Jet A Explosions - Field Test Plan
1/4-Scale Experiments

J. E. Shepherd, J. C. Krok and J. J. Lee
Explosion Dynamics Laboratory
California Institute of Technology
Pasadena, CA 91125

M. M. Birky
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington DC 20594

June 27, 1997

Revised December 6, 1997

Explosion Dynamics Laboratory Report FM97-17

Prepared for and supported by the National Transportation Safety Board
Under Order NTSB12-97-SP-0127

Contents

List of Figures

List of Tables

1 Introduction

The TWA 800 crash investigation is focusing on the explosion of Jet A-air mixtures in the ullage of the center-wing tank (CWT), see Fig. 1, as the key event in the accident. Laboratory tests are being carried out on Jet A-air mixtures in the 1.2-m^3 HYJET facility at Caltech (Shepherd et al. 1997), and preparations are being made for larger-scale field testing. This document is a proposal for the first phase of the field testing.

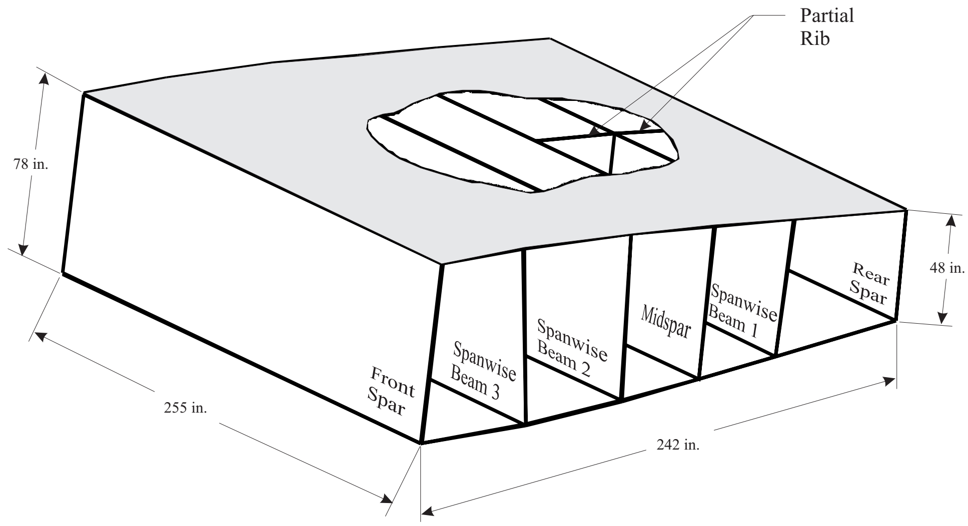

Figure 1: Cut-away view of the 747-100 Center Wing Tank (CWT) showing beams and spars that partition the tank into compartments. Passageways and external vents are not shown.

At the present time, one of the main goals of the investigation into TWA 800 is to determine the location and source of ignition in the CWT. The experimental test program has been designed to develop basic information that will aid the investigators in reaching this goal. Laboratory experiments have so far examined issues relating to fuel chemical properties, flammability limits and pressure histories during controlled laboratory explosions of Jet A vapor and air. Laboratory testing to determine ignition energies and flame speeds is in progress.

All the laboratory testing has been carried out in simple test facilities consisting of a single, unvented chamber that is relatively small compared to the CWT, which has an approximate volume (not including the dry bay) of 50 m^3. Field testing is needed to address the effect of size, compartmentalization, and other factors such as vents in the center wing tank. The CWT is divided into six wet bays and one dry bay, see Fig. 1. There are passageways between the bays and vents to the outside of the airplane in four of the bays. The sequence analysis of the CWT failure indicates that the front spar (FS), the spanwise beam 3 (SWB3) and the manufacturing panel in spanwise beam 2 (SWB2) all failed and were ejected from the airplane early in the event.

The construction of the tank and accident sequence analysis indicate that it is important to understand the phenomena associated with flame propagation in a multicompartment, vented tank and to also consider the coupling between the flame propagation and structural failure. A program of field tests has been developed to examine these issues. The experimental testing will proceed in conjunction with numerical simulations while maintaining constant feedback between the two programs in order to optimize the experimental conditions and minimize the number of tests to be conducted.

The field testing has been divided into three phases.

1. 1/4-scale tests in a CWT-like geometry.
2. Full-scale tests of actual CWT or mockups.
3. Full-scale tests using actual aircraft.

The general objective of the Phase 1 tests is to obtain information about combustion in a multicompartment, vented enclosure geometrically similar to the CWT. Phase 2 full-scale tests will be carried out to examine the effects of scale and more realistic structural failure on combustion . The airplane tests in phase 3 are intended to simulate as realistically as possible an explosion of a Jet A-air mixture within the ullage of the CWT in a 747-100 with a pressurized fuselage.

This document focuses exclusively on the 1/4-scale tests. Subsequent documents will describe the test program in Phases 2 and 3. The program is proceeding sequentially, with information developed in the earlier phases being used to define the test program in subsequent phases.

2 Issues

We believe that the following issues are significant in determining the combustion phenomena in the CWT:

1. Amount of fuel vapor

   One of the uncertainties is the amount of fuel present in the vapor form within the ullage. The reason for this uncertainty is due to the spatial variation in temperature within the tank and the lack of measurements appropriate to this specific situation. Fuel vapor mass effects have been examined extensively in the laboratory tests and at least two levels of fuel vapor concentration will be compared in the proposed 1/4-scale (Phase 1) tests.

2. Ignition location

   The primary objective of the investigation is to determine the location and source of ignition in the CWT. This will be examined in the Phase 1 tests by carrying out tests with ignition sources in each compartment of the tank as shown in Fig. 4. The pattern of flame propagation, failure of partitions between compartments, and resulting depressurization may give an indication as to the possible ignition locations that could produce the observed CWT failure sequence in TWA-800. One key objective of these tests will be to determine if that is possible in a scale model.

3. Flame propagation between compartments

   One of the key features of the CWT is the compartmentalization (Fig. 1). Significant effects are expected due to both the gas motion and the flame propagation through the passageways connecting the compartments. Turbulence generated by jetting through the passageways may increase the flame speed. Opposing this is the possible quenching effect of mixing colder, unburned gas into the jets created by the flow through these small openings.

   This will be investigated in the 1/4-scale tank using rigid partitions with scaled passageways. The partitions will be designed to withstand the peak pressure differential generated by the flame. Tests will be performed successively with two, three, and four compartments as shown in Fig. 4. Comparisons between the single compartment laboratory tests in 1.2 m^3 and the multi-compartment 1/4-scale tests will serve to determine the effects of compartmentalization. Visual observations of the flame, thermocouple, and photodiode output will be used to track the flame. Pressure measurements in each compartment will quantify the tradeoff between turbulence accelerating and quenching the flame.

4. Venting out of tank

   The tank is vented to the surrounding atmosphere through vent stringers with openings located in the two rear compartments and connecting lines in the forward compartment. Venting of burned and unburned gas will occur during an explosion, resulting in a reduction in the peak pressure produced by the explosion. Since the venting is distributed within the tank, this will result in further flow between the compartments during the explosion. Tests will be carried out with scaled vents in the 1/4-scale tank to compare with unvented laboratory tests.

5. Structural failure of partitions between compartments

   The failure of the FS, SWB3 and the manufacturing panel in the MS are significant features of the explosion. The primary mode of failure is believed to be the fracture of the connections at the top, bottom and sides, resulting in the ejection of the SWB3 and FS from the tank. The manufacturing panel failure was apparently due to a combination of in-plane shear and pressure differential. The venting produced by these failures will result in a very rapid depressurization of the adjacent compartments. If this occurred while the explosion was in progress, then a significant influence on flame propagation is anticipated. Partition failure will be simulated in the 1/4-scale tests by using deliberately weakened connections between the partitions and the tank top, bottom and sides. Results will be compared to those of tests with strong (non-failing) connections. Major effects on peak compartment pressures and flame speed are expected.

6. Liquid layer participation in explosion

   The presence of a layer of liquid fuel on the floor of the CWT raises the possibility of secondary burning if the liquid fuel is lofted and mixed with the air in the ullage.

This may be particularly significant during the explosive decompression that occurred when the FS and SWB3 failed. A layer of liquid will be placed on the floor of the 1/4-scale tank in selected tests with weak partition connections (Fig. 4d). Visual observations of the flame propagation and measurements of pressure (internal and external to the tank) will indicate the extent and effect of fuel lofting and secondary burning.

3 Testing Program

We propose a limited campaign of about 26 tests in a 1/4-scale mockup of the center wing tank. The issues we are examining in these tests are discussed below. This campaign is designed to systematically investigate these issues by varying the number of compartments, strength of the partitions, location of ignition, amount of fuel vapor and liquid. The tests will proceed in a logical sequence from the simplest configuration to the most complex.

The 1/4-scale tank model will be extremely simplified compared to the actual CWT. Volumes and vent areas will be geometrically scaled (see scaling discussion below), however, there will be very limited scaling of the structure and no attempt to replicate crack propagation, deformation or other structural failure mechanisms. Initially, only the effects of combustion in a rigid tank with various numbers of compartments will be examined. Later tests will study the effect of the complete failure of the connections of partitions corresponding to the FS and SWB3 to the upper and lower skin of the tank. Finally, tests will be carried out with lightweight, weak beams, spars and partial ribs.

3.1 Tank Model

The 1/4-scale tank will essentially consist of a rectangular vessel (Fig. 2) with nonyielding steel top, bottom, rear spar, and transparent sides. The tank can be divided by a variable number of partitions which can be either be rigidly connected to the top and bottom or else have weak connections designed to fail at a predetermined pressure difference between adjacent compartments or bays. The tank can be divided into seven bays, representing the six fuel tank “wet” bays and the dry bay. The division is by metal panels that represent the main spars or beams and transparent, high-strength plastic (Lexan) that represents the partial ribs. The partitions representing SWB1, SWB2, MS and the partial ribs will have scaled communicating passageways. The front compartment is a dry bay which is not filled with the fuel-air mixture like the other compartments. The front spar and attached water bottles will be simulated in some tests. The top plate is fitted with diagnostic gauges and also contains scaled vents to the exterior.

The required amount of fuel will be introduced into the tank using a propane-hydrogen gas simulant for the Jet A vapor and cold liquid Jet A in the case of the liquid fuel. The tank will be sealed and partially evacuated before introducing the gaseous and liquid fuel. The method of partial pressures will be used to meter in the correct amount of fuel

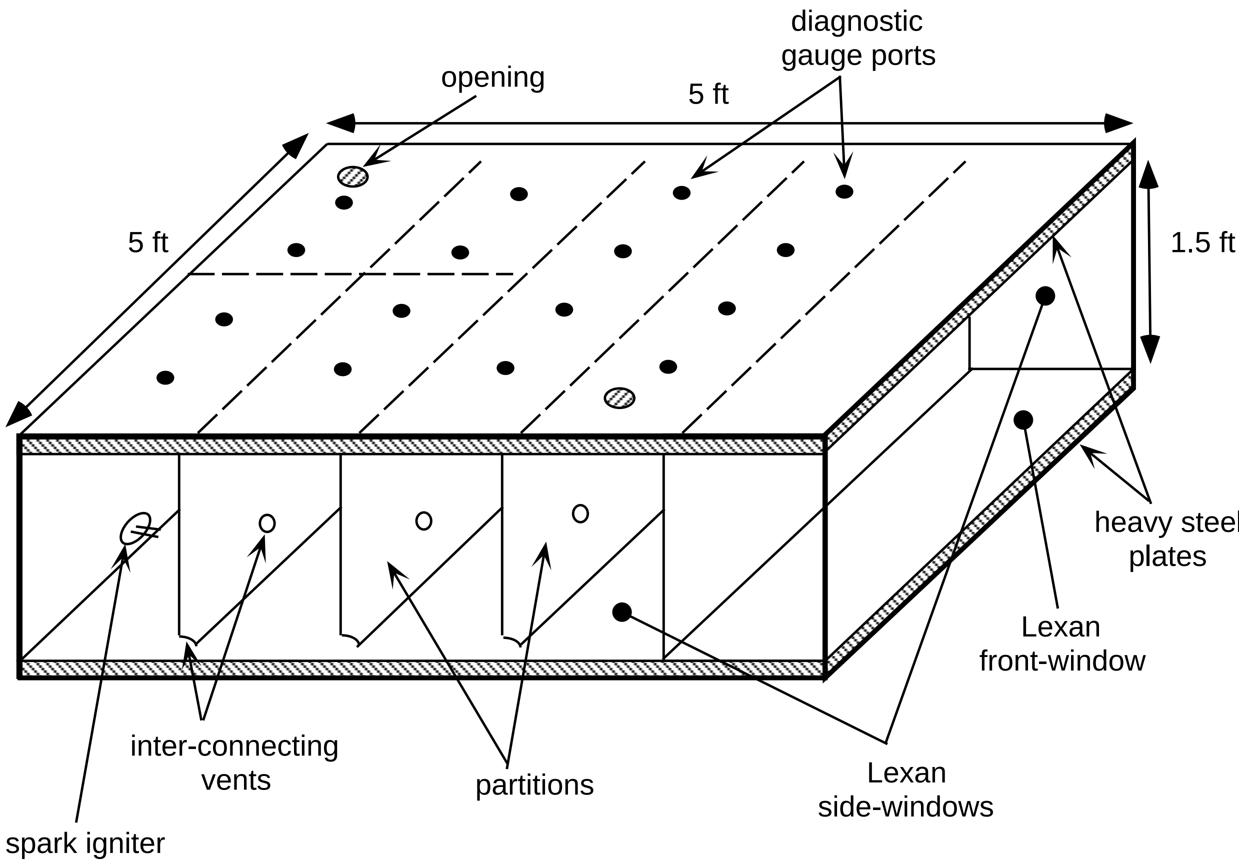

Figure 2: Schematic of the 1/4-scale model of the CWT.

vapor. The liquid Jet A will be at a sufficiently low temperature that its vapor pressure will make no contribution to the initial fuel-air mixture. The fuel will be distributed to each compartment by a manifold and subsequently mixed with the air by circulating the mixture through the tank with a mixing pump connected to the external vents.

The partitions consist either of thick (0.75-in) or thin (0.090-in) aluminum sheets fixed to the rigid top and bottom plates. The thick partitions are designed to be fixed boundaries and not to fail or to move during the tests. High strength fasteners will be used to attach the thick partitions securely to the upper and lower plates of the test fixture. The lightweight (thin) partitions are attached at the top and bottom edges with shear pins designed to fail when a critical pressure difference (about 20 psi) is applied on the partition. Each type of partition contains scaled passageways between the bays. The partitions are interchangeable as shown in Fig. 3 and can be chosen to have weak or rigid connections depending on the requirements of the experiment.

3.2 Test Matrix

We propose to divide the testing in the 1/4-scale tank into three series (see Table 1).

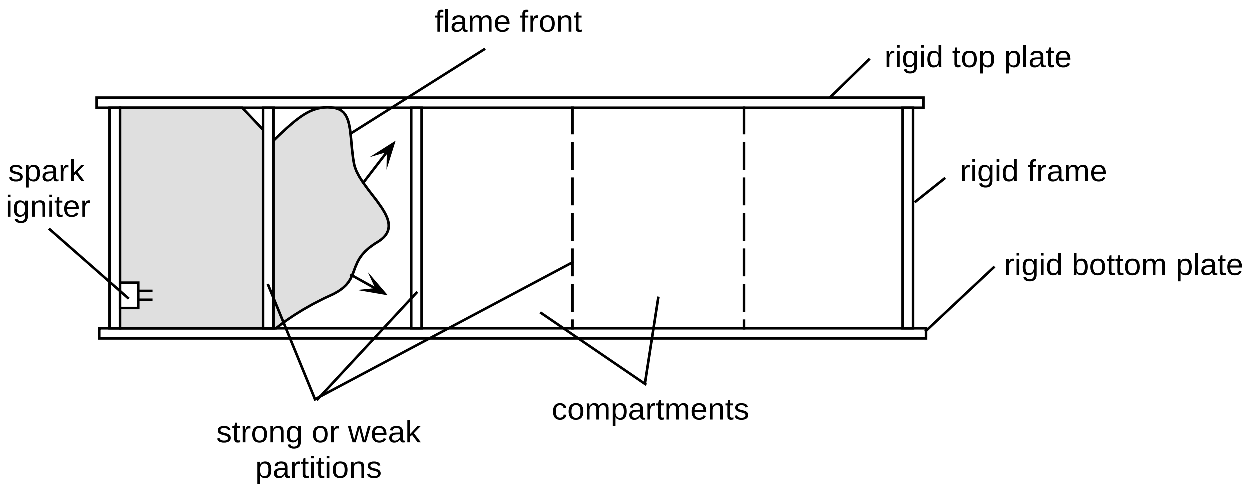

Figure 3: Side view schematic of the 1/4-scale model of the CWT.

The first series consists of *ALPHA* tests with an increasing number of rigid partitions, as shown in Figs. 4a through 4c. These start with a single volume and work up to four subdivisions. The ignition location is fixed and the tank is not vented, although communication through the vents can occur.

The second series of *BETA* tests will use rigid partitions to observe the effect of ignition location on flame acceleration process from one compartment to the next. Tests with a single partition will be used to examine the effect of distributed passageways vs. a single hole.

In the third series of *GAMMA* tests, the effects of partition failure and ignition location will be investigated. Partitions with weak connections will be used in these tests and the ignition source will be placed in different compartments as shown in Fig 4d. In each series, some tests will be carried out with a layer of liquid fuel placed on the tank floor to investigate the possibility of fuel lofting and secondary combustion. Tests with high (H) and low (L) fuel concentrations will be carried out in addition to the standard (S) level.

The *DELTA* series tests are reserved for repeating tests with anomalies or doing a variation that is decided during the course of the test series.

The summary of all parameter combinations tested are shown in matrix form in Table 1.

The proposed number of tests is 26. We anticipate that the number and sequence of tests will change as the test program proceeds. The results will be assessed on an ongoing basis to determine if modifications to the test conditions are appropriate. A tentative set of test conditions for each of the 26 tests is proposed in Table 2. This set of conditions is for planning purposes only.

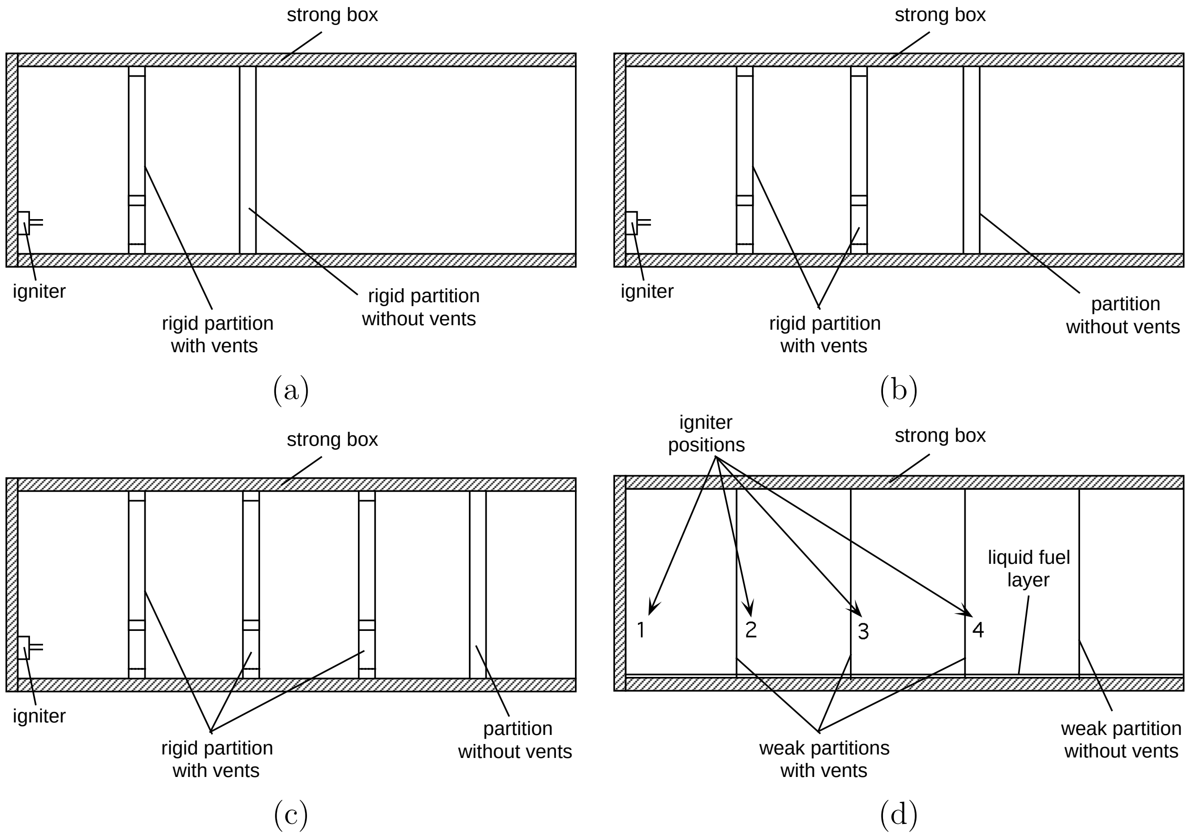

Figure 4: Combustion tests in the 1/4-scale model of the center wing tank. a) to c) Tests with rigid partition connections to top and bottom plates. d) Tests with weak partition connections and variable ignition location.

Table 1: Factorial representation of test parameters

Partition connections	Strong				Strong				Weak			
Number of compartments	1	2	3	4	6				7			
Ignition compartment	5				5	3	2	1	5	3	2	1
Vapor fuel	S	S	S	S	S	S	S	S	L, S, H	S	S	S
Liquid fuel					X				X	X	X	X

Table 2: Proposed Tests

Test	Config.	Ign.	Partitions	Vented	Fuel	Comments
			ALPHA			
A1	All strong	5	none	No	Standard[1]	Baseline
A2	All strong	5	MS	No	Standard	2-compartment
A3	All strong	5	MS,SWB2	No	Standard	3-compartment
A4	All strong	5	MS, SWB2, SWB1	No	Standard	4-compartment
A5	All strong	5	MS with 2-in diam hole	plugged	Standard	Validation test
			BETA			
B1	All strong	5	All[2]	Yes	Standard	Full-up
B2	All strong	3	All[2]	Yes	Standard	Full-up
B3	ll strong	2	All[2]	Yes	Standard	Full-up
B4	All strong	1	All[2]	Yes	Standard	Full-up
B5	All strong	5	All[2]	Yes	Standard w/liquid	Full-up
B6	All strong	6R[3]	All[2]	Yes	Nominal	Ignition location
B7	All strong	1R[3]	All[2]	Yes	Nominal	Ignition location
			GAMMA			
C1	One weak	5	SWB3 weak	Yes	Standard	Model test
C2	All strong	5	All strong with weak access door in SWB2	Yes	Standard	Access door fail
C3	2 weak	5	SWB3, FS weak, weak access door in SWB2	Yes	Standard	Access door fail
C4	All weak	5	All[2]	Yes	Standard	failing partitions
C5	All weak	5	All[2]	Yes	Standard w/liquid	lofting
C6	All weak	2L[3]	All[2]	Yes	Standard w/liquid	lofting
C7	All weak	1	All[2]	Yes	Standard w/liquid	lofting
C8	All weak	2L[3]	All[2]	Yes	Low 1	7% total fuel
C9	All weak	2L[3]	All[2]	Yes	Low 2	6% total fuel
C10	All weak	2L[3]	All[2]	Yes	Standard	Comparison
C11	All weak	2L[3]	All[2]	Yes	Standard w/liquid	Tilt tank, 6 deg
			DELTA			
D1-D3	TBD	TBD	TBD	TBD	TBD	Repeats

Notes:

1 Standard mixture is 1.4% C3H8, 7% H2, 91.6% air

2 All partitions includes: SWB1, MS, SWB2, and both Partial Ribs

3 Ignition location that simulate fuel probes: 1R, far right side next to SWB2 at top; 6R, far right next to SWB1 at top; 2L, Butt line, 2-in from bottom (compensator)

4 Fuel-air mixture

Since the exact TWA-800 ullage conditions (composition, pressure, temperature) at the time of the explosion are difficult to reproduce in outdoor testing with vented tanks, a vapor fuel simulant will be used instead of Jet A vapor. The mixtures to be used in the tests have been chosen to mimic the properties of Jet A and the environmental conditions of the explosion at 14 kft in TWA 800 (see the discussion in Shepherd et al. 1997).

Recent flight testing (Bower 1997) indicates that at the time of the explosion, the temperatures in the air within the CWT ranged between 38 and 54°C (100 and 130°F), and the tank lower surface temperatures ranged between 38 and 60°C (100 and 140°F). Based on these temperatures and measured vapor pressures at Caltech, the fuel-air composition within the tank was in the flammable range with fuel-air mass ratios[1] between 0.040 and 0.072 (mole fractions between .0089 and .015). These estimates are corroborated by the vapor sampling Sagebiel (1997), who measured fuel-air mass ratios between .048 and .054 (mole fractions between 0.010 and 0.012) at 14kft. These values should be compared with a lean limit fuel-air mass ratio of 0.030 (mole fraction of 0.007) and a stoichiometric fuel-air mass ratio of 0.070 (mole fraction of 0.015).

The fuel simulant is blend of hydrogen and propane. Jet A will be used for the fuel liquid in the cases where the liquid fuel layer on the tank floor is simulated. The fuel simulant was chosen on the basis of laboratory testing comparing explosions of Jet A vapor in air at a simulated altitude of 14 kft with propane/hydrogen air mixtures at the pressure altitude of the test site (.83 atm).

Peak pressures for fuel-air mixtures depend primarily on the fuel-air mass ratio ($f = M_{fuel}/M_{air}$). For a vapor fuel this depends purely on the fuel type and the partial pressure of fuel. For a vapor that is produced by and in equilibrium with a liquid, the vapor state is determined by the liquid fuel type, mass loading (mass of fuel per vapor volume) and the temperature.

If the exact composition of the fuel is known, the pressure can be estimated by performing a constant volume calculation. However Jet A is a complex blend of several hundred species, and the actual measured pressures are lower due to heat transfer between the mixture and the confinement walls. Therefore experimental tests must be performed to determine the peak explosion pressure. These tests have been carried out in laboratory scale experiments for Jet A and for the proposed simulant mixtures.

The results of experiments on Jet A at a mass loading of 3 kg/m^3 (appropriate to the TWA 800 CWT conditions) and temperatures between 40 and 60°C are shown in Fig. 5. As shown, the peak pressure rise varies between 2 and 4 bar for initial temperatures between 40 and 60°C. From these measurements and the previous considerations about the temperatures and fuel concentrations measured in the flight test, we have selected the 50°C condition as being representative of TWA tank contents at 14 kft. In terms of Jet A vapor concentration, this case has a fuel-air mass ratio of 0.055 and a fuel mole fraction of 0.012.

[1] In making these computations, we have used Sagebiel's estimated Jet A vapor composition of $C_{9.58}H_{17.2}$, which has an average molar mass of 132 g/mole.

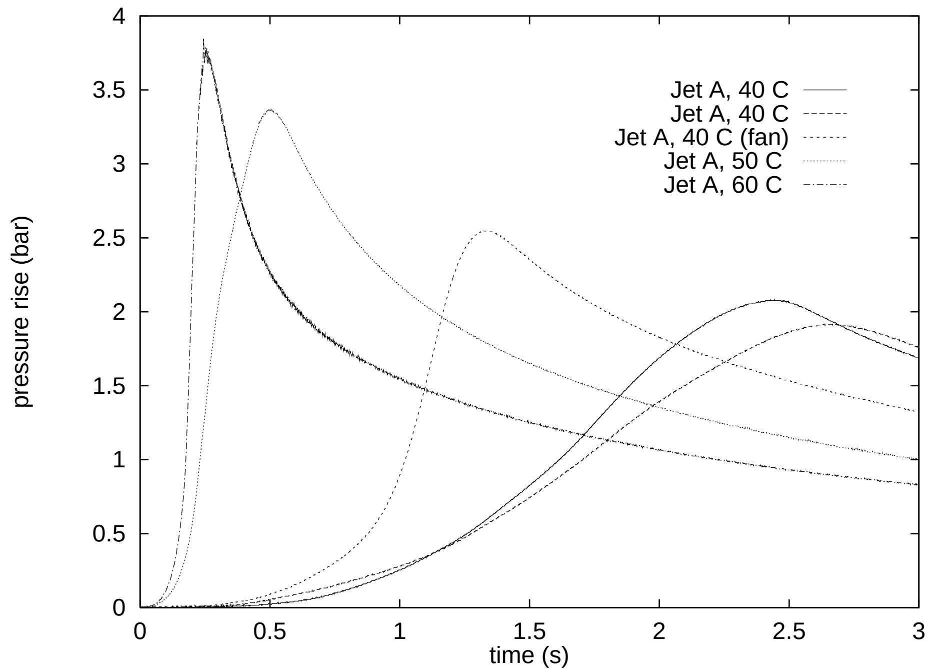

Figure 5: Combustion tests using LAX and El Monte Jet A in the Hyjet Facility (1180 liters), mass loading of 3 kg/m^3, spark ignition, pressure of 0.585 bar (14 kft equivalent).

After a series of experiments, a combination of fuels was found that approximately simulated the pressure-time characteristics of Jet A at 50°C. This combination was tested at a reduced pressure (0.83 bar) to correspond to the higher elevation of the proposed test site. A comparison between the simulant mixture of 1.4% propane, 7% hydrogen and 91.6% air and Jet A is shown in Fig. 6. Analysis of these pressure traces indicates that peak pressure rise is slighty larger for the simulant ($\Delta P_{max} = 3.65$ bar) than for the Jet A ($\Delta P_{max} = 3.36$ bar). However, the simulant has a slightly lower effective burning velocity (as determined by the $\Delta P^{1/3}$ analysis discussed in Shepherd et al. (1997)) of 52 cm/s as compared to 60 cm/s for the Jet A. Note that at 40°C, Jet A has an effective burning velocity of 15 to 18 cm/s and at 60°C, 66 cm/s.

In addition to matching the peak pressure and flame speed, some considerations about the scaling of flame propagation are needed. Previous work on scale models of explosions (Mercx et al. 1995) indicate that small concentrations of oxygen or hydrogen may be required in order to increase the laminar burning velocity and prevent quenching. Separate laboratory experiments on quenching were carried out to show that the simulant mixture did not quench when passing through a 0.5-in diameter hole, the smallest size used to simulate the passageways through the beams, spar and partial ribs. However, quenching was observed with a 0.25-in diameter hole. These tests were carried out in the Hyjet facility, starting the flame in the 27-liter driver vessel which was connected at one end by the orifice to the 1180-liter main vessel.

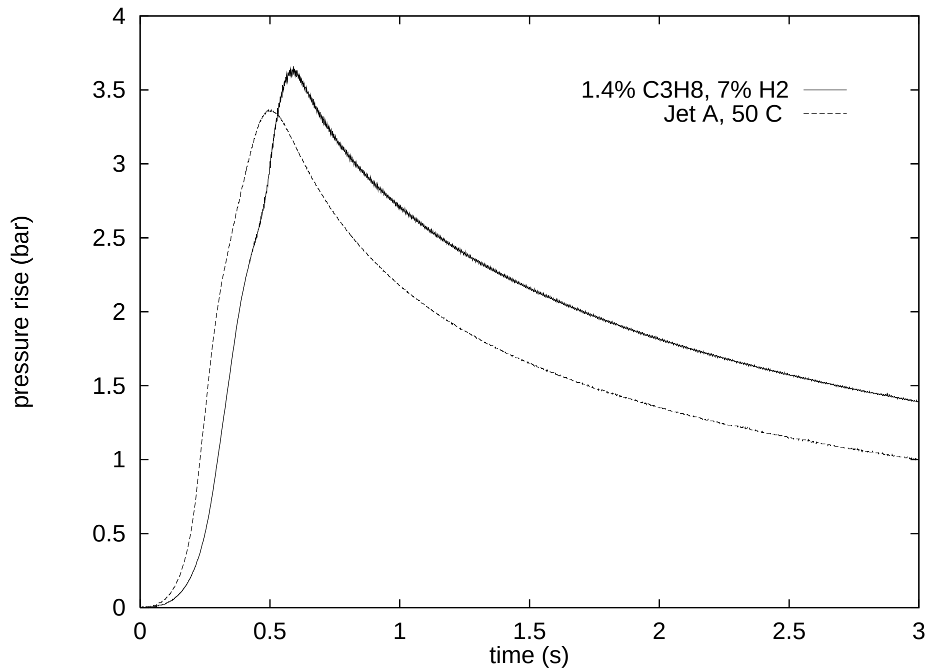

Figure 6: Comparison of combustion tests using LAX Jet A at 50°C mass loading of 3 kg/m^3 and 0.585 bar, and propane/hydrogen (1.4%/7%) at 25°C and 0.83 bar in the Hyjet Facility (1180 liters), both with spark ignition.

5 Scaling issues

A basic geometric scaling of the main CWT dimensions is performed. Passageways between compartments and exterior vents are scaled to achieve similarity in the fluid flow and flame propagation phenomena. The effect of partition motion on the flame propagation is investigated with a scaled mass partition designed to "fail" (disconnect from the top and bottom surfaces of the tank model) at a prescribed pressure difference. Complete similarity of the model is not attempted because that would be overly complex for the purposes of the present study. For example, we do not propose to include the numerous stringers and stiffeners that are used in the actual CWT. Nor do we propose to model the type of structural failure that was observed. We only propose to model those features (partitions, vents, passageways between compartments) that are important to the basic combustion processes that the 1/4-scale tests are intended to address.

5.1 Geometrical scaling

The main geometrical features of the tank will be scaled in proportion to the common scaling factor $\alpha = 1/4$. All lengths L will therefore be smaller in the model by that factor, areas will be reduced by α^2, and volumes by α^3.

$$\mathrm{L}_{\mathrm{model}} = \alpha \mathrm{L} \qquad \mathrm{A}_{\mathrm{model}} = \alpha^2 \mathrm{A} \qquad \mathrm{V}_{\mathrm{model}} = \alpha^3 \mathrm{V} \tag{1}$$

The full-scale CWT has a total volume (excluding the dry bay) of 50.1 m^3. The 1/4-scale model should therefore have a volume of 0.78 m^3 and the same proportions as the actual tank. Our model is a compromise between exact geometric similarity and ease of construction.

As shown in Fig. 1, the actual CWT is rectangular in planform but increases 50% in height in going from the rear spar to the front spar. For simplicity, we have neglected the height variation and approximated the CWT as a rectangular box with a constant height. The nominal dimensions chosen for the box (60-in wide $\times$ 60-in long $\times$ 18-in high) correspond closely to actual 1/4-scale dimensions (63.75-in wide $\times$ 60-in long $\times$ 12-in high at the RS, 19.5-in high at the FS). The location of the model SWBs, MS and FS have been chosen to give the exact scaled volumes of the corresponding compartments in the CWT. The actual volumes, scaled volumes and locations are given in Table 3. The notation is given in the plan view layout, Fig. 7. The locations of the partitions are nominal values that do not account for the partition thickness. Dimensions of the test tank will be adjusted to compensate for the partition thickness.

Table 3: Volume scaling and partition locations.

Compartment	V (actual) (m^3)	V (1/4-scale) (in^3)	Location from RS (scale) (in)
5	6.25	5956.	11.06
6	6.25	5956.	11.06
3	5.55	5291.	20.8
4	5.55	5291.	20.8
2	11.1	14707.	30.6
1	15.4	14707.	44.2
total ullage	50.1	47770.	-
0	15.2	14524.	57.75

As a first approximation, vent and passageways will be scaled geometrically but there are other considerations as discussed below.

5.2 Fuel Amount Considerations

It is estimated that about 50 gal or 150 kg of liquid fuel remained in the bottom of the tank when TWA 800 reached JFK. Determining how much was in the vapor state at the time of the explosion is a complex problem (Shepherd et al. 1997). The tank would have

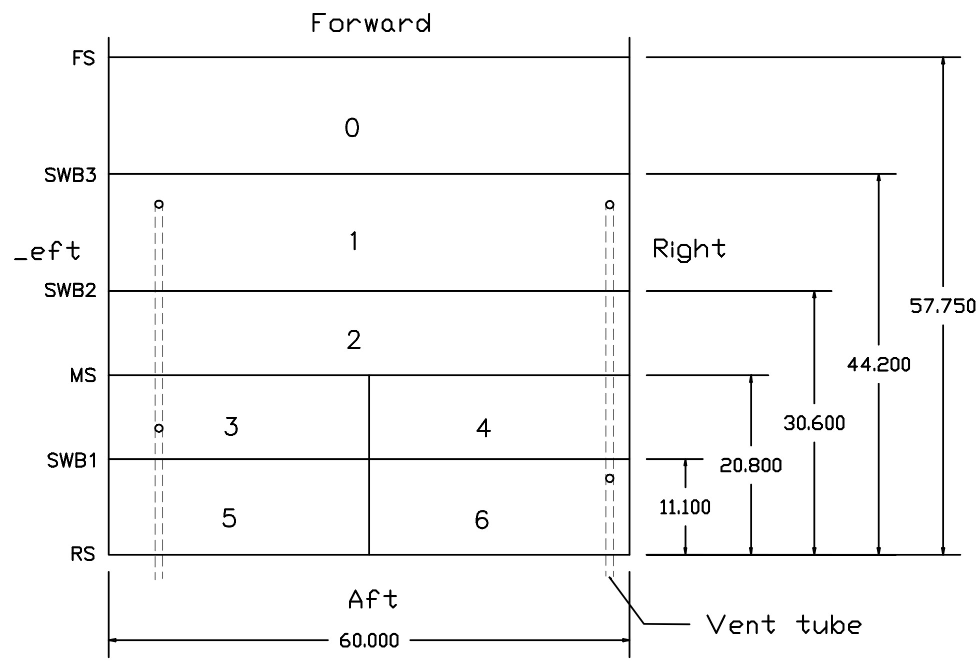

Figure 7: Plan view of 1/4-scale facility showing the compartment labeling, locations of partitions, and vents.

to be filled with appropriate mass of Jet A, differentially heated, and dynamically vented to a pressure of 0.585 bar (corresponding to 14 kft) in order to simulate the events leading up to the explosion. Even if this was done, it is not clear that this is the appropriate method of handling the fuel in a sub-scale model since heat transfer and quenching do not scale directly with the linear scale factor. Requiring the model tank to accommodate a sub-atmospheric pressure also substantially complicates the design.

This is why we propose to use the propane/hydrogen blend as the main fuel vapor rather than creataing the vapor with warm Jet A in these tests. Jet A will be used as the liquid fuel, but it will be cool, i.e., at ambient temperature. The liquid fuel amount is proportional to the volume scale factor, which yields 2.34 kg or about 3 l of liquid for the 1/4-scale model. The vapor fuel amount (8.4% fuel, fuel-air mass ratio of 0.029) was discussed above and is chosen to have a pressure-time history that is close to the nominal Jet A behavior measured in laboratory (Shepherd et al. 1997) experiments. Because hydrogen has very different combustion characteristics than the much heavier hydrocarbons that make up Jet A, it is not possible to directly compare the amount of simulant.

Simulant combustion properties for a range of fuel concentrations are given in Table 4. The computed adiabatic, isochoric, complete combustion (AICC) pressures are given for a range of compositions on a warm day. The effect of ambient temperature on the peak pressure is computed for the nominal composition of interest and presented in Table 5.

Table 4: Fuel-air mass ratios, equivalence ratios, and adiabatic combustion pressure (.83 atm, 23°C) for propane/hydrogen blend in air combustion.

Fuel fraction	Fuel-air mass ratio	Equivalence ratio	C_3H_8	H_2	Air	O_2	N_2	P_{AICC} (bar)
1			0.167	0.833				
0.14	0.051	0.97	0.023	0.117	0.860	0.181	0.679	7.41
0.13	0.047	0.89	0.022	0.108	0.870	0.183	0.687	7.25
0.12	0.043	0.81	0.020	0.100	0.880	0.185	0.695	6.86
0.11	0.039	0.74	0.018	0.092	0.890	0.187	0.703	6.51
0.1	0.035	0.66	0.017	0.083	0.900	0.189	0.711	6.23
0.09	0.031	0.59	0.015	0.075	0.910	0.191	0.719	5.79
0.08	0.027	0.52	0.013	0.067	0.920	0.193	0.727	5.30
0.07	0.023	0.45	0.012	0.058	0.930	0.195	0.735	4.95
0.06	0.020	0.38	0.010	0.050	0.940	0.197	0.743	4.41
			Standard					
0.084	0.029	0.55	0.014	0.07	0.916	0.192	0.724	5.6

Table 5: Effect of initial temperature on AICC pressure at an initial pressure of .83 atm for the nominal propane/hydrogen blend in air combustion.

T (°C)	P_{AICC} (bar)
-15	6.32
-10	6.22
-5	6.11
0	6.01
5	5.91
10	5.82
15	5.72
20	5.64
25	5.55
30	5.47

5.3 Passageways and Vents

Vented explosion analyses and experiments have identified a simple scaling parameter for venting during combustion:

$$\frac{C_d A}{V^{2/3}} \frac{S_u}{c_o} (\frac{\rho_u}{\rho_b} - 1) \tag{2}$$

This is for a compartment of volume V vented through an area A with loss coefficient C_d, laminar burning velocity S_u, initial sound speed c_o, densities ρ_u for unburned gas and ρ_b for burned gas. Note that $V^{2/3}$ corresponds to the total compartment surface area as long as the aspect ratio is not large. The thermophysical parameters are all evaluated for the initial conditions in the tank, i.e., before any compression or venting of the contents has occurred.

After the gas is burned, there will be venting of the burned gas through the vent stringers and any openings created by failure of the tank pressure boundary, e.g., SBW3 and SWB2 access door. This is controlled by the parameter $A/V^{2/3}$, again indicating that geometric scaling of the vent areas is appropriate.

The vent scaling indicates that if we match the thermophysical properties, i.e., use the same fuel and initial conditions in the scale model as the actual tank, then the vent area should be scaled with the geometric-area scaling factor α^2. Venting occurs both between compartments (through the passageways) and from the tank to the atmosphere (through the vent stringers). Each case is discussed separately below.

5.3.1 Passageways

The passageways between the compartments will be simulated by drilling or cutting holes in the partitions in the scaled locations. The size of each hole will be such that the scaled area of the corresponding passageways is reproduced. The details of the actual penetrations and areas have been provided by Boeing and are attached in the Appendix. The scaled and actual areas between each compartment are given in Table 6.

5.3.2 Vent Stringers

There are two vent stringers. Each stringer is approximately 100 ft long and has a cross section of 2.75-in by 4.75 (nominal) for a combined area of 26 in^2. One stringer (left) is connected to compartments 3 and 1, the other (right) to 6 and 1. The stringers in the rear compartments are connected to the tank through a short length (8-in long) of 2-in OD tube. Compartment 1 is connected to the vent stringers by 3.5-in OD tubes.

The scaled area of both vents combined is 1.68 in^2 — not accounting for the flow resistance of the 100-ft long stringer. The venting in the 1/4-scale model will consist of 1-in diam openings in the top plate in compartments 5 and 6. These will be connected through tubing to “tees” that connect on one side to 1-in diameter lines connecting to 1-in diameter openings in the top of compartment 1 and on the other side to 1-in diameter lines connected to the atmosphere through a restricting orifice to simulate the 100-ft length of vent stringer.

Table 6: Actual and scaled areas between compartments of the center wing tank and 1/4-scale model.

Partition	Flow path	Actual Flow Area (in^2)	Scaled Flow Area (in^2)
Aft Partial rib	5-6	108.3	6.8
Forward Partial rib 2	3-4	44.5	2.8
SWB1 (L)	5-3	20.65	1.29
SWB1 (R)	6-4	26.2	1.64
MS (L)	3-2	25.2	1.58
MS (R)	4-2	24.2	1.51
SWB2	2-1	34.4	2.15
FS	0-FCB	316	19.75

A simple analysis of subsonic and choked flow at the stringer exit indicates that a restriction of 0.45-in diameter would adequately represent the effect of both the flow resistance of the stringer and the flow rate reduction due to choking (high-speed flow).

5.4 Quenching

It has been suggested (Mercx et al. 1995) that it is important to model the possible effects of flame quenching in sub-scale gas explosion experiments. Several techniques are suggested for this and the simplest is to increase the flame speed as follows

$$S_{u,model} = S_{u,actual}\alpha^{-1/4} \quad (3)$$

In the present case, this corresponds to increasing the flame speed by a factor of 1.4. Since we are already treating the fuel amount as uncertain and simply varying it as a parametric quantity, factors of 1.4 in the flame speed will not be resolved anyway. It will only be important to make sure that the passageways are larger than the quenching diameter for that mixture. The quenching diameters for the propane/hydrogen-air mixtures has been measured in laboratory experiments at Caltech and is less than 0.5-in. One test will be carried out with a single large diameter (2-in) opening of equal area to the distributed openings in the MS to examine this issue.

5.5 Structural

5.5.1 Failure

The essential idea is to match the pressure difference between compartments at which failure is expected to occur in full scale. Failure pressure differentials for the various beams and spars have been estimated by Boeing and are given in Table 7. The first value

ΔP_1 is the pressure differential required for failure if all adjacent panels are intact and the second value ΔP_2 is that needed for failure when an adjacent beam or spar is already failed. There are access doors in SWB1, MS and SWB2 which are also expected to fail when the pressure differential reaches about 20 psi. Failure pressures for the various access doors were estimated by Boeing and are given in Table 8.

The accident sequence investigation indicates that FS, SWB3, and the manufacturing access panel in SWB2 all completely failed at the earliest stage of the process. SWB2, MS, SWB1, RS and the partial ribs are believed to have remained intact until the aircraft completely broke up.

The accident sequence postulated is a progressive failure of first SWB3 (due to the pressure differential resulting from the explosion), the rotation of SWB3 into the FS and subsequent failure of the FS. The motion of the FS is inhibited by the mass of the two potable water bottles attached on the Forward Cargo Bay side. The rapid decompression of the CWT tank resulting from FS and SWB3 failure combined with the in-plane shear loads on SBW2 apparently resulted in the failure of the access panel in SWB2.

Based on the estimated failure pressures and the accident sequence analysis, a nominal failure pressure differential of 20 psi has been selected for the partitions representing spanwise beams 2 and 3, and 7 psi for the front spar. Instead of modeling the failure of the access panel only in SWB2, for simplicity we will allow the entire partition to fail. Failure in the 1/4-scale model means that the connection between the partitions and the rigid tank structure will shear at this pressure differential. Based on a panel area of 1080 in^2 and a pressure differential of 20 psi, this will occur at a total shear load of 21,600 lb. Distributed among 12 shear pins or fasteners (5 on the top, 5 on the bottom and 2 on each side), each pin must fail with a shear load of 1800 lb. In the case of the front spar, the failure shear load will be 630 lb.

Table 7: Estimate pressure differentials required to fail spanwise beams and spars in the CWT. Information provided by Boeing in briefing of Feb. 6, 1997.

Structure	ΔP_1 (psi)	ΔP_2 (psi)
rear spar	55	
partial ribs	48	
spanwise beam 1	48	32
midspar	33	11
spanwise beam 2	21	19.5
spanwise beam 3	21	16
front spar	35	7

Table 8: Failure pressure differentials of maintenance and manufacturing doors. Information provided by Boeing in letter of May 30, 1997.

	SWB3		SWB2		MS	SWB1
	MFG (psi)	Maint. (psi)	MFG (psi)	Maint. (psi)	Maint. (psi)	Maint. (psi)
Yield	35†	21* (fwd) 29† (aft)	35†	21‡ (fwd & aft)	21‡ (fwd & aft)	21‡ (fwd) 12† (aft)
Ultimate	45†	22* (fwd) 31† (aft)	45†	22* (fwd) 24‡ (aft)	23* (fwd) 24‡ (aft)	24‡ (fwd) 13* (aft)
Fail propagation§	-	-	12†	-	-	-

* Joint ultimate tension strength.
† Joint yield and ultimate shear strength.
‡ Flat honeycomb sandwich structure strength.
§ Residual strength after some fasteners are failed in shear.

5.5.2 Motion

The essential idea is to match the scaled acceleration of the panels that have failed and are being ejected from the tank. The acceleration can be computed from Newton's law. Neglecting the effects of aerodynamic drag and gravity, we have

$$\frac{\mathrm{d}^2X}{\mathrm{d}t^2} = \frac{\Delta PA}{M} \tag{4}$$

Assuming that length and time scale directly as the linear scale factor α, which is the correct scaling if the flame and sound speeds are the same in partial and full scale, then the mass of the panels should be scaled with the volume factor α^3. The mass of FS and SWB3 were supplied by Boeing and the mass of SWB2, MS and SWB1 were scaled in proportion to the height of these partitions relative to SWB3. The values of actual or estimated mass and scaled mass of the partitions are given in Table 9. Since the variation in height of the CWT is not simulated in the 1/4-scale model, all of the beams and spars of similar construction have the same scaled mass.

The potable water bottles mounted on the front of the FS have a significant amount of inertia and will be modeled by an equivalent mass located at the scaled center-of-gravity in the 1/4-scale model. The rear spar, upper and lower wing panels and side-of-body ribs are modeled as rigid structures. The structural analysis indicates that these portions of the tanks are quite stiff and strong (RS, upper and lower wing skin) and the sequencing analysis indicates that they did not fail during the initial explosion event. The side of body ribs form the side of the wing inner fuel tanks which were full. This provides an enormous amount of confining inertia and the sequence analysis indicates that they did not fail during the initial explosion but only later after the airplane structure catastrophically failed.

Table 9: Actual or estimated panel mass and scaled value for 1/4-scale facility

Object	Actual Mass (lb)	1/4-scale mass (lb)
Potable water bottles (2)	897 ea	14 ea
FS	710	11
SWB3	488	7.1
SWB2	454	7.1
MS	415	7.1
SWB1	372	7.1

6 Diagnostic measurements

Diagnostic instrumentation will be used to characterize the initial state of the tank and the development of the explosion. The purposes of this instrumentation will be to characterize the following aspects of the experiment:

1. Combustion:
    (a) Pressure at selected points within each compartment
    (b) Temperature at selected points within each compartment
    (c) Movement of the flame
2. Partition failure:
    (a) Time of partition failure
    (b) Motion of the partition
3. Fuel lofting:
    (a) Development of fuel aerosol and combustion
    (b) External blast pressure measurements

The top plate of the tank will be instrumented as shown in Fig. 2. A number of diagnostic gauges will be located in each compartment, as shown in more detail in Fig. 8. Each gauge will be mounted in a fixture that threads into the top plate. These fixtures will all be identical to enable rapid replacement or substitution of the gauges.

6.1 Pressure

Two types of pressure measurements will be made: slow, quasi-static measurements of the pressures developed by the flame, and fast pressure measurements of decompression and

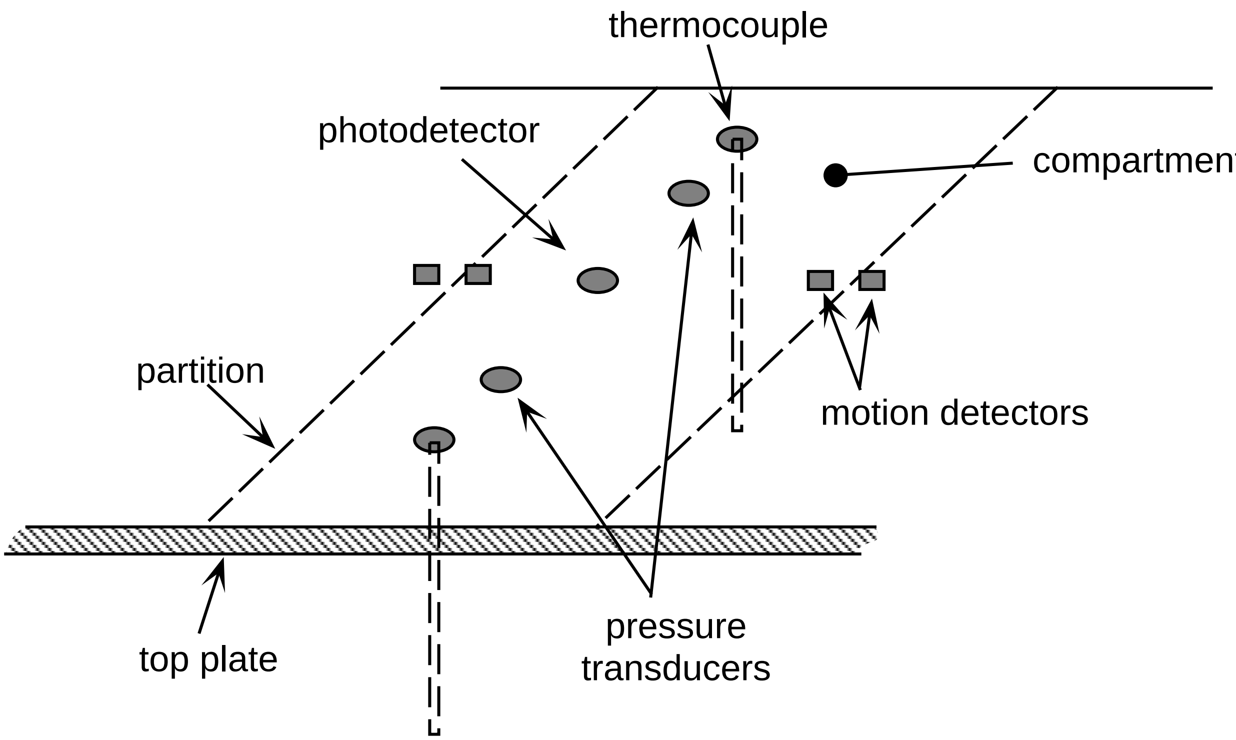

Figure 8: Positioning of the gauges on the top plate of the tank in one compartment.

blast-wave phenomena. Quasi-static pressure will be measured using Endevco pressure gauges protected by sintered metal filters, and fast pressure changes will be measured with Piezotronic PCB113A21 gauges. One Endevco gauge will be placed in each compartment. These gauges are strain-gauge bridges and require an excitation voltage of 10 V and have a nominal output of 100 mV at the maximum pressure of 250 psi. We expect pressures of 50 to 100 psi in these experiments.

Two PCB gauges will be placed in each compartment and three will be placed outside the tank for blast wave measurements. The PCB gauges require an ICP power supply and voltage follower and produce an analog output. The sensitivity of these gauges is 27 mV/psi, so it is possible that signal levels up to 1 V might be produced, however the blast waves will be at a much lower level, less than 5 psi, so that signals less than 150 mv are expected. If standard power supplies are used, then we expect to only record the rapid transients associated with depressurization. It will therefore be necessary to have appropriate fiducials or timing information in order to plot these traces together with rest of the data recorded at slower speeds. Another possibility is to alter the power supply time constant (up to 100 s), in order to capture both combustion and depressurization. This is more problematic due to the strong thermal response of unprotected piezoelectric gauges.

6.2 Temperature

The flame time-of-arrival and an estimate of flame temperatures will be obtained using .005-in diam type-K thermocouples with exposed junctions in each compartment. The thermocouples are mounted from the top plate and extend to the center of the compartment. There will be two thermocouples in each compartment. The maximum signal output will about 20 (500 C) to 40 mV (1000 C). The air and fuel temperatures will be recorded before each test using these thermocouples and a hand-held electronic readout.

6.3 Flame Speed

If the flame is sufficiently luminous, the film and video cameras will be the primary means of determining flame speed. Secondary measurements will be made with the thermocouples and photodetectors. The photodiodes will produce a low level (10 to 100 mV) analog output.

6.4 Partition motion

In experiments with aluminum partitions, partition motion will be observed by two means. The simplest is through the film and video records made during the test. A secondary method is to place break wires or switches on one side of the partition to electrically detect failure of the joint. These switches will be connected to a debouncing circuit and produce a TTL level output voltage that will be recorded by the instrumentation circuit. We will only place switches to detect the forward motion of the partitions corresponding to the FS, SWB3, and SWB2. There will be four switches per partition, one at each corner.

6.5 Visualization

The flame propagation process will be recorded using 400–500 frame-per-second pin-register type cameras located around the tank as shown in Fig. 9. Four cameras are located at tank level in front of the transparent side panels of the tank. These will be used to visualize the motion of the flame, the partitions and lofting of the liquid fuel.

Two additional cameras located above and in front of the tank provide a downward diagonal view of the flame propagation into the next-to-last compartment adjacent the dry bay. Four scientific-quality video cameras will duplicate the film camera coverage for quick-look results. A video camera and a motor-drive SLR camera sequenced with the ignition will be placed a large distance from the tank for an overall view.

The diagnostic gauges and visualization instrumentation to be used in the tests are summarized in Table 10.

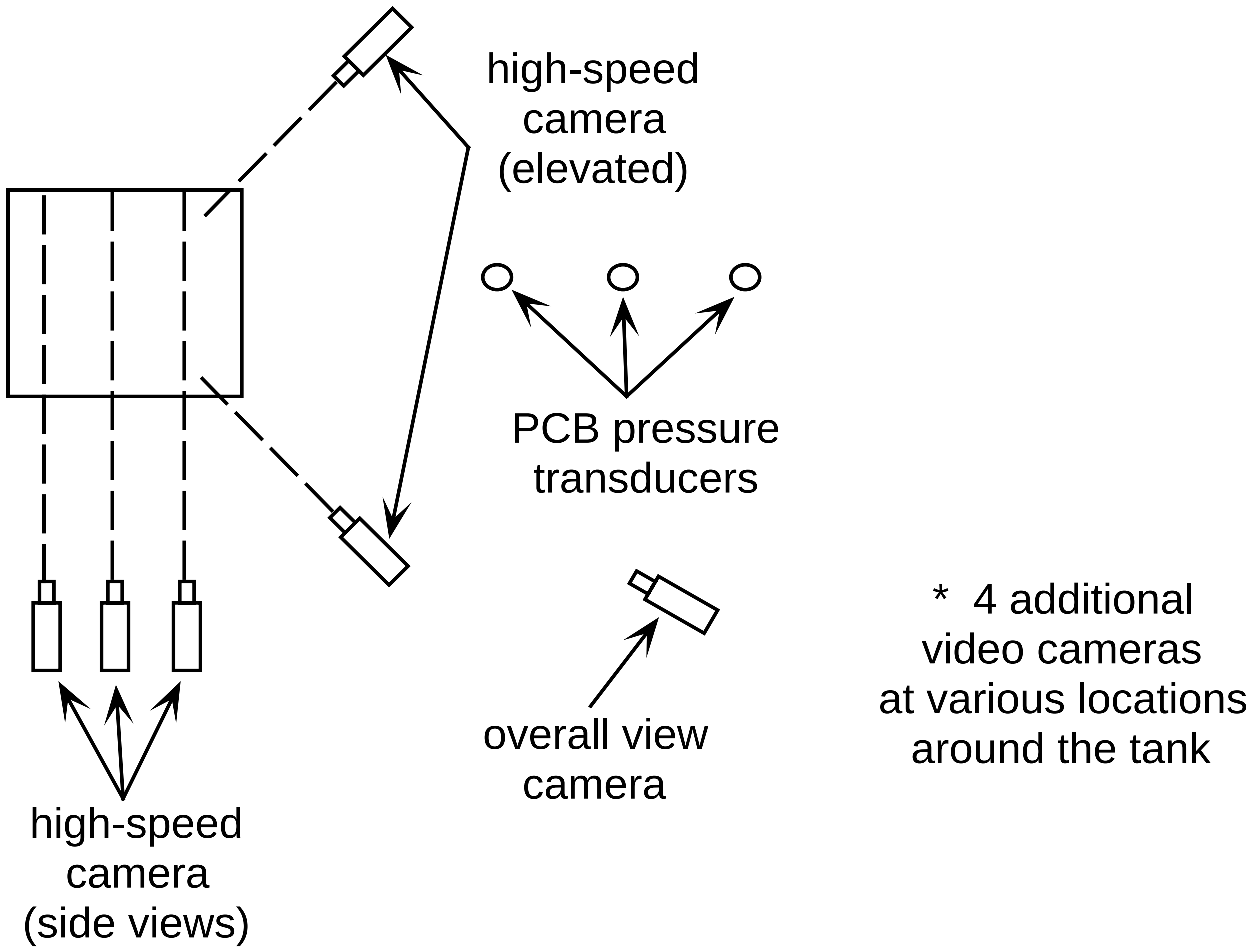

Figure 9: Conceptual design for location of cameras used in visualization of the flame propagation and partition motion.

6.6 Data Acquisition

The data acquisition should have two types of channels, fast and slow. The burn is expected to take about 1 s total (based on the laboratory experiments at Caltech) and the subsequent venting events may last 2-3 s. All instruments except the piezoelectric gauges (PCBs) will be connected to the slower channels. A preliminary estimate of sampling speed is 1 kHz for the slower channels and 250 kHz for the faster channels. A total of 46 slow channels and 13 fast channels is anticipated. Room for expansion up to 20% should be planned.

6.7 Fuel Handling

The fuel will be injected remotely from reservoirs attached to the tank prior to the test with quick-release fittings. Vacuum feed will be used to move the liquid from the

Table 10: Summary of diagnostic instrumentation

Instrument	Number
Pressure, slow (Endevco)	7
Pressure, fast (Piezotronics PCB)	10
Blast gauges (fast) (Piezotronics PCB)	3
Light, (photodiode)	7
Temperature, (thermocouple)	14
Motion detectors	18
Film (400–500 fps) exterior	6
Video exterior (scientific quality)	4
35 mm timed SLR	1

reservoir into the tank. Solenoid valves will be used for the remote control and timing of the injection process. The control signals needed are 12 VDC-level voltages for the solid-state relays to actuate the solenoids. Caltech will supply the 12 VDC power supply and control panel with switches. Semaphores will be mounted on the valves to determine the actuation and position by remote video monitor.

The propane/hydrogen mixture will be obtained from premixed supply in a bottle obtained from a commercial supplier. A two-stage regulator will be used to reduce the bottle pressure of about 500 psi to 7 psi used for filling. The tank will first be evacuated to a pressure than is 91.6% of ambient before filling with gas and then mixing. The gas is introduced through an orifice in a pipe fitting mounted in each of the 6 bays. The orifice for the larger bays is twice the area of the smaller bays. After the gas is filled it is circulated by a bellows pump for about 15 minutes to insure uniformity.

The liquid layer will be injected by sucking a measured quantity of fuel from a reservoir into the tank through four ports mounted along the centerline in the bottom plate of the tank. The suction will be created by slightly evacuating the tank. This is done prior to loading the vapor fuel. For most cases, the tank will be level and for at least one case, a rearward tilt (simulating climb) will be deliberately introduced.

6.8 Ignition System

Ignition will be carried out by rapidly heating the filament of a type 1156 taillight bulb (12 VDC) with the discharge from a fireset containing a 1400 μF capacitor charged to 150 VDC. The glass bulb is deliberately broken and the base of the lamp mounted into a standard holder connected with stiff wires through an insulating feedthrough to the firing line. The function and timing of this igniter has been determined in separate laboratory ignition tests. A backup igniter is provided in case the primary igniter fails.

6.9 Safety Considerations

In all cases, the fuel will simply deflagrate or burn and a very limited blast and fragment effect is expected. However, for the purposes of safety evaluation, the net explosive weight can be bounded by estimating the equivalent mass of HE as 15 lbs. This corresponds to 3 kg of fuel with an energy values of 43 MJ/kg and an explosive equivalent of 4 MJ/kg. But under no circumstances will the combustion event be equivalent to detonating that amount of HE.

In the "strong" configurations, no prompt venting or fragment production is expected. In the "weak" configurations, venting will occur and a blast wave will be produced.

7 Caltech, Contractor and NTSB Roles

Caltech is the lead technical organization and has developed this test plan in concert with the NTSB. The Contractor will provide the test site, test implementation, data acquisition, and imaging. The Contractor will provide a detailed proposal indicating how each of elements will be implemented, a schedule and a detailed budget. Caltech, the Contractor and the NTSB will work together in this test campaign. Caltech personnel and NTSB observers will be present during the actual testing. The NTSB is responsible for providing all funding for this project.

7.1 Caltech Responsibilities

Caltech will supply the test tank (including partitions and plastic sides), instruments, fuel supply system, gas sampling system and ignition system.

Caltech will ensure that the instruments function correctly and will work with the Contractor to make sure that the electrical interfaces are properly defined.

Caltech will supply personnel to work with the Contractor in setting up the test, and in installing and checking out instruments, fuel distribution and ignition systems.

Caltech and the NTSB will work together to provide a set of test conditions (fuel type and amount, ignition location, measurement details) prior to the start of testing. This test matrix will be used by the Contractor to plan the tests.

Caltech will work with the Contractor to develop the test procedures and safety assessments. Changes in the test conditions may be requested by Caltech during the test series depending on the outcome of the ongoing testing. Changes in the test conditions or procedures during the test should be made in consultation between the Contractor, Caltech, and the NTSB.

7.2 Contractor Responsibilities

The Contractor will supply the test site, data-acquisition system, photographic systems, control system, and the personnel to operate the test site and related equipment. The data acquisition system includes the cabling and connections from the 1/4-scale tank to the data-acquisition location, signal-conditioning equipment, digitizers, computer and necessary peripherals.

The Contractor will be responsible for all test site preparations, range safety and administrative control over the test site.

The Contractor will be responsible for executing each test and ensuring that the data are properly obtained.

The Contractor will provide preliminary data plots after each test and copies of the raw data in digital form (e.g., zip drive) to Caltech and NTSB as soon as possible after each test. All necessary information such as calibration factors, format, and channel IDs will be provided so that Caltech can process the data. The data will be considered as proprietary and access should be limited to those personnel directly involved in the test.

The Contractor will be responsible for processing the film, providing prints and video format results to Caltech.

7.3 Reporting

Caltech will be responsible for preparing interim and final reports.

The Contractor will be responsible for providing a data report within 30 days after the end of the campaign. This report will summarize all the instrument and data acquisition parameters for each test, and provide hardcopy plots of each instrument output.

Caltech will provide interim reports as the campaign progresses. These will be in the form of letter reports after each phase of the testing is complete. Caltech will provide a final report within 90 days after the end of testing.

7.4 Information Release

No information regarding these tests or this request for proposal should be released to the public. All requests for information should be referred to the NTSB.

8 Schedule

A proposed schedule for testing is given in Fig. 10. The first 8 weeks will be used to prepare procedures, construct instrumentation, design and build the 1/4-scale tank, and to prepare the test site. The next 8 weeks will be used for test implementation. The data report will be published within 4 weeks of the completion of testing and the analysis report will be published within 12 weeks of the completion of testing.

9 Budget

Caltech and the Contractor will develop detailed budgets for this project and submit them to the NTSB.

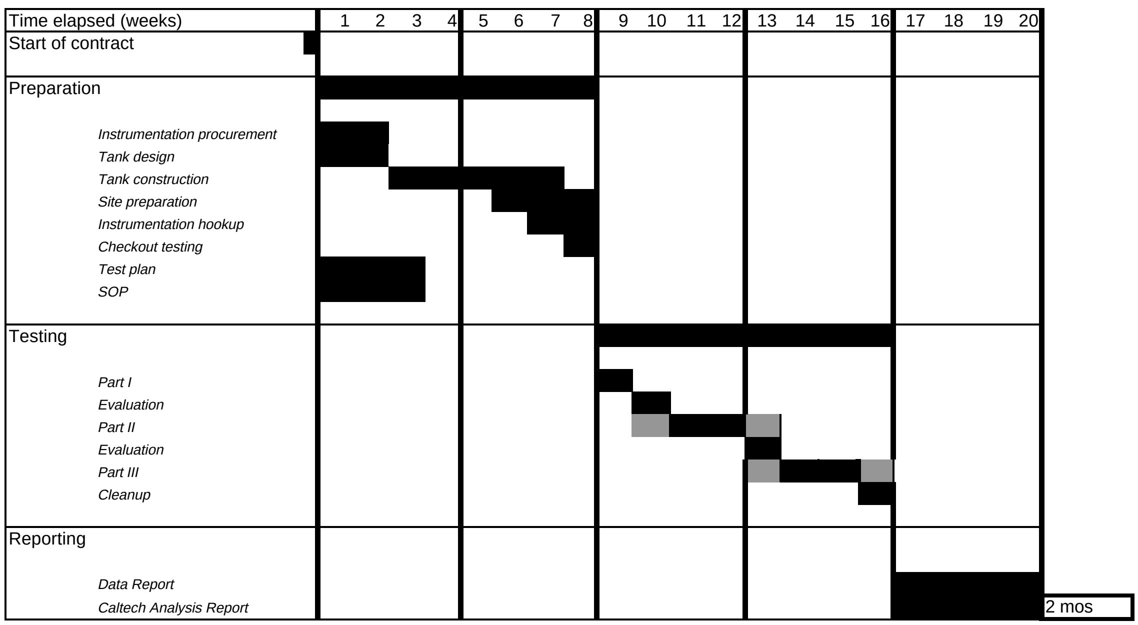

Figure 10: Proposed schedule for 1/4-scale test program.

10 Technical Contacts

The responsible parties are:

Caltech:

J. E. Shepherd
Aeronautics, f105-50
Caltech
Pasadena, CA 91125
TEL 626 395 3283, FAX 626 449 2677, e-mail: jeshep@galcit.caltech.edu

NTSB:

M. M. Birky
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington DC 20594
TEL 202 314 6503, FAX 202 314 6598, e-mail: birkym@ntsb.gov

References

Bower, D. (1997, November). Flight Test Chairman's Factual Report. Accident DCA-96-MA-070, NTSB Docket SA-516, Exhibit 23, National Transportation Safety Board.

Mercx, W. P. M., D. M. Johnson, and J. Puttock (1995). Validation of scaling techniques for experimental vapor cloud explosions. *Process Safety Progress 14*(2), 120–130.

Sagebiel, J. C. (1997, November). Sampling and analysis of vapors from the center wing tank of a test Boeing 747-100 aircraft. Final report for NTSB, Desert Research Institute.

Shepherd, J. E., J. C. Krok, and J. J. Lee (1997, June). Jet A explosion experiments: Laboratory testing. Explosion Dynamics Laboratory Report FM97-5, California Institute of Technology.

A CWT Geometry

The geometry of the center wing tank is described in this appendix. This description is based on proprietary information provided by Boeing in a series of letters and faxes to Caltech during the period January 1997 to June 1997. The location of the CWT within the 747 is shown in Fig. 11. The CWT is located within the fuselage between the wings. Directly in front of the CWT is the forward cargo bay. Directly behind the CWT, the inner landing gear are stowed. Above the CWT is the cabin floor and directly beneath the CWT are the air-cycle machines (ACM) which condition the air that is used to pressurize the cabin. Two perspective views with nominal dimensions are shown in Fig. 12. The tank is framed by the structural members of the wings (beams and spars), the upper and lower wing surfaces and the side-of-body ribs that separate the CWT from the inner wing tanks, see Fig. 13. With the exception of two vent stringers that connect the CWT to vents at the wing tips, the wet bays of the tank are sealed off (see Fig. 14) from the outside atmosphere.

The tank is divided into compartments by three spanwise beams (SWBs) and the midspar. A side view indicating the location of these partitions is shown in Fig. 15. In the 747-100, the portion of the tank that contains fuel is between SWB3 and the RS. The compartment between SWB3 and the FS is a dry bay. It communicates with the exterior of the airplane (see Fig. 16) through two openings so that it is at ambient pressure during flight. Attached to the front spar are two potable water bottles (Fig. 17) which have a substantial inertia that plays a role in the structural failure sequence.

There are a number of openings (passageways) and access doors in the partitions between the compartments. The locations and dimensions are given in Figs. 18 to 21. Details about the passageway dimensions and areas are given in Tables 11 to 13. The doors are fastened onto the beams and spars in normal operation and do not serve as passageways. There are penetrations in the rear spar for fuel pumps but these are not shown in Fig. 22. Along the centerline of the tank between the RS and MS, there is a partial rib. Details on the flow passageways and other penetrations are given in Figs. 23 and 24, and also Table 14.

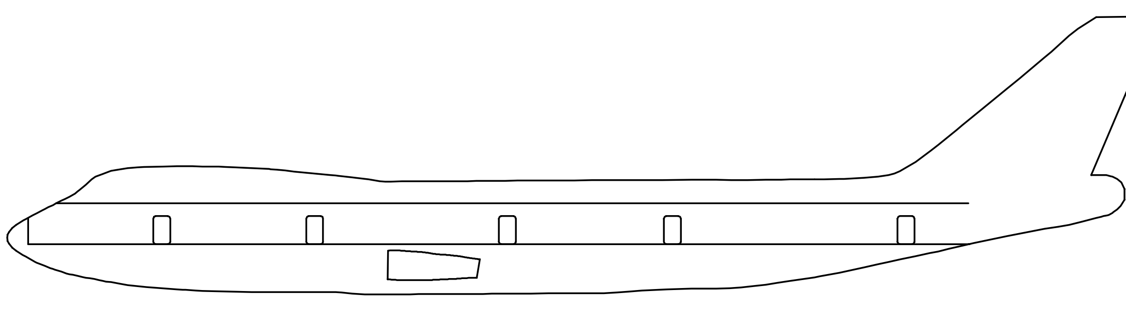

Figure 11: Schematic of 747-100 showing the location of Center Wing Tank.

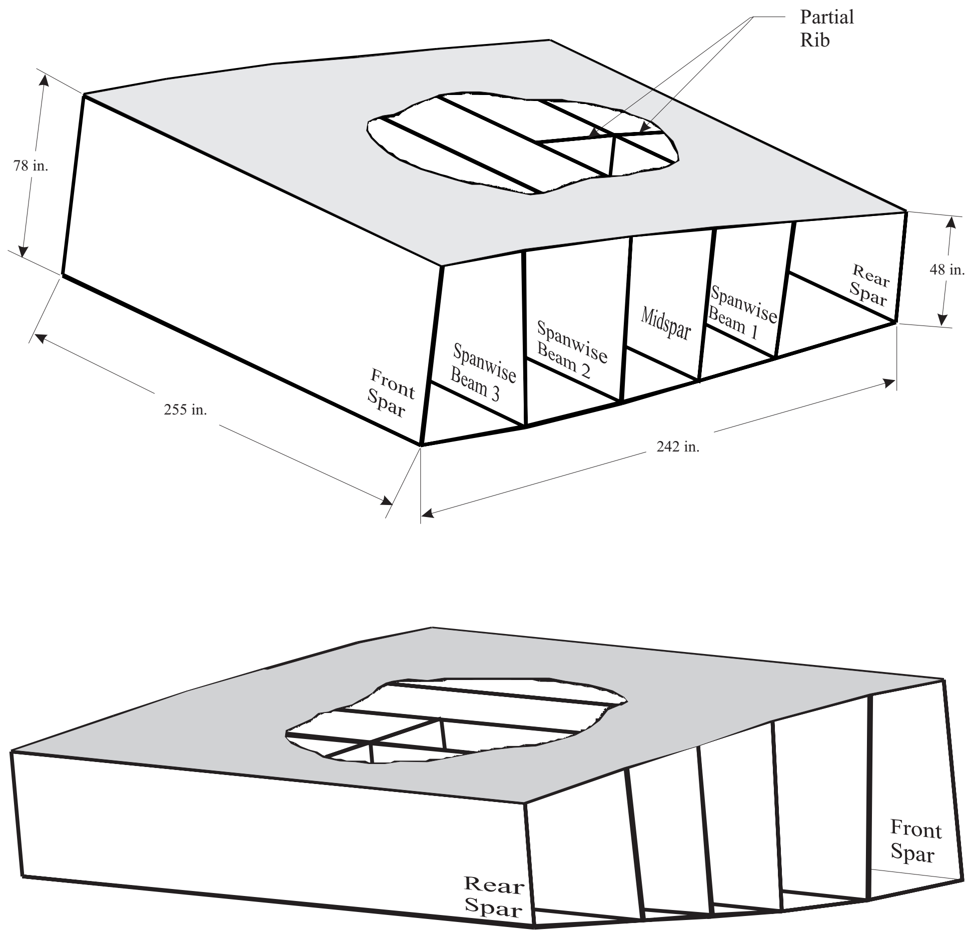

Figure 12: Perspective views of Center Wing Tank.

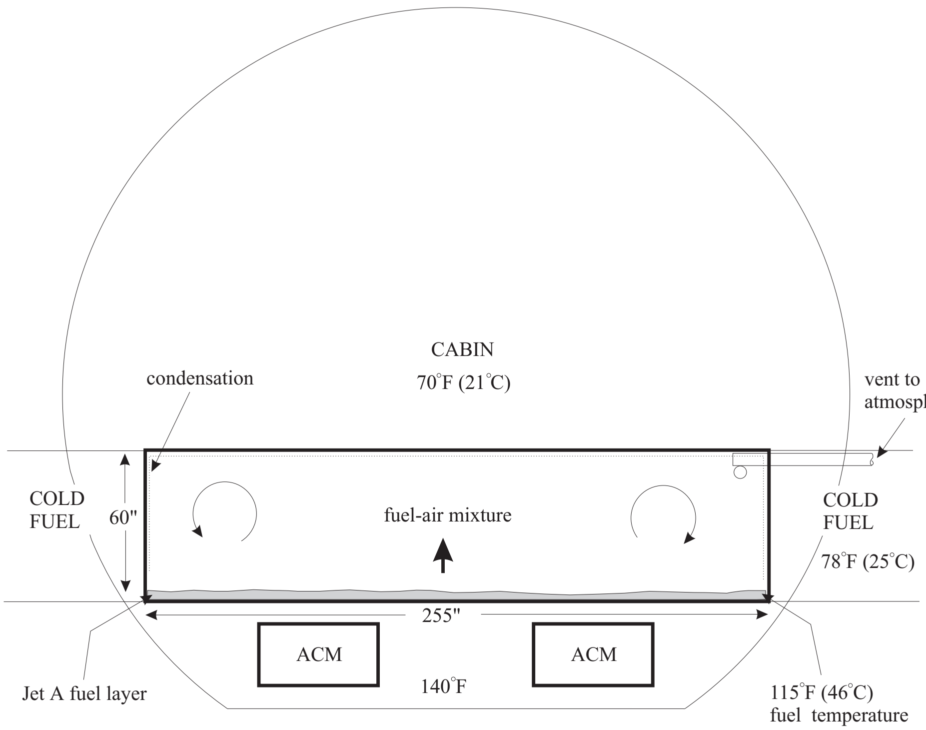

Figure 13: Location of the CWT within the fuselage, cross sectional view showing ACMs.

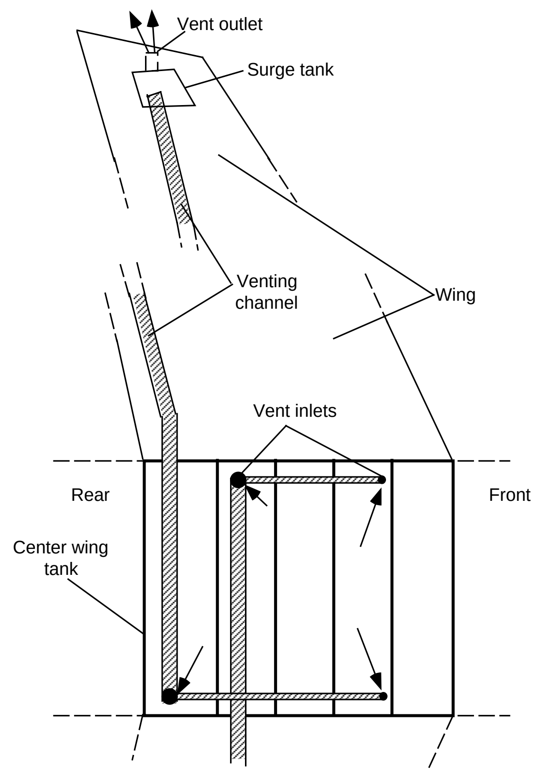

Figure 14: Schematic of 747-100 CWT venting arrangement.

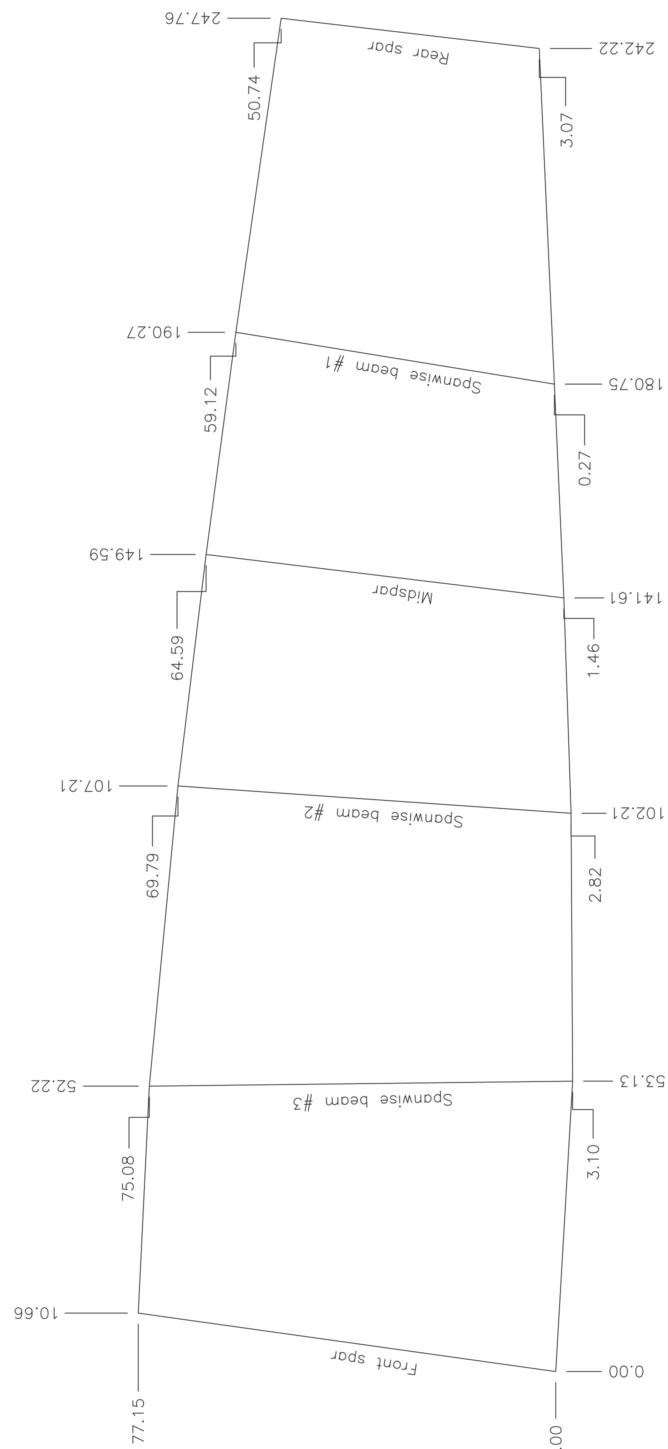

Figure 15: Side view of CWT. Actual dimensions.

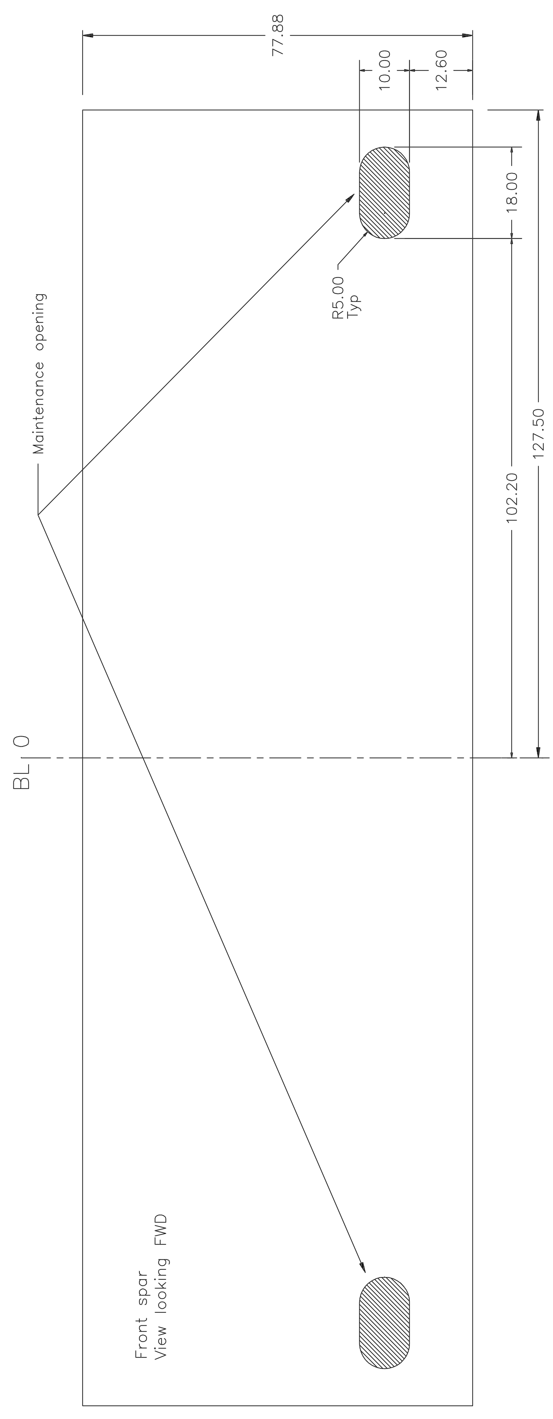

Figure 16: Front spar (FS) of CWT. Actual dimensions.

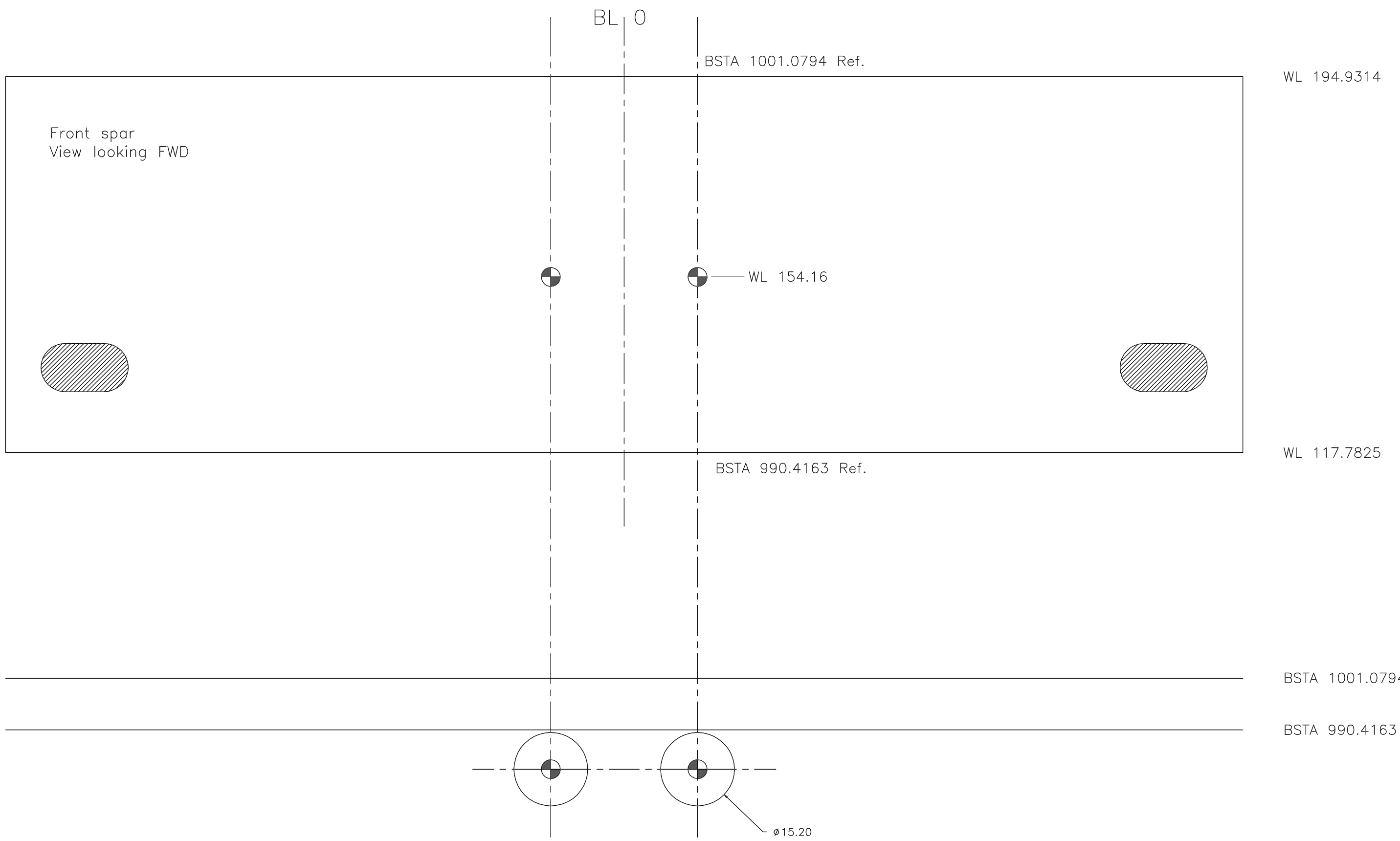

Figure 17: Location of water bottles on Front spar (FS) of CWT. Actual dimensions.

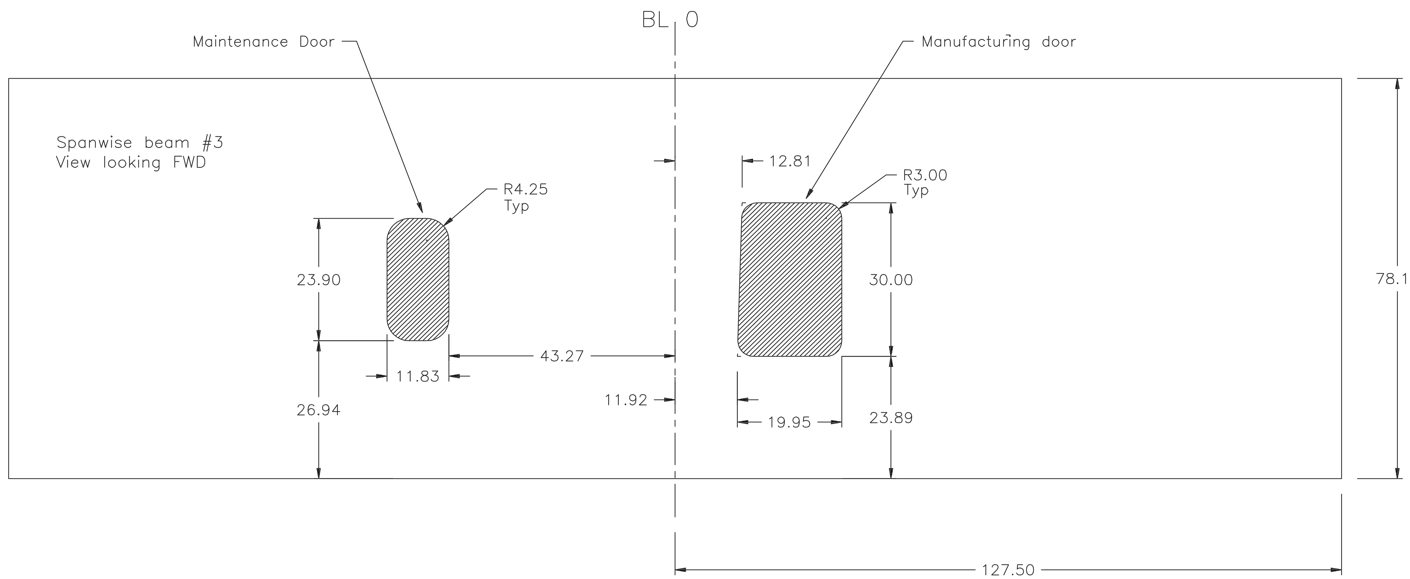

Figure 18: Spanwise beam 3 (SWB3) of CWT. Actual dimensions.

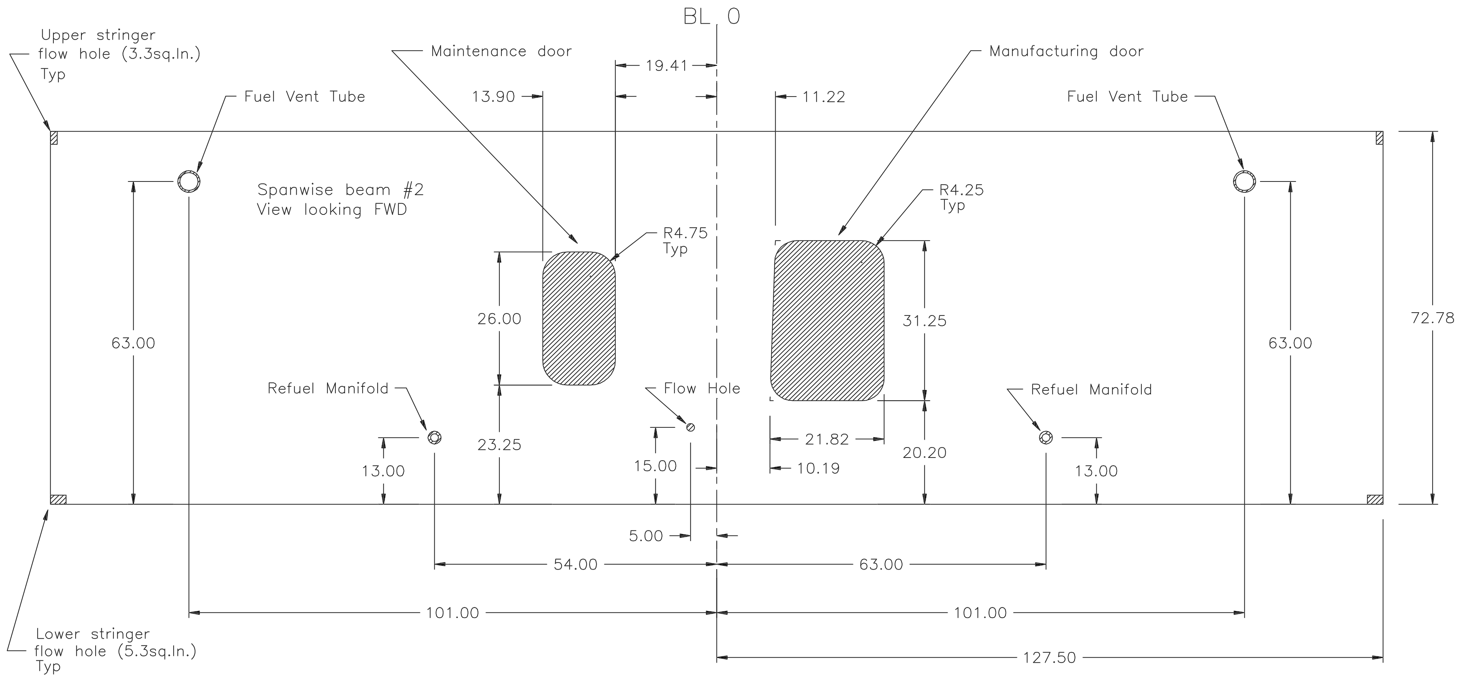

Figure 19: Spanwise beam 2 (SWB2) of CWT. Actual dimensions.

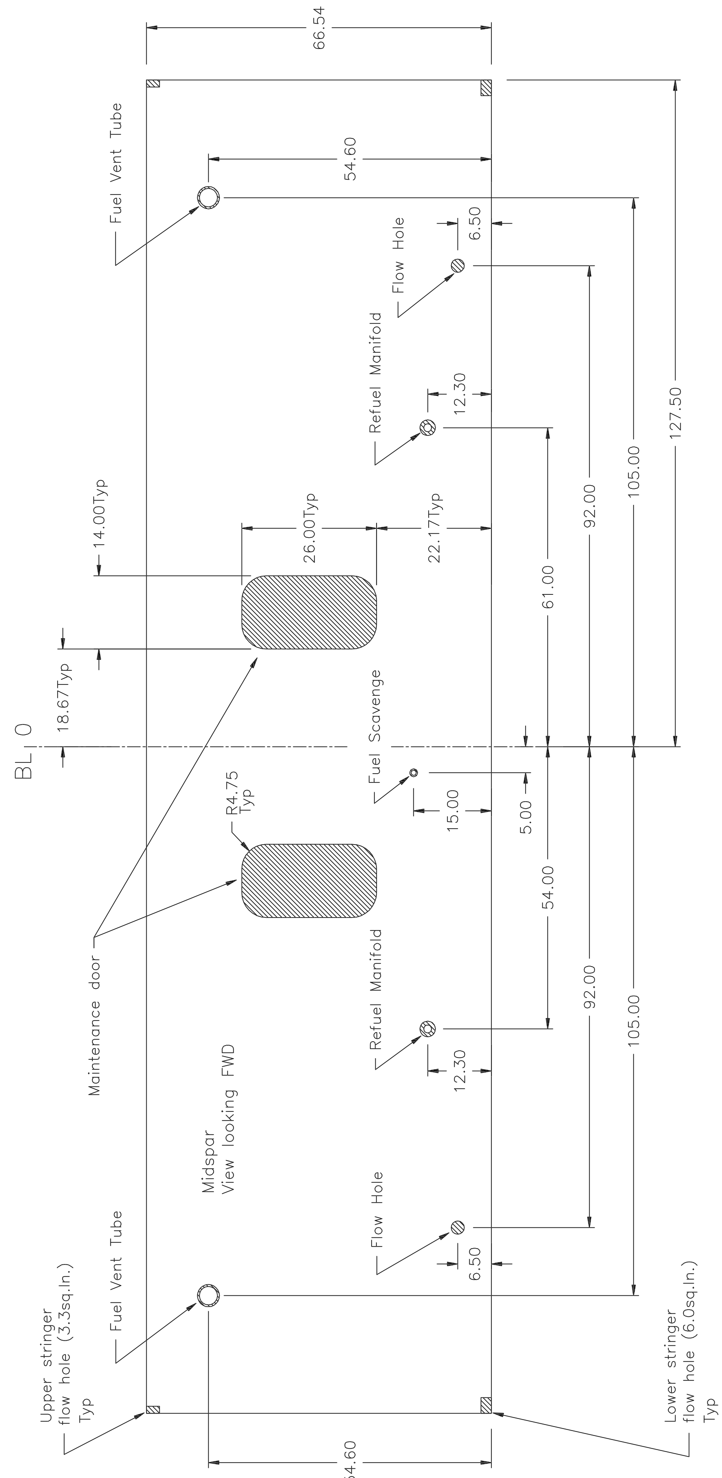

Figure 20: Midspar (MS) of CWT. Actual dimensions.

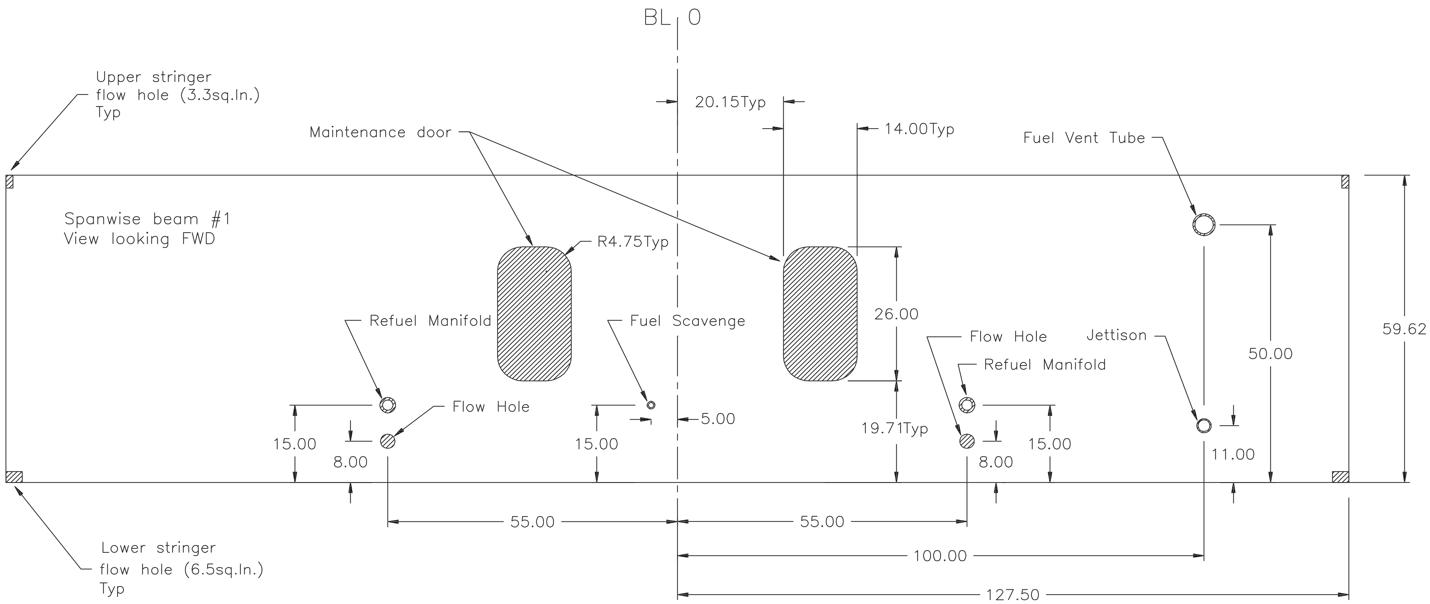

Figure 21: Spanwise beam 1 (SWB1) of CWT. Actual dimensions.

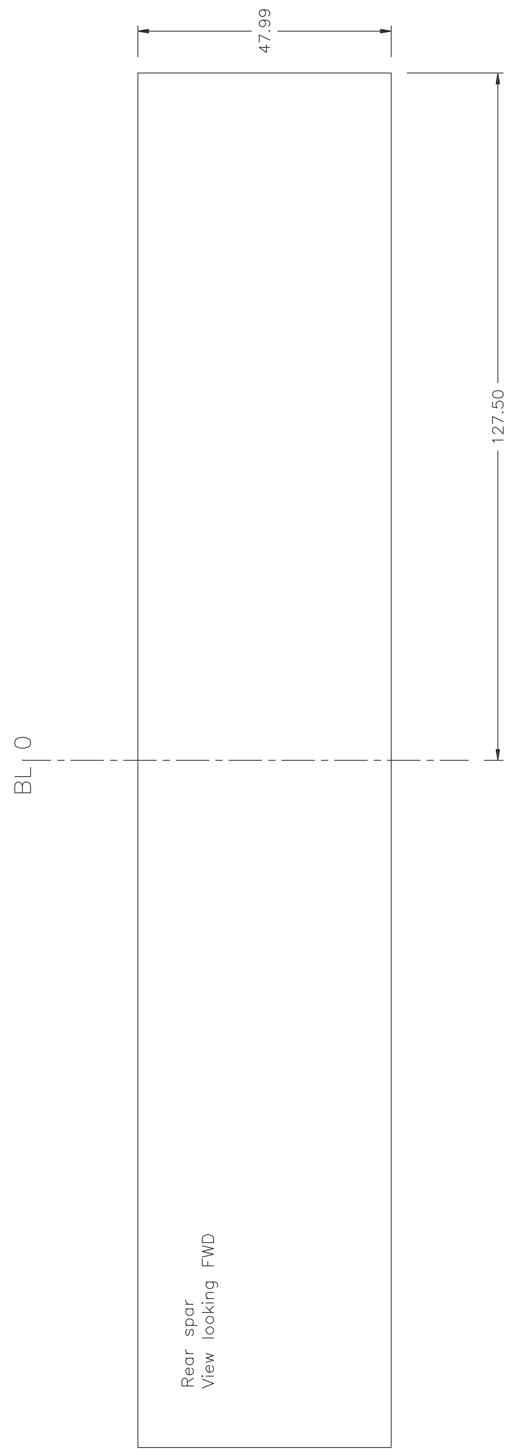

Figure 22: Rear spar (RS) of CWT. Actual dimensions.

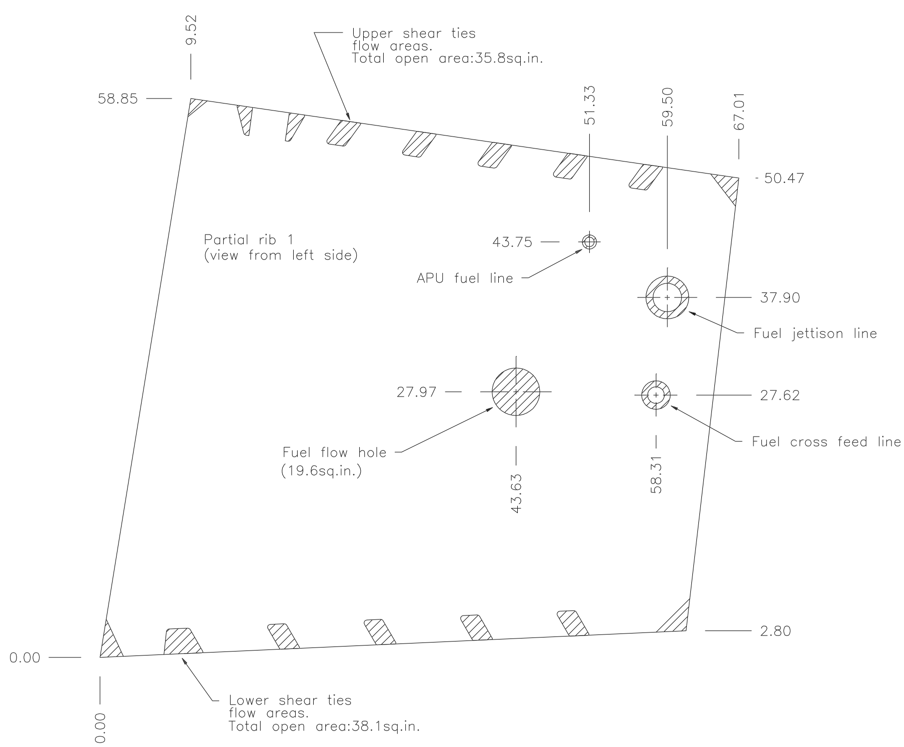

Figure 23: Partial rib between RS and SWB1 of CWT. Actual dimensions.

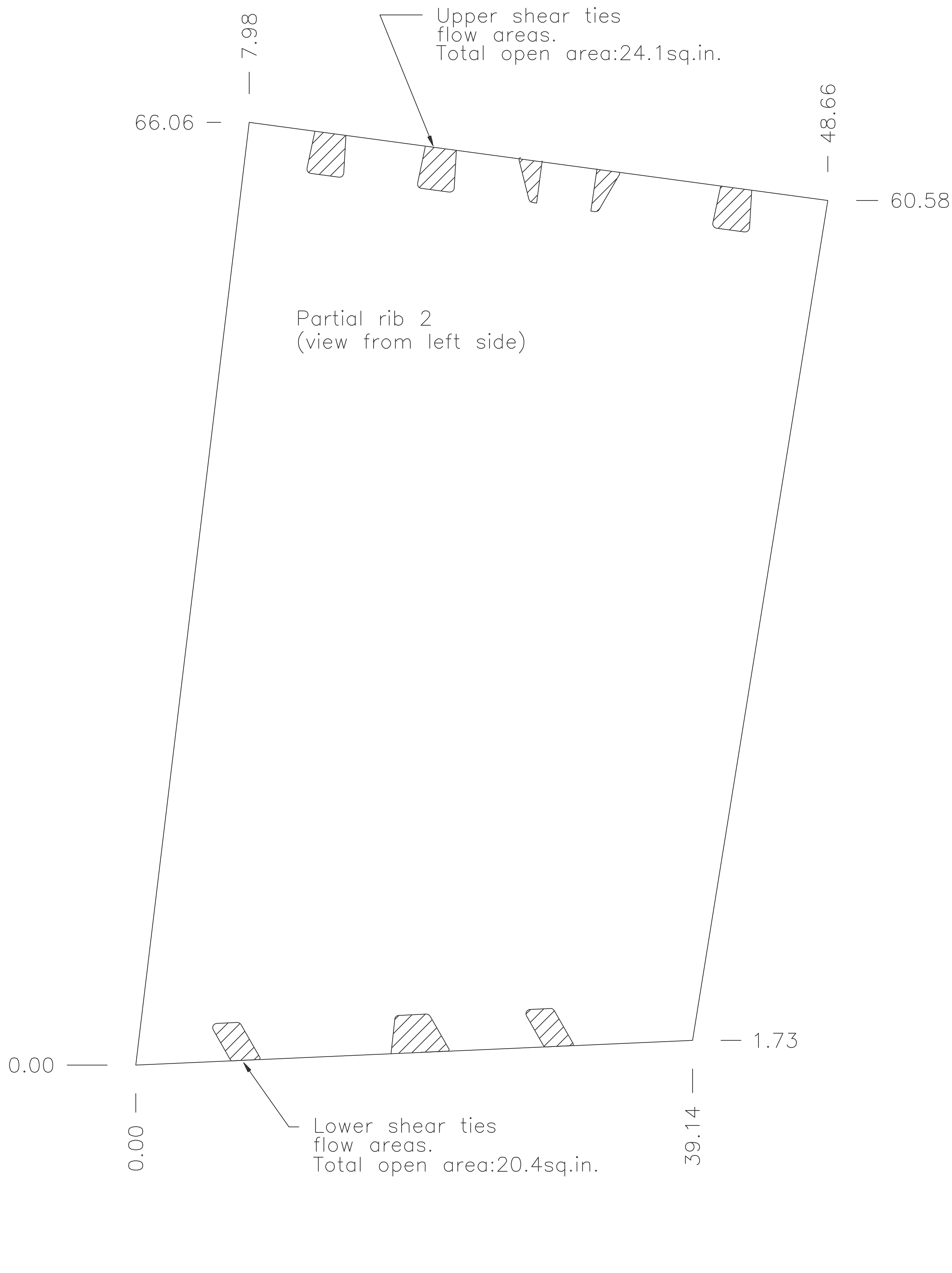

Figure 24: Partial rib between SWB1 and MS of CWT. Actual dimensions.

Table 11: Passageways in Spanwise Beam 1 (SWB1).

Passageway	Hole dia. (in.)	Tube OD (in.)	Flow area (in^2)	Quantity
Lower stringer flow area	-	-	6.50	2
Upper stringer flow area	-	-	3.30	2
Fuel vent	4.25	3.50	4.57	1
Refuel manifold	3.00	2.00	3.93	2
Jettison	2.75	2.25	1.96	1
Scavenge	1.50	1.00	0.98	1
Flow hole	2.75	none	5.94	2
Total vent area (in^2)	46.84			

Table 12: Passageways in the Midspar (MS).

Passageway	Hole dia. (in.)	Tube OD (in.)	Flow area (in^2)	Quantity
Lower stringer flow area	-	-	6.00	2
Upper stringer flow area	-	-	3.30	2
Fuel vent	4.25	3.50	4.57	2
Refuel manifold	3.00	1.50	5.30	2
Scavenge	1.50	1.00	0.98	1
Flow hole	2.53	none	5.03	2
Total vent area (in^2)	49.37			

Table 13: Passageways in Spanwise Beam 2 (SWB2).

Passageway	Hole dia. (in.)	Tube OD (in.)	Flow area (in^2)	Quantity
Lower stringer flow area	-	-	5.30	2
Upper stringer flow area	-	-	3.30	2
Fuel vent	4.25	3.50	4.57	2
Refuel manifold	2.50	1.50	3.14	2
Flow hole (scavenge)	1.50	none	1.77	1
Total vent area (in^2)	34.38			

Table 14: Passageways in the partial rib between the Rear-spar (RS) and the Mid-spar (MS).

Passageway	Between RS and SWB 1			Between SWB 1 and MS
	Hole dia. (in.)	Tube OD (in.)	Flow area (in^2)	Flow area (in^2)
Lower shear ties	-	-	38.1	20.4
Upper shear ties	-	-	35.8	24.1
Flow hole	5.00	none	19.6	none
APU fuel line	1.50	1.00	0.98	none
Crossfeed line	3.00	1.75	4.66	none
Fuel jettison line	4.50	3.00	8.83	none
Total flow area	107.98			44.5

B 1/4-Scale Facility

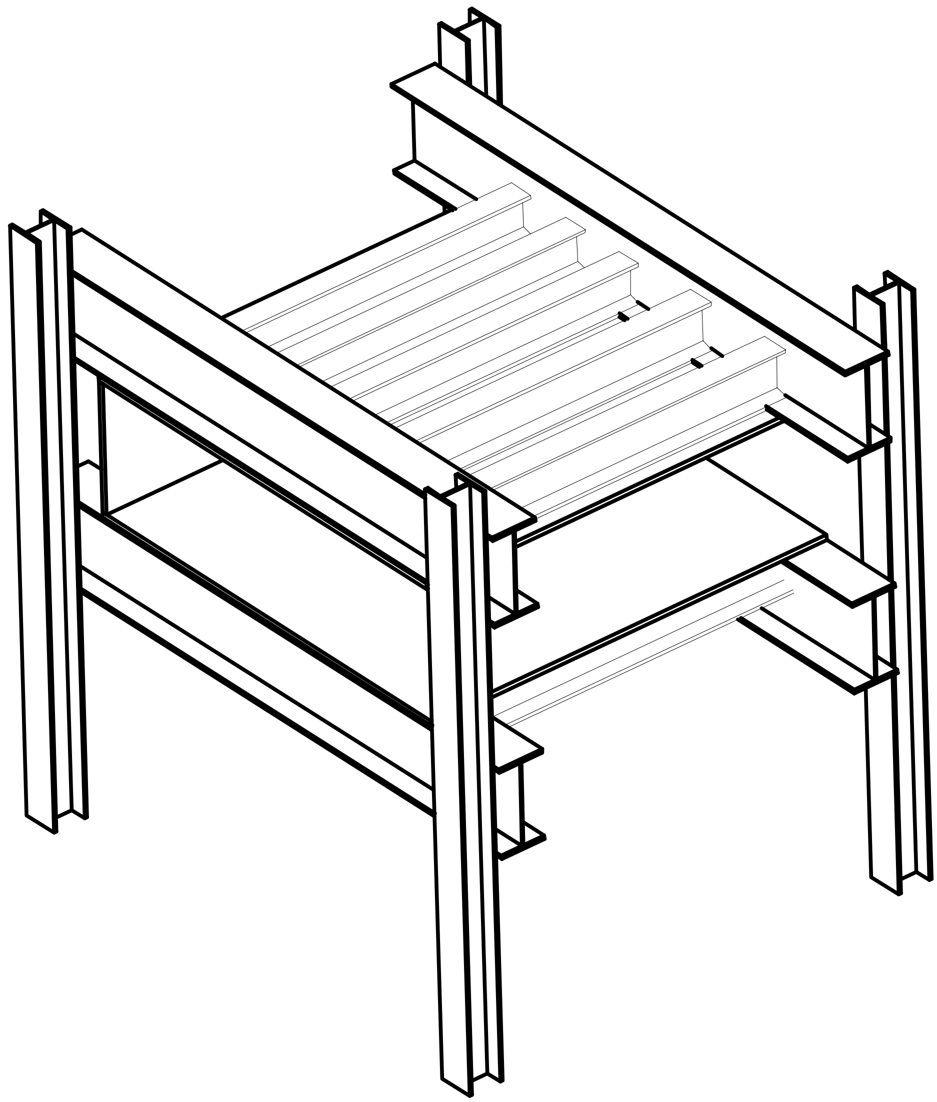

Figure 25: Perspective view of assembled 1/4-scale facility.

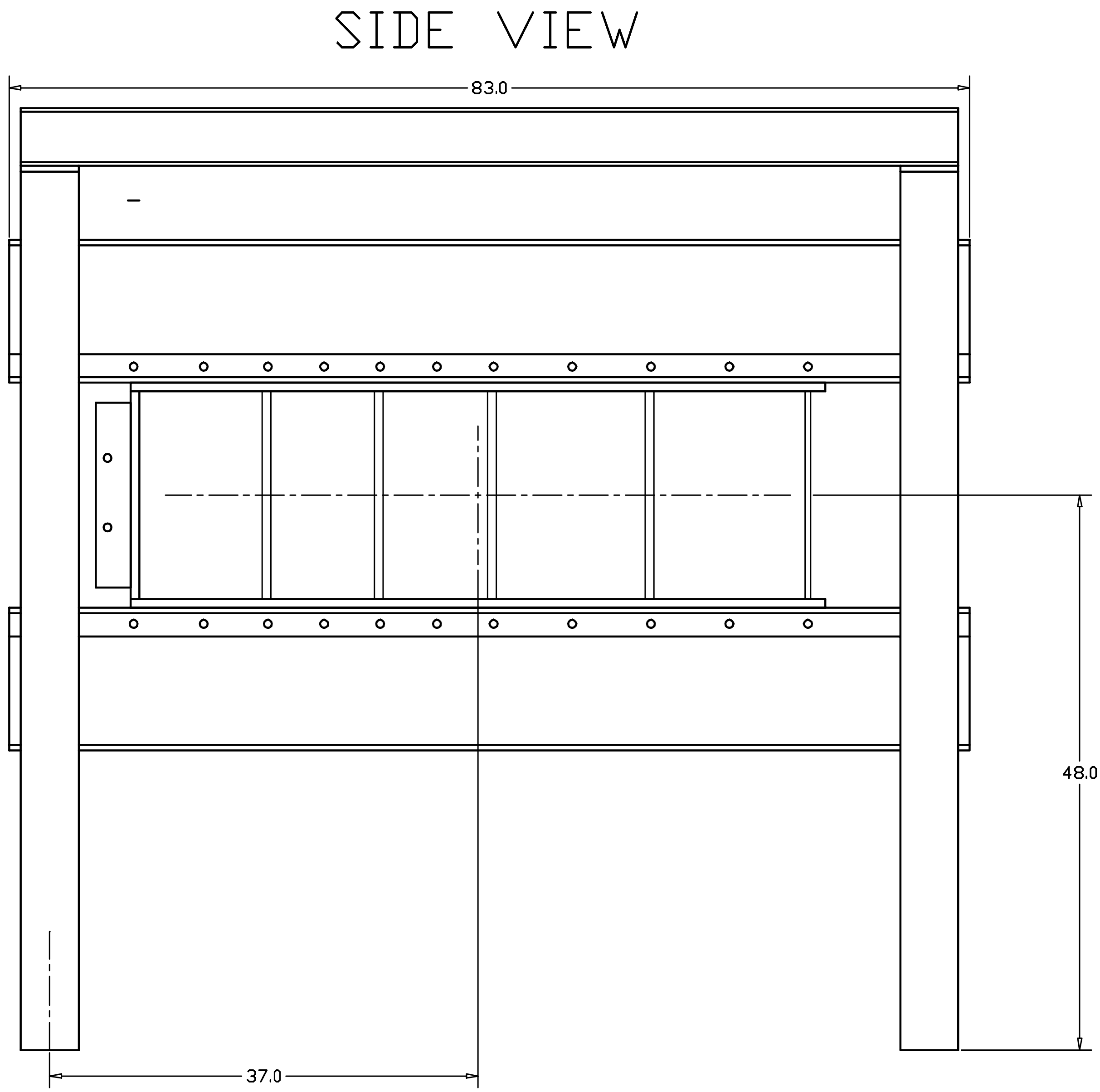

Figure 26: Side view of assembled 1/4-scale facility.

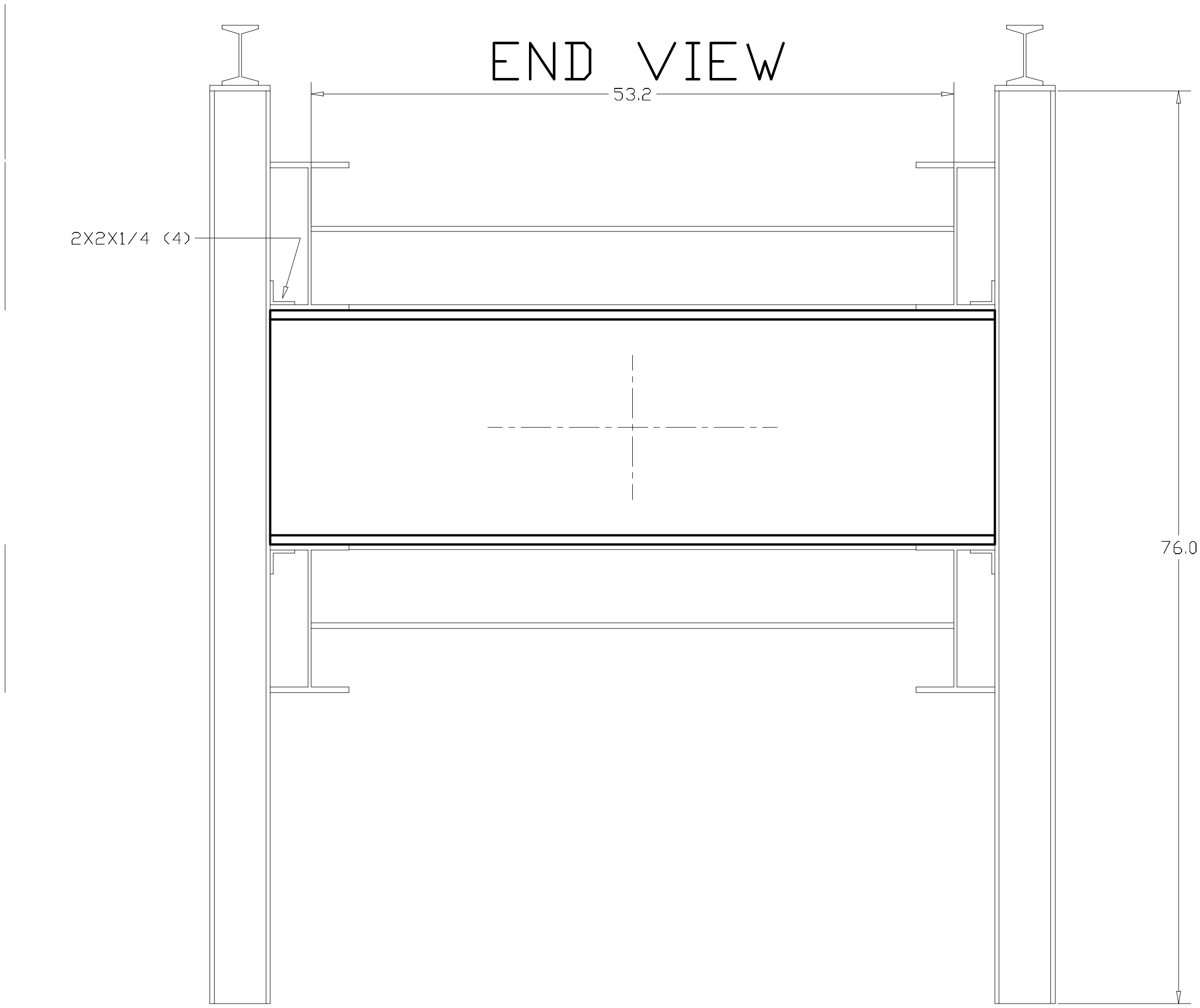

Figure 27: End view of assembled 1/4-scale facility.

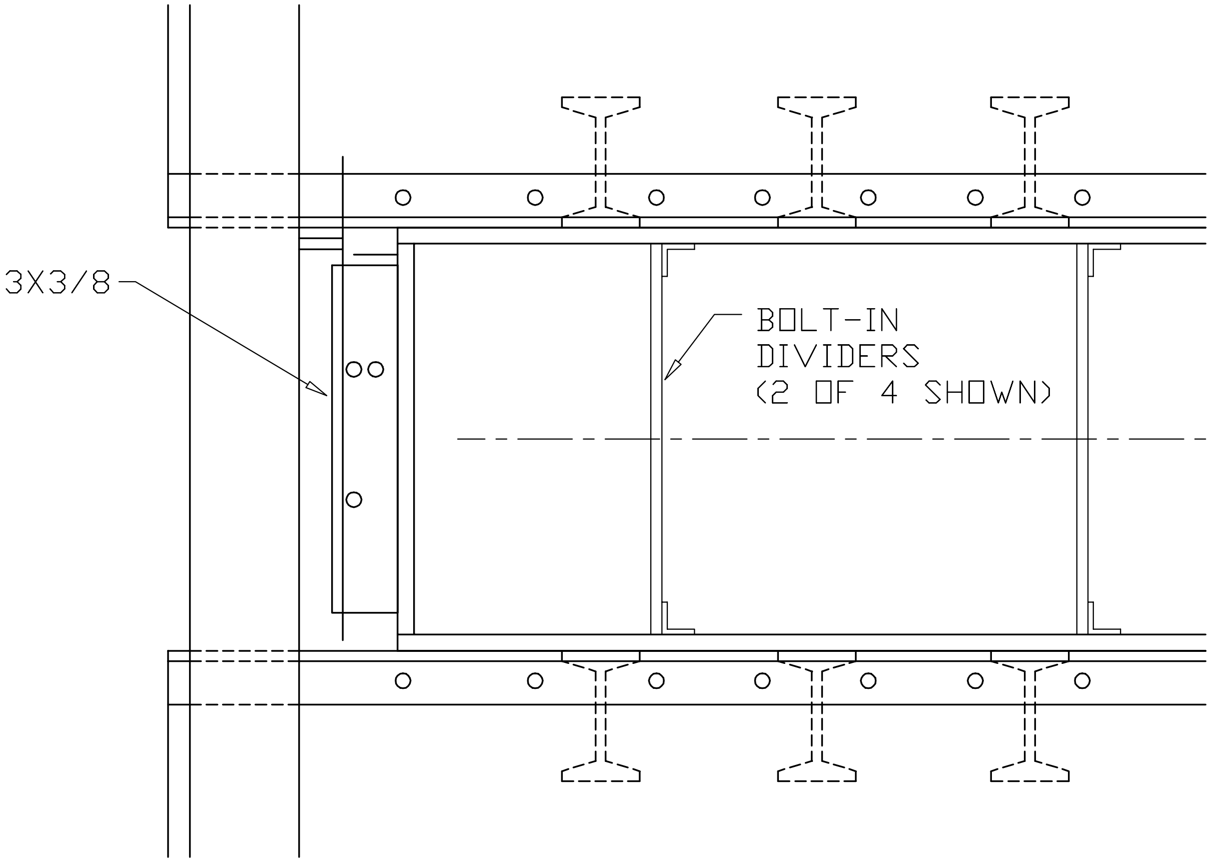

Figure 28: Close-up side view of assembled 1/4-scale facility.

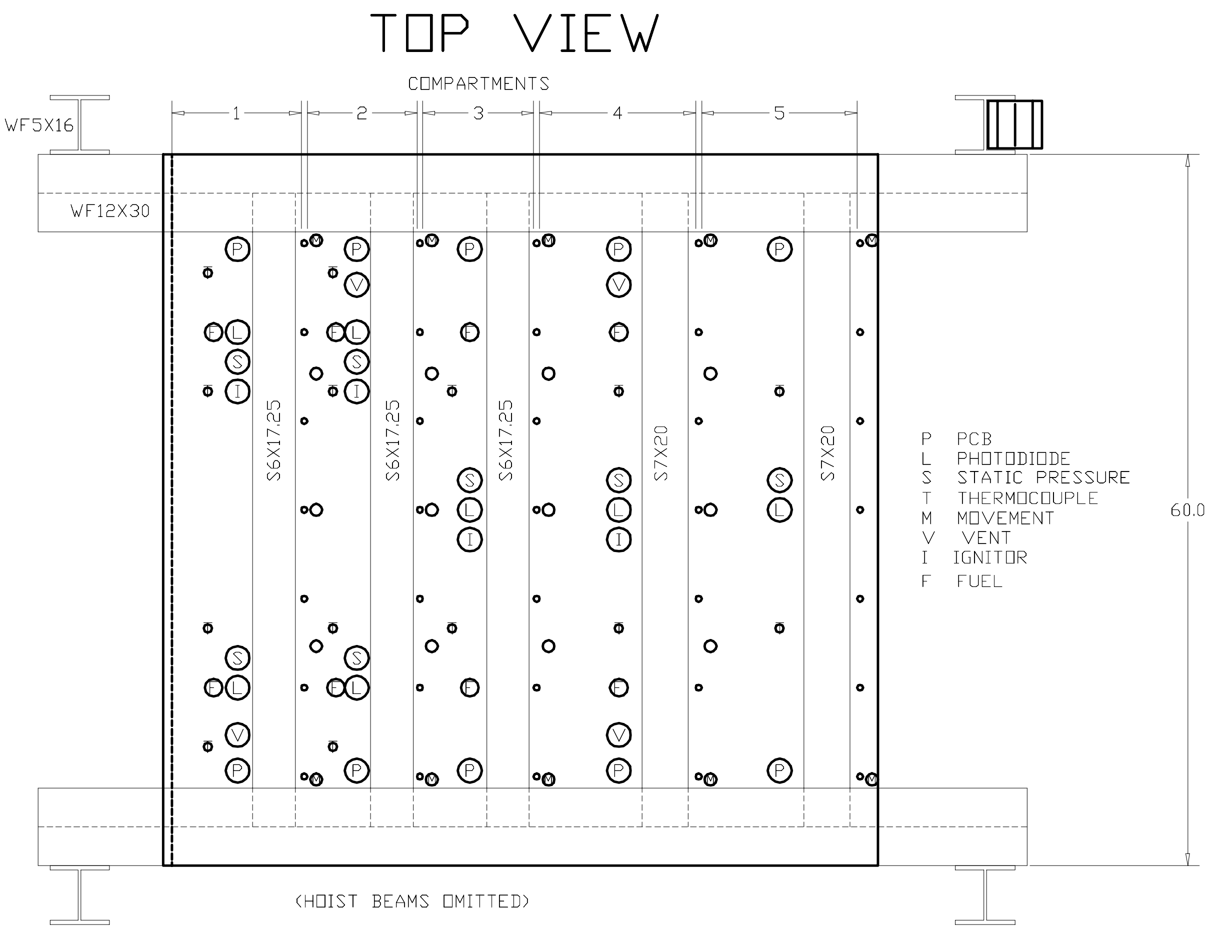

Figure 29: Top plate layout for 1/4-scale facility.

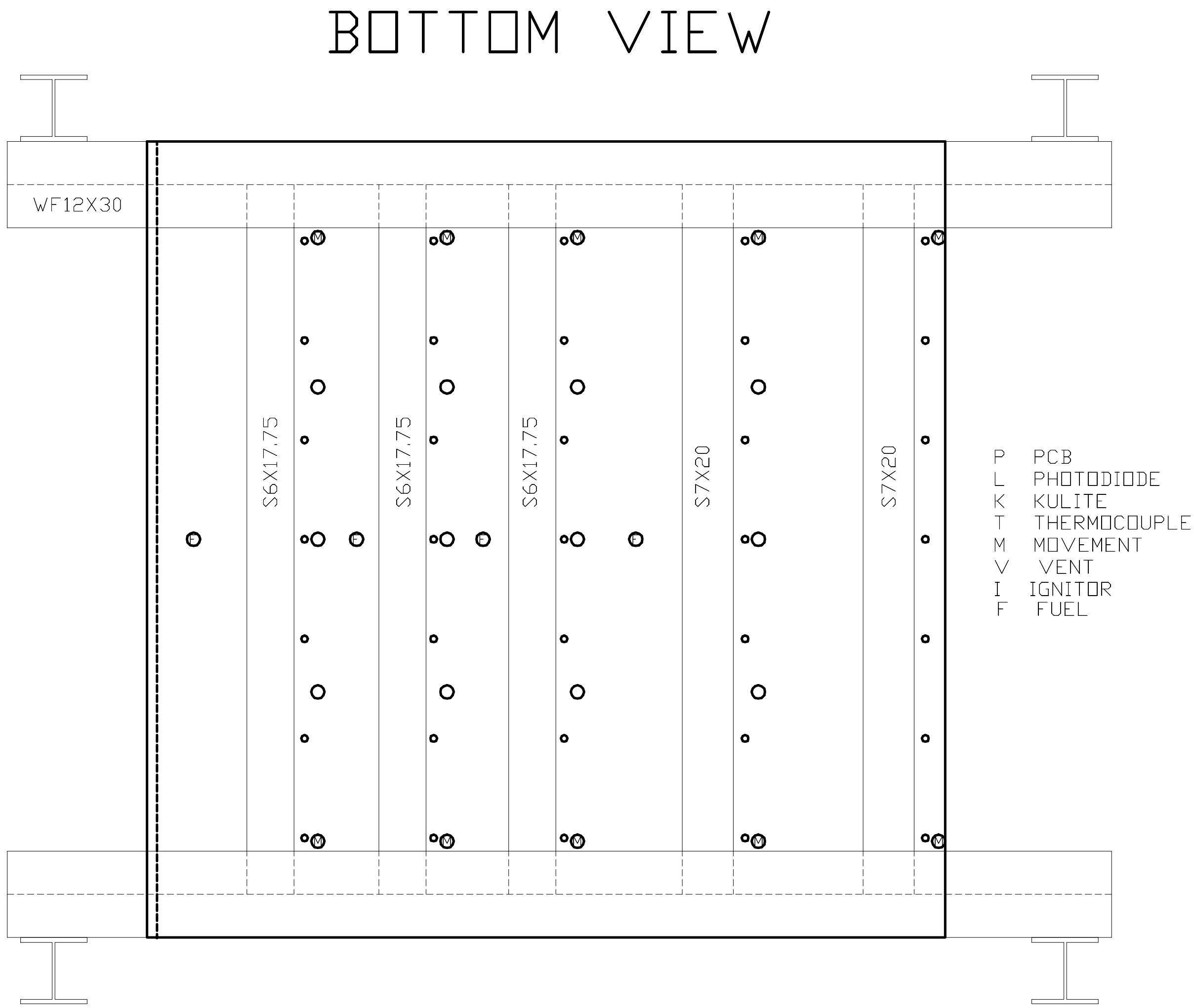

Figure 30: Bottom plate layout for 1/4-scale facility.

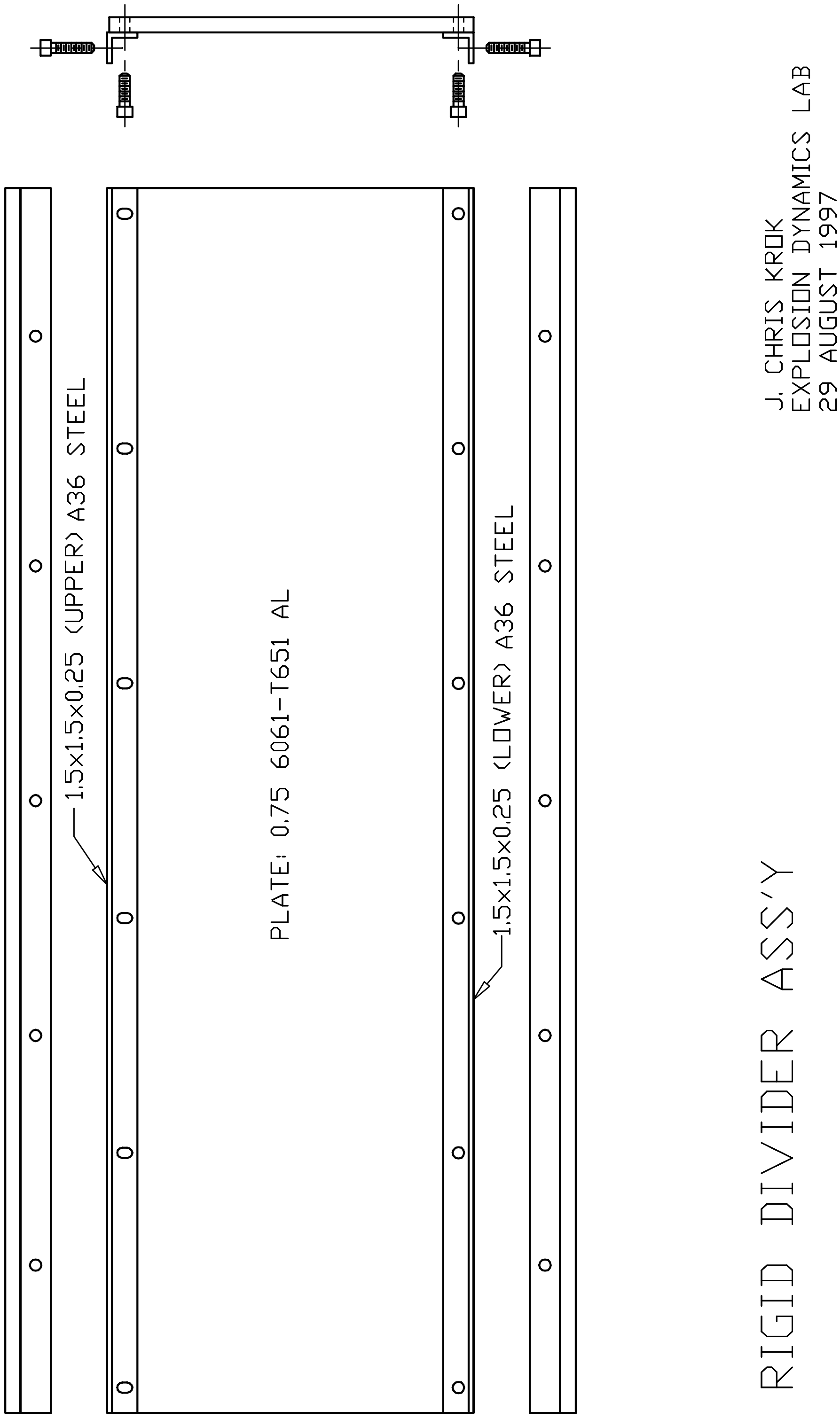

Figure 31: Strong partition mounting scheme. 1/4-scale facility.

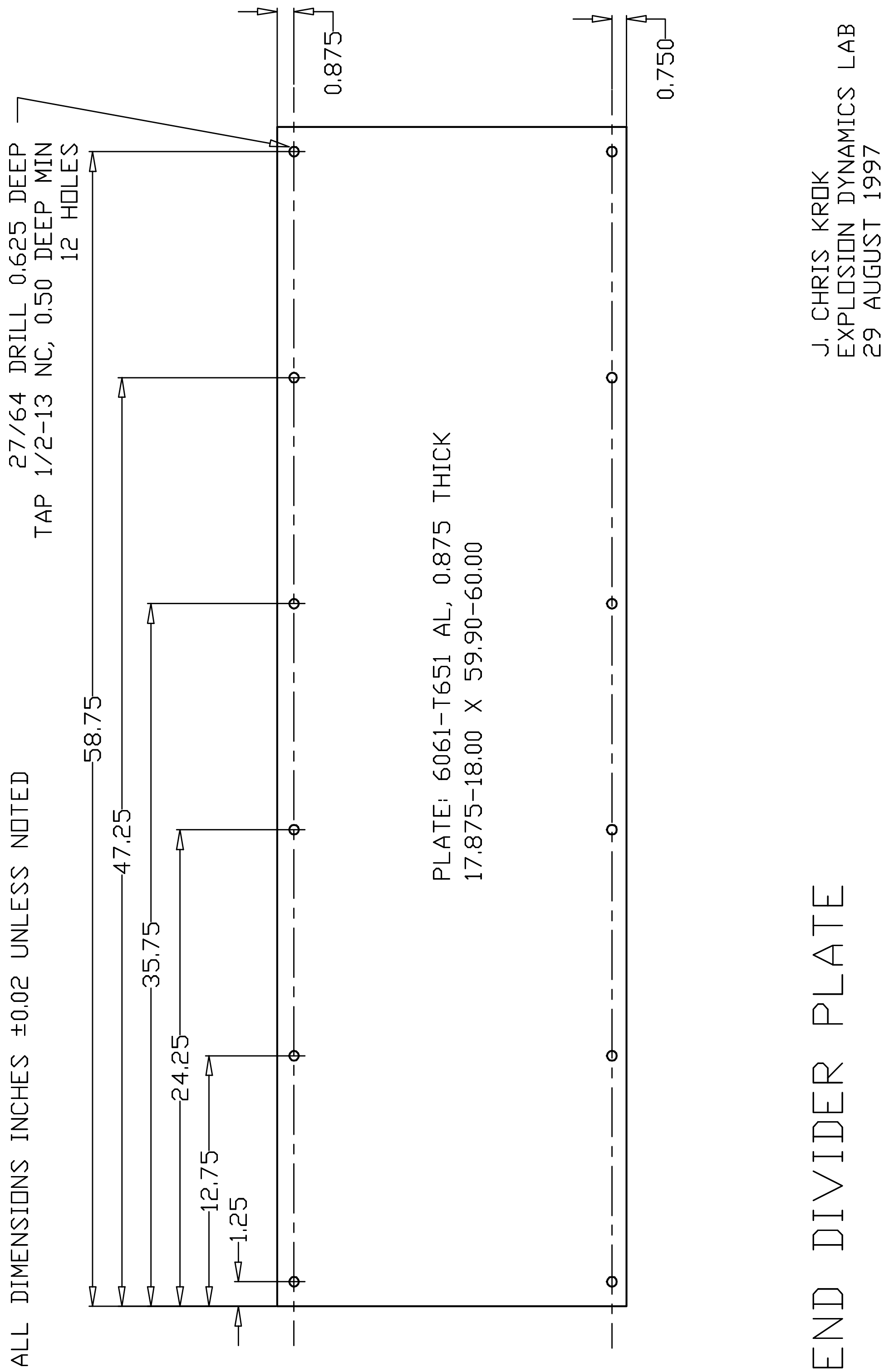

Figure 32: Strong partition mounting holes. 1/4-scale facility.

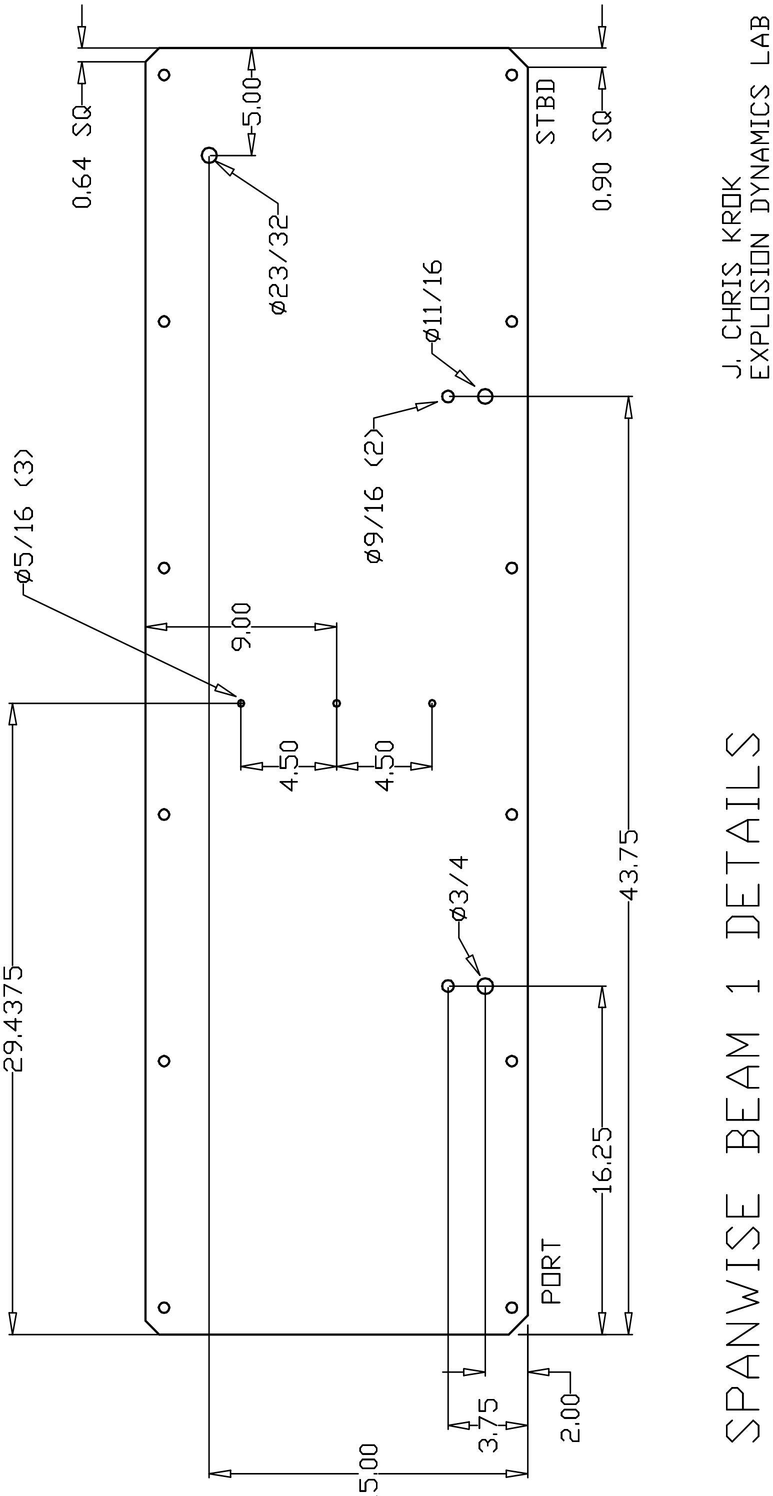

Figure 33: SWB1 hole layout for 1/4-scale facility.

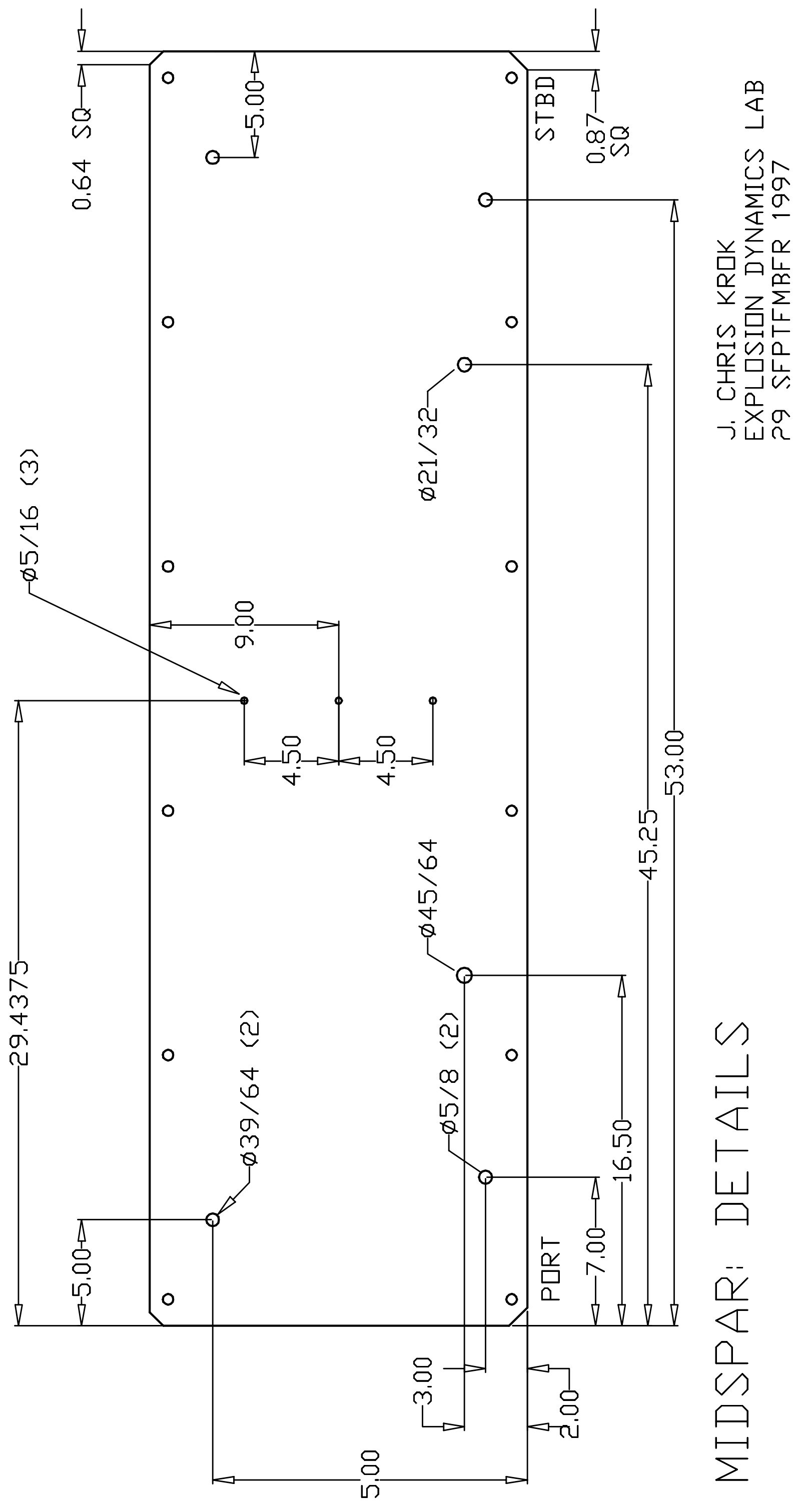

Figure 34: MS hole layout for 1/4-scale facility.

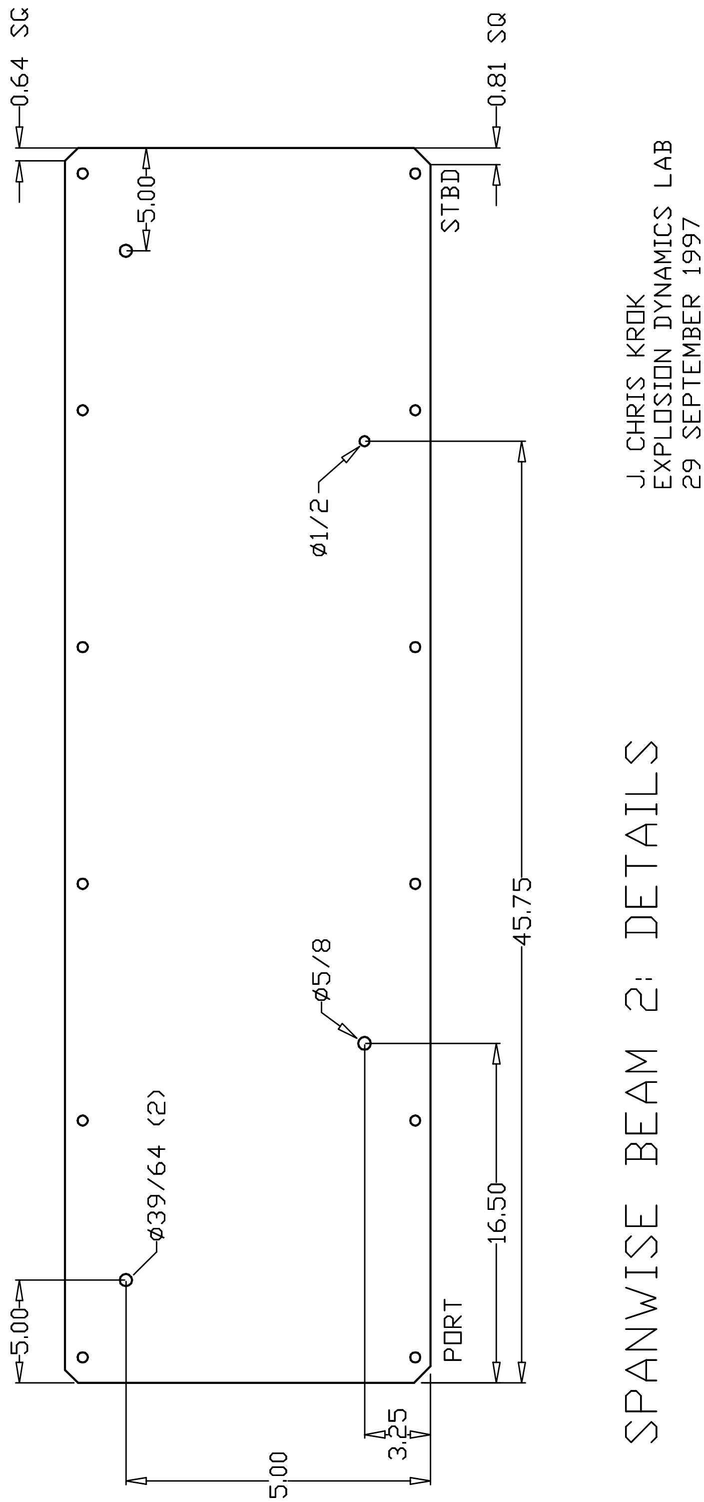

Figure 35: SWB2 hole layout for 1/4-scale facility.

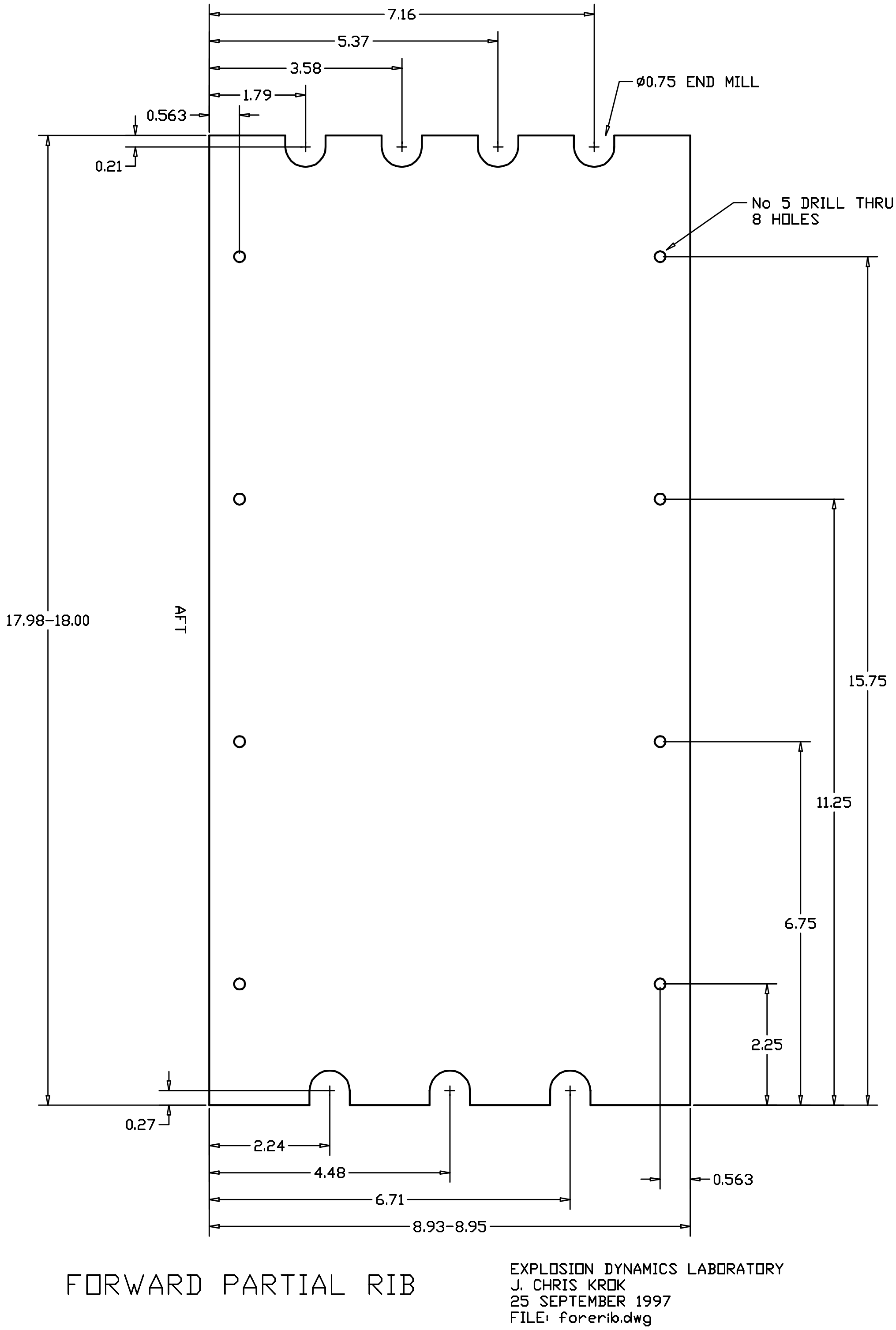

Figure 36: Forward partial rib hole layout for 1/4-scale facility.

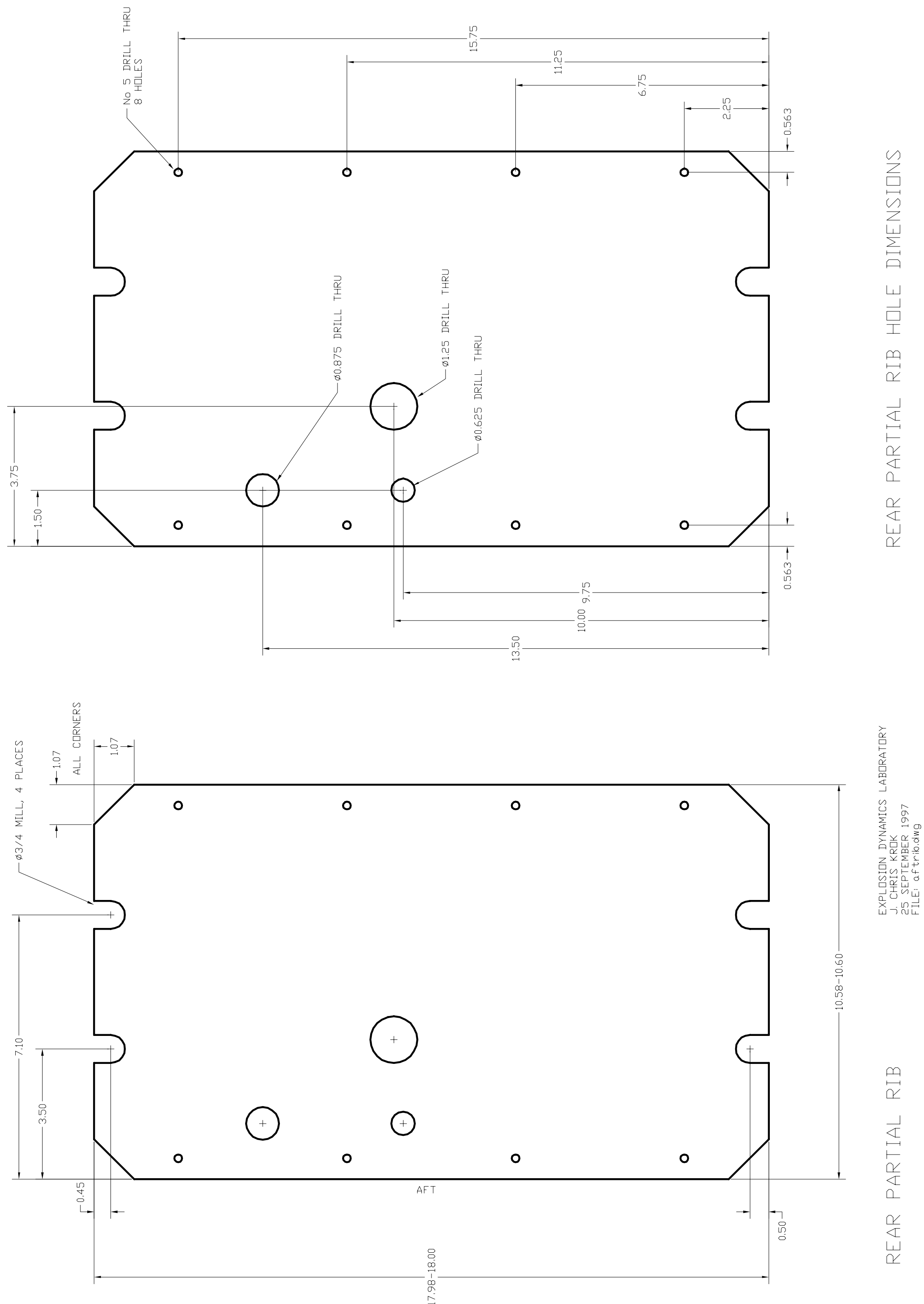

Figure 37: Aft partial rib hole layout for 1/4-scale facility.

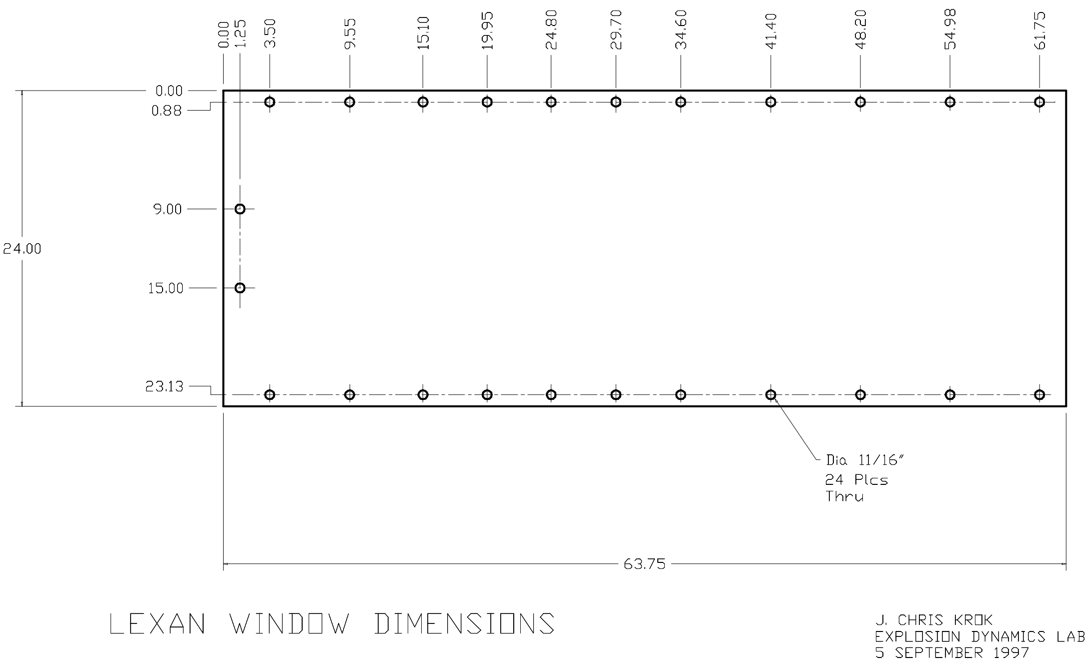

Figure 38: Window hole layout for 1/4-scale facility.

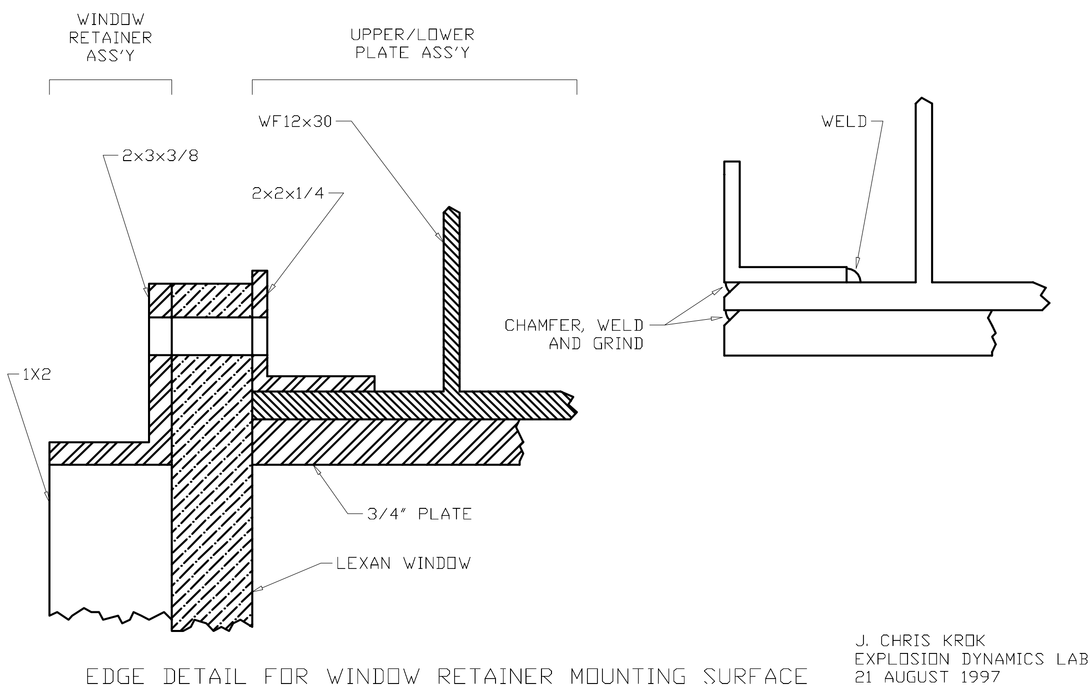

Figure 39: Window sealing detail for 1/4-scale facility.

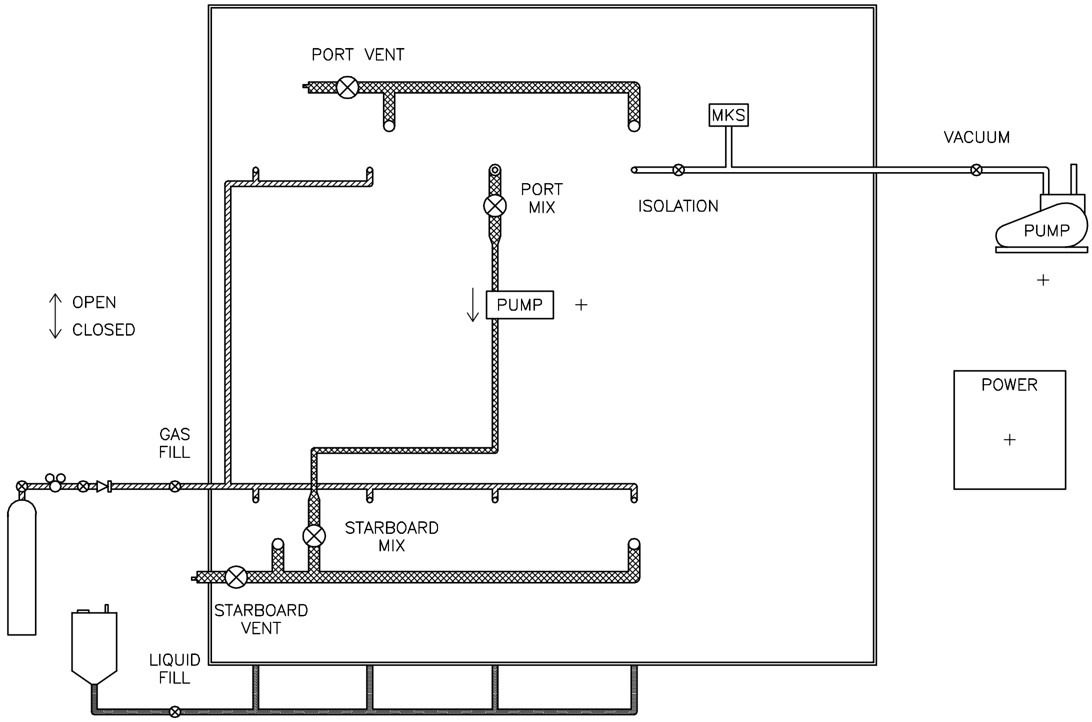

Figure 40: Plumbing detail for 1/4-scale facility.