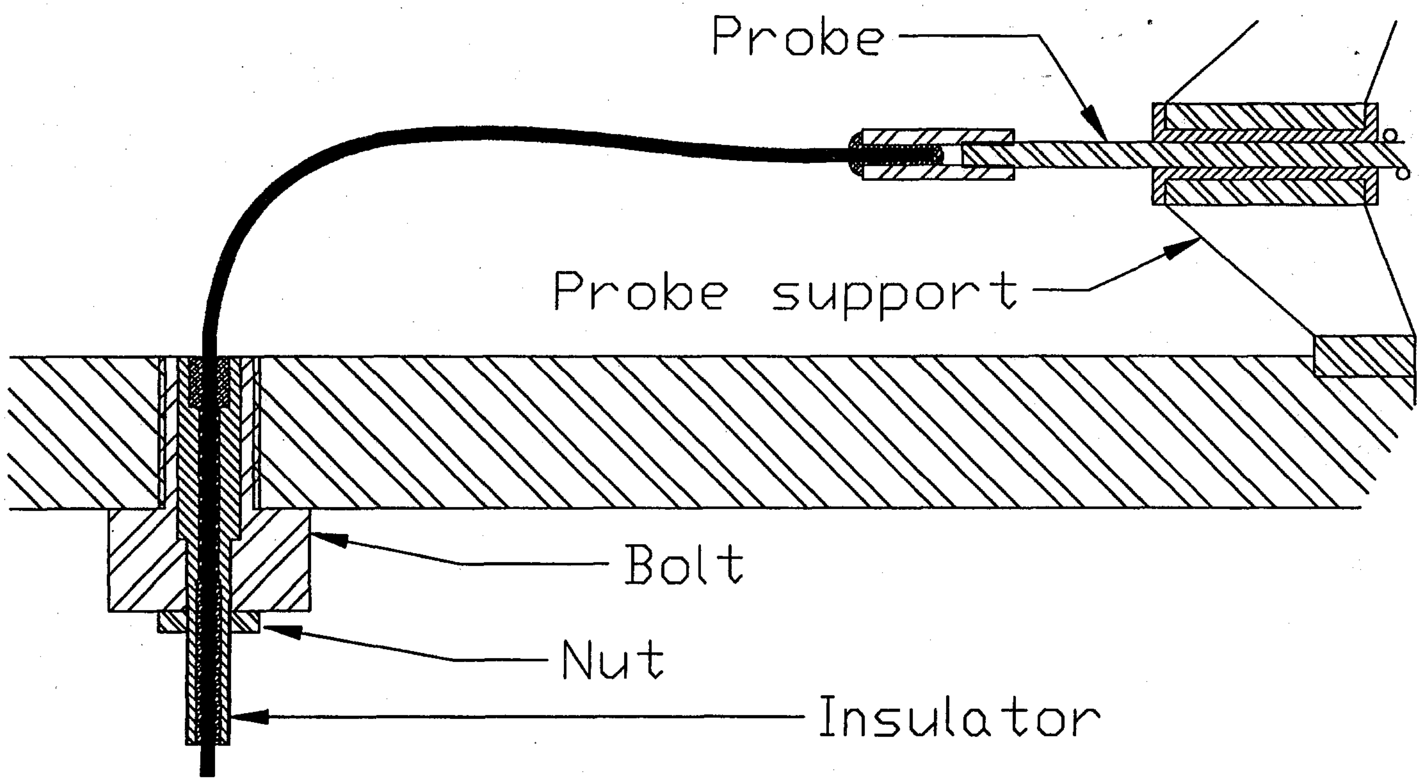

Figure 2. Detailed view of the diaphragm bursting system.

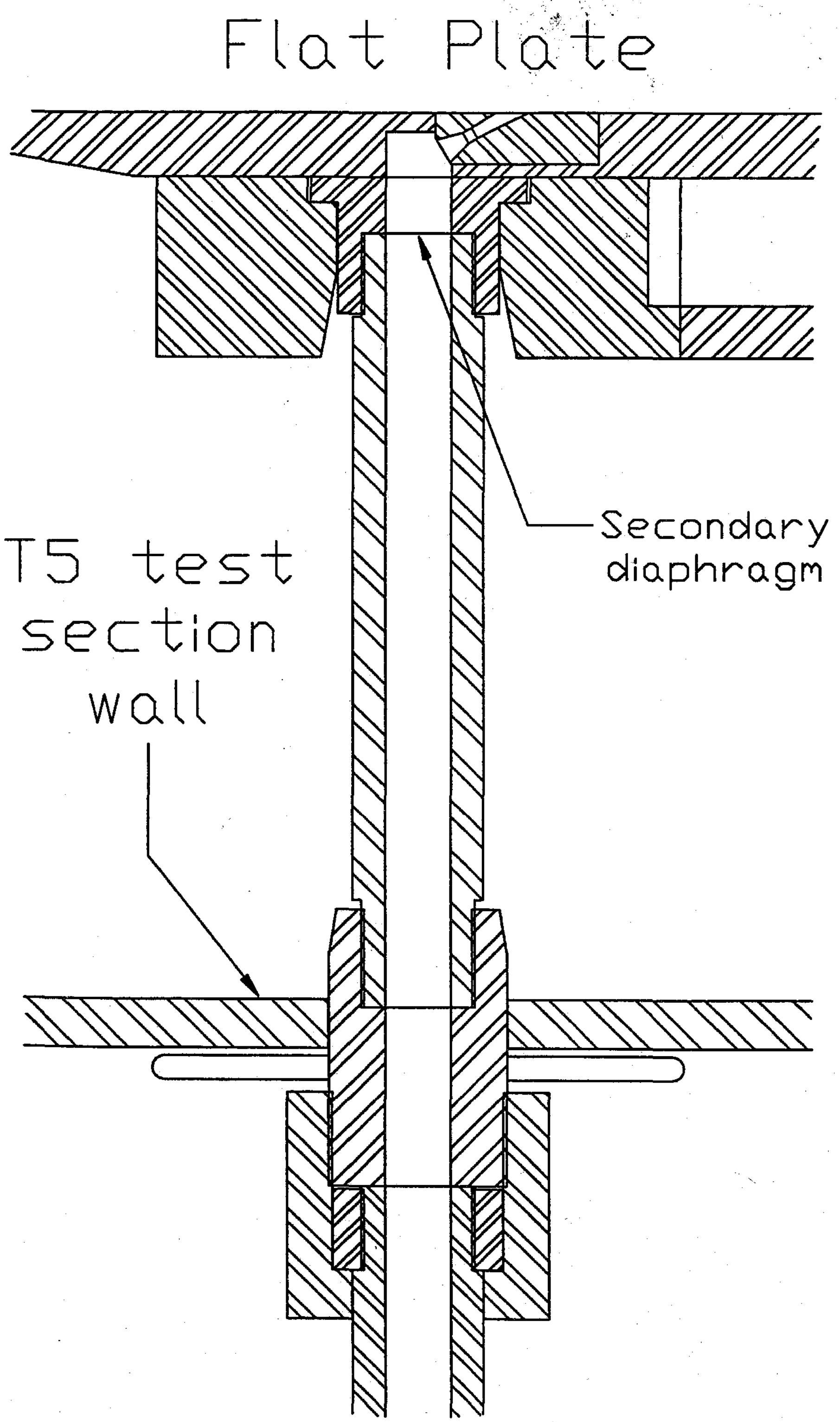

Figure 3. Part of the driven section inside the test section of T5.

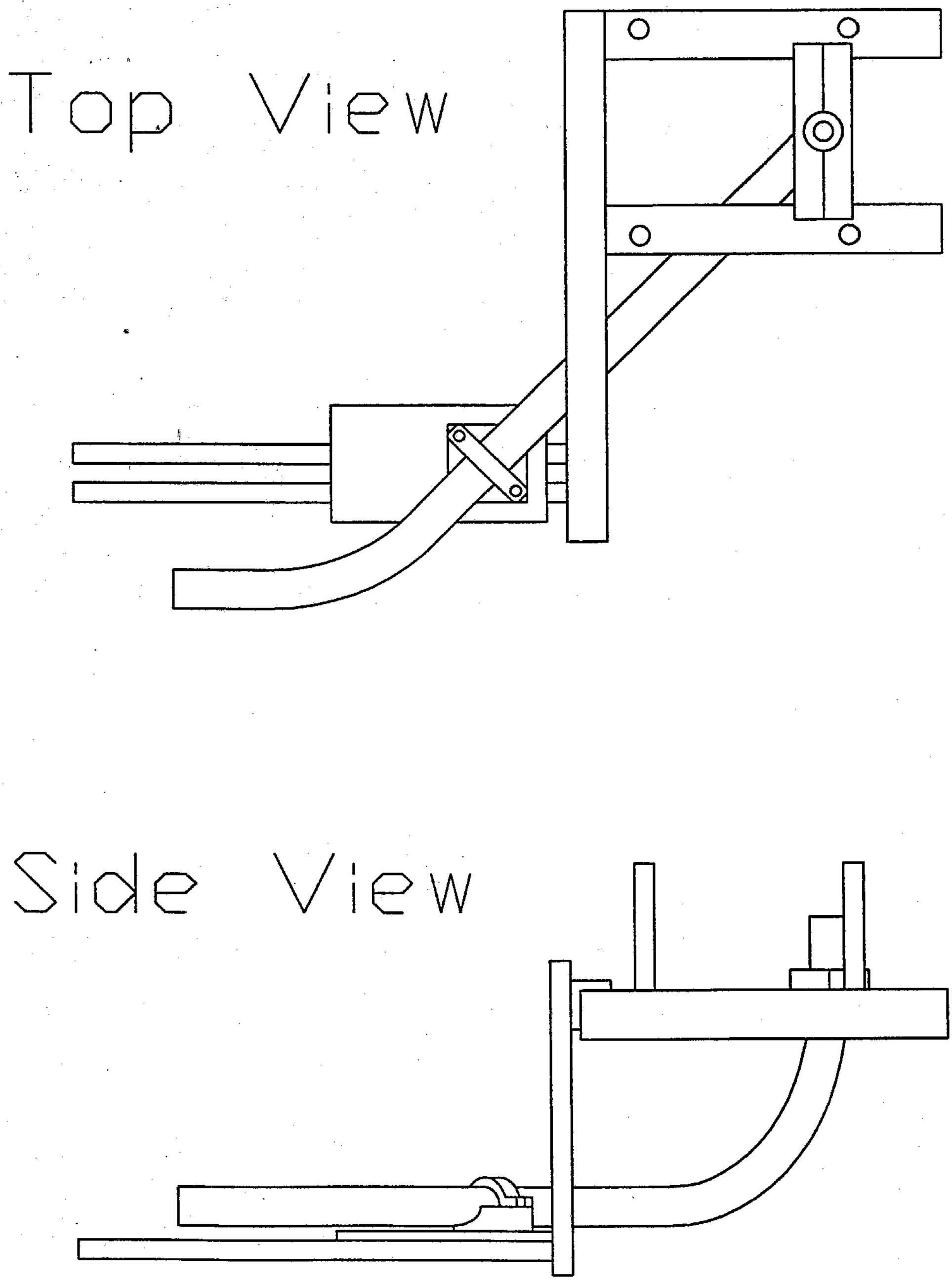

Figure 4. Support system of the long driven section piece when disconnected from the rest of the system

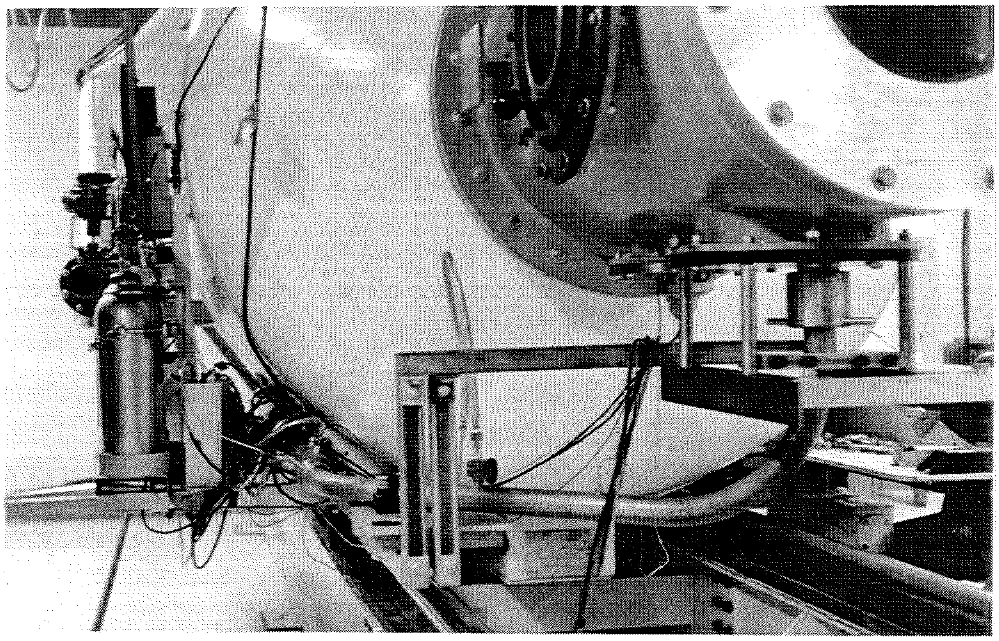

Figure 5. View of the system mounted on the test section-dump tank of T5.

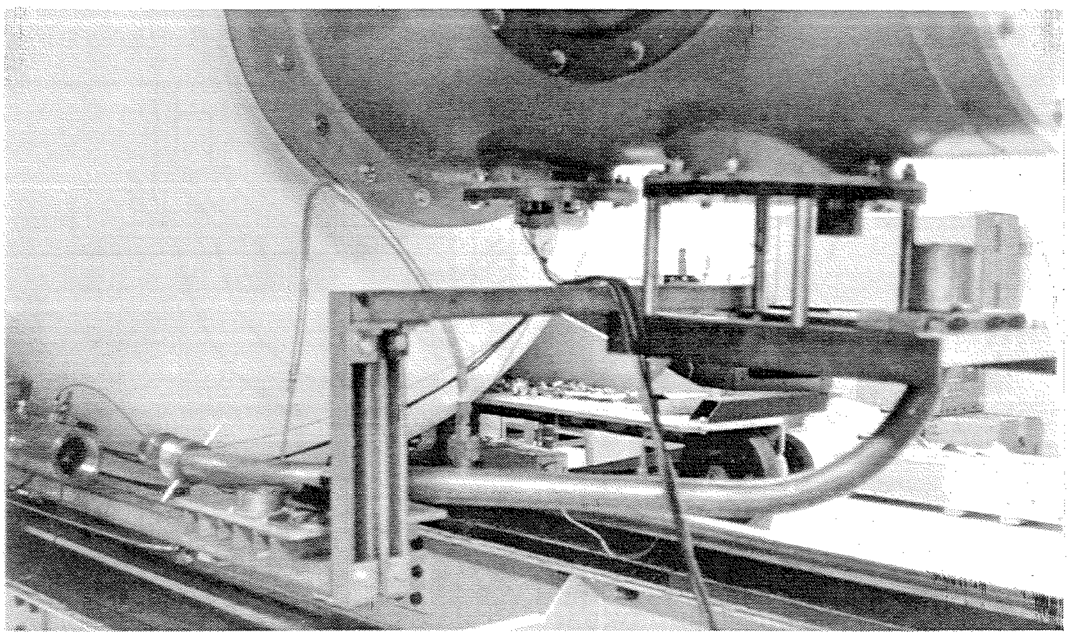

Figure 6. View of the system mounted on the test section-dump tank of T5.

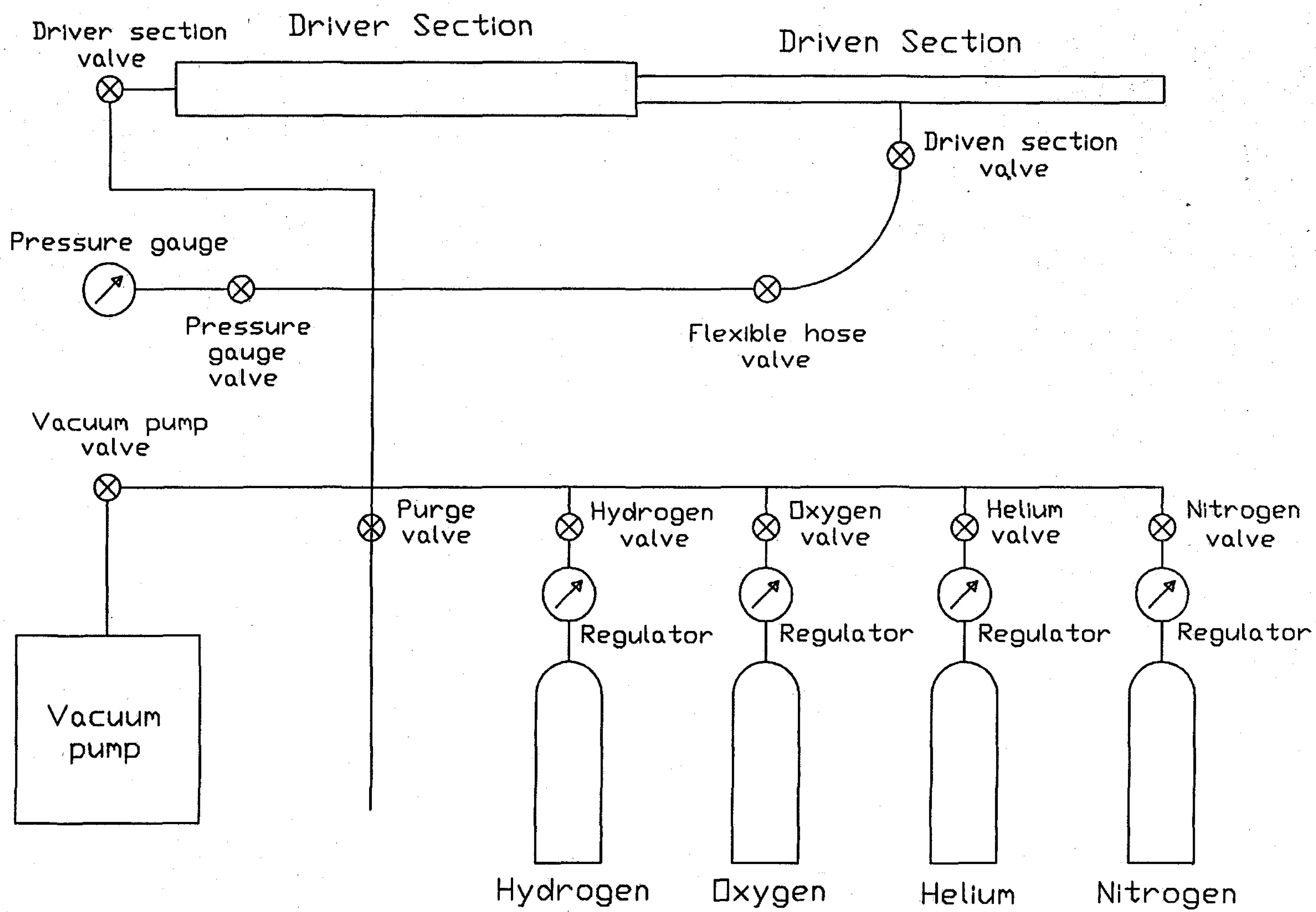

Figure 7. Schematic of the filling system.