PURDUE IGNITOR DESIGN AND OPERATIONS MANUAL

David Helderman

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1. PURDUE IGNITOR DESIGN

The Revision 3 design of the Purdue Ignitor has been used since March, 2007 with considerable success. The Revision 3 design is the current "state-of-the-art" and consists of three main components: ignitor casing, ignitor insert, and spark plug. Detailed drawings of each part are provided in the appendix in addition to drawings for a brass sealing washer, and insert removal tool. A detailed bill of materials (BOM) is shown below in Table 1.1.

Table 1.1: Purdue Ignitor Revision 3 Bill of Materials

Name	Manufacturer	P/N or Drawing #	Material	Date
Ignitor Casing	Purdue	PU-IG-Casing Rev. 7/23/07	Copper 101/110, Inconel 625, Nickel 200	7/23/2007
Ignitor Insert	Purdue	PU-IG-002	Ni 200	01/02/2007
Sealing Washer	Purdue	Lower Shim	Brass	9/10/2008
Insert Removal Tool	Purdue	535-IG-TL-01	Aluminum / SS304	7/23/2006
Spark Plug 1	Champion	CH31887-3	Inconel	-
Spark Plug 2	Auburn	I-33	Inconel	-
O-ring	McMaster-Carr	9263K173	Viton	-
Metal Seal	Garlok Helioflex	U2310-01186 NPD	Teflon coated metal	-
	Advanced Products Co.	EON-001186-05-03-1-TCC		

1.1. Ignitor Insert

The ignitor insert is made from Ni200 due to the high melting temperature (2651°F) and oxygen compatibility. During typical operation ignition of the core flame occurs inside the insert, which is only partially cooled. The insert also serves as a fuel manifold

separating the two fuel streams, and the anode for the spark plug. The insert, shown in Figure 1.1, and Figure 1.2, allows oxygen flow from the top, around the spark plug where the O_2 is ionized. Two jets of hydrogen then impinge into the ionized O2 stream causing ignition. The primary length of the insert is then cooled by additional hydrogen along the outside of the sleeve. At the end of the insert the additional hydrogen is added to the core flame greatly reducing the overall O/F ratio.
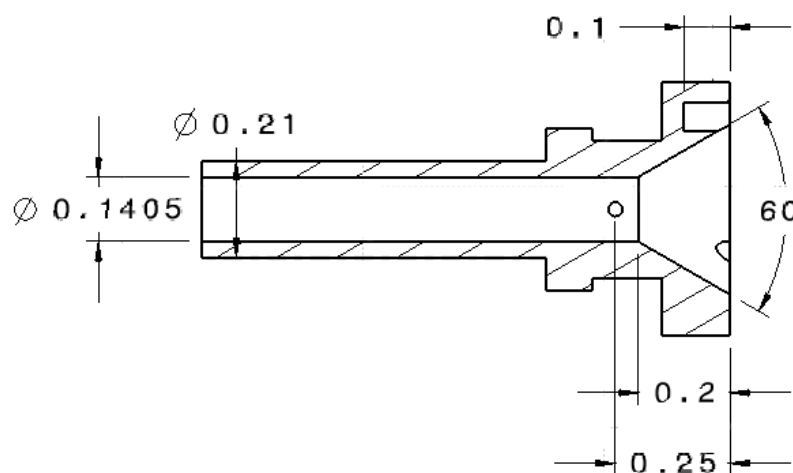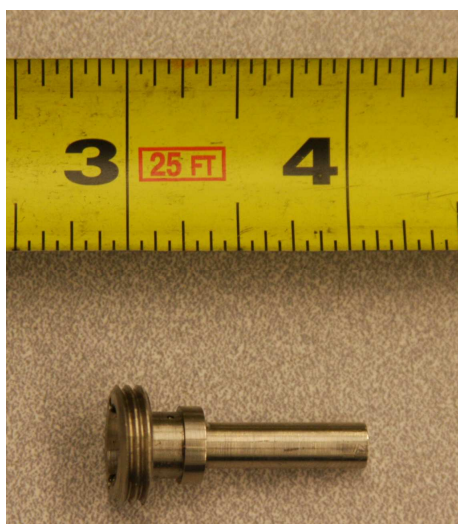

Figure 1.1: Ignitor Insert (PU-IG-002) Cutaway view

Figure 1.2: Ignitor Insert (PU-IG-002)

1.2. <u>Ignitor Casing</u>

The preliminary ignitor work was done with a baseline Cu 101 housing for heat transfer purposes. The initial Rev 3 housing was Cu 110 for the preliminary HOMEE project, but was switched to Inconel 625 for the primary HOMEE testing. The primary reason for the switch to Inconel was due to the installation and handling damage and the ease of scratching of the sealing surfaces. On later testing with a Cu 110 casing for the Purdue PreBurner the internal copper threads were found to damage easily and often required retapping of the threads in order to install the insert or spark plug. When a copper casing is used it is best practice to disassemble the ignitor as little as possible due to the ease with which the threads can be damaged. Figure 1.3 and Figure 1.4 show the R3 Version 1 and R3 Version 2 designs for the ignitor casing. With the exception of the preliminary HOMEE test program all other test programs have used the V2 design. The V1 design required an adapter plate to mate to the existing hardware. This design also was estimated to have a maximum of 1sec ignitor fire before the O-ring would be damaged, and as such all future programs used the V2 design with a metal seal.

PU-IG-Casing-0226

PU-HOMEE-IG-Adapter
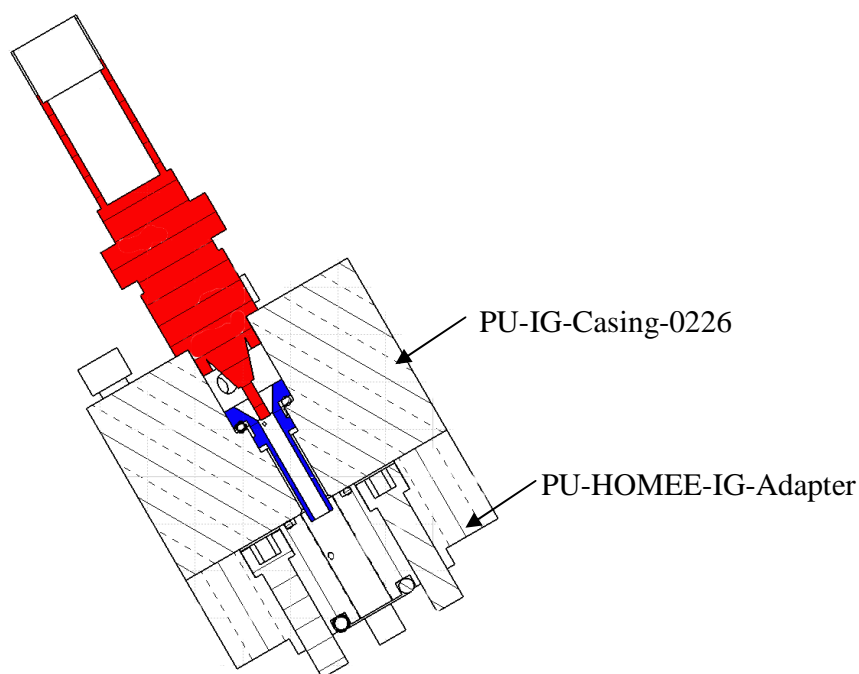
Figure 1.3: Ignitor Assembly using Casing R3 V1
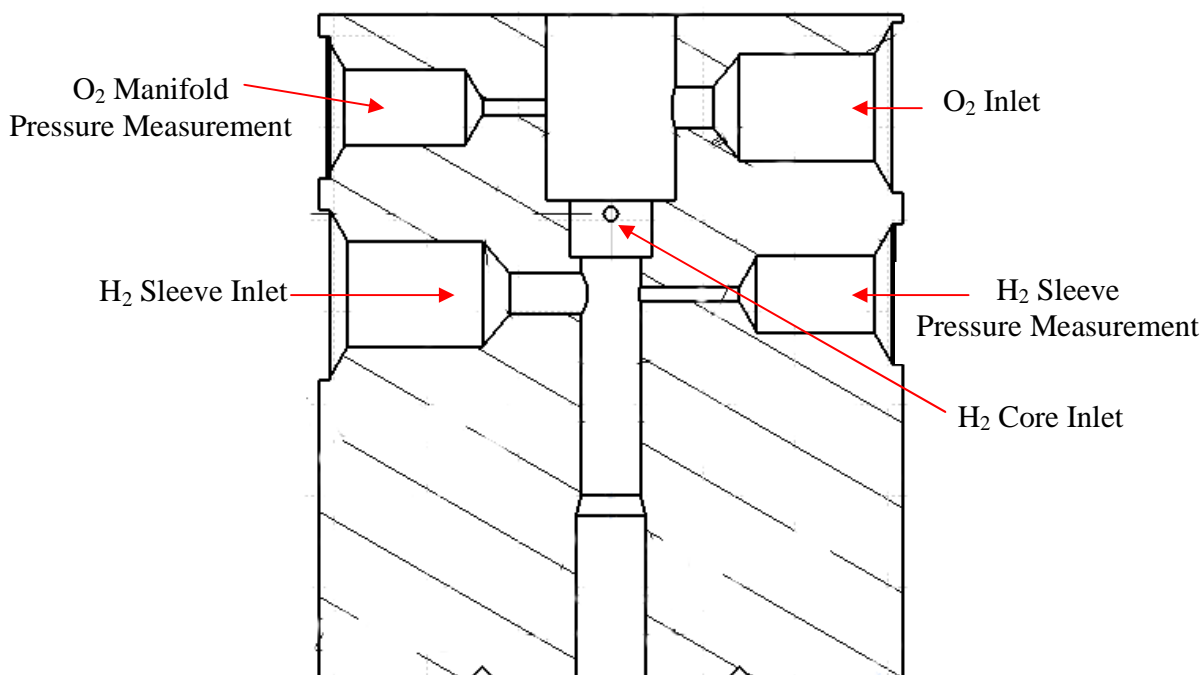
Figure 1.4: Ignitor Casing R3 V2 (PU-IG-Casing Rev. 7/23/07)

During the preliminary HOMEE project the viton O-ring sealing the casing to the chamber was determined to be the failure point for the entire program, and as such a new metal seal design was used for all future programs. This design has been previously used by George Repas, and Purdue on prior ignitor work, and had demonstrated a high degree of success. The metal seal does however require careful attention to ensure proper compression on all sides. During the primary HOMEE testing with the Inconel casing the seal was not fully compressed on one side leaving a substantial internal void. The seal held pressure and did not leak, but the void allowed for the hot combustion gasses to accumulate and over the course of the test program the ignitor casing was significantly damaged as shown in Figure 1.5.

Figure 1.5: Inconel 625 Ignitor Casing (PU-IG-Casing Rev. 7/23/07) after Primary HOMEE testing, showing damage from improper seal compression

1.3. Spark Plugs

Two different spark plugs have been used with substantial success on the Purdue Ignitor. The primary spark plug is a Champion CH31887-3, which is custom made for AeroJet, and has significant cost and lead time problems. At current Champion requires a minimum quantity of 20 spark plugs to make a production run with each plug often costing in excess of $1000. Plugs in use at Purdue were procured from Jeff Muss at Sierra Engineering, Inc who acquired a supply and then resold them individually. These plugs have shown to be extremely robust over hundreds of thermal cycles and cryo-cycles with minimal damage. The ceramic is most often the first failure as it begins to break off, however Purdue has shown that spark plugs with significant amounts of missing ceramic still function with no adverse effects. The plugs have also been shown

to work and seal at pressures exceeding 2000psia. Majority of ignitor tests have been performed with the Champion model CH31887-3 or model CH31887-2 spark plugs.

The second type of spark plug used was an Auburn furnace transformer spark plug, model I-33. This plug was used primarily due to the low cost and lead time associated with procurement. A typical price was less than $30 with a 2-3 week lead time, offering a much better alternative. These spark plugs have not shown the reliability of the Champion plugs and are prone to failure. The welds on the Auburn plugs are usually the first part to fail, sometimes ejecting the core of the spark plug out the rear housing. The spark plug has also been repeatedly shown to fail a hydroproof test at above 700psia, and as such is not useful for high pressure testing.

CHAPTER 2. IGNITOR OPERATION

The Purdue Ignitor has been operated in several different configurations for the various test programs. Primarily there have been three different tested configurations: nominal, high pressure, and low flow. The nominal flow configuration was used for the preliminary and primary HOMEE programs for the NASA CUIP Program, and the INSpace LOX/LCH$_4$ thruster programs at Purdue. The high pressure case was used on the Purdue Preburner for the LST and SDS test programs for Sierra Engineering, Inc. The low flow case has been demonstrated and is slated for use on a variety of test programs including a low flow rate Purdue preburner.

In addition to the three different flow configurations each specific test program used slightly different timing based on the size of the chamber, plumbing configuration, and ignition transients. The timings shown throughout this chapter are test program specific and should be used only as general guidelines for ignitor operation.

2.1. Nominal Flow

The nominal flow condition has been used successfully on four test programs to date. The preliminary and primary HOMEE test programs, and the IN Space LOX/LCH$_4$ Thruster programs all used the nominal flow conditions with a high degree of success. The Purdue Preburner attempted to use the nominal flow condition, however significant problems were found due to the venturis unchoking during the start up transient. As a result the high pressure condition was tested to allow for use with the high back pressure.

The nominal flow condition uses a core stream of O$_2$ with a core and sleeve flow of H$_2$. The two H$_2$ flows have been set to run from a single supply source as shown in Figure

3.2.   The mass flow rates, set pressures, and venturis typically used for the nominal condition are shown below in Table 2.1. The core O/F ratio is approximately 36.9 with a final O/F ratio of 3.4.

Table 2.1: Ignitor Nominal Flow Conditions

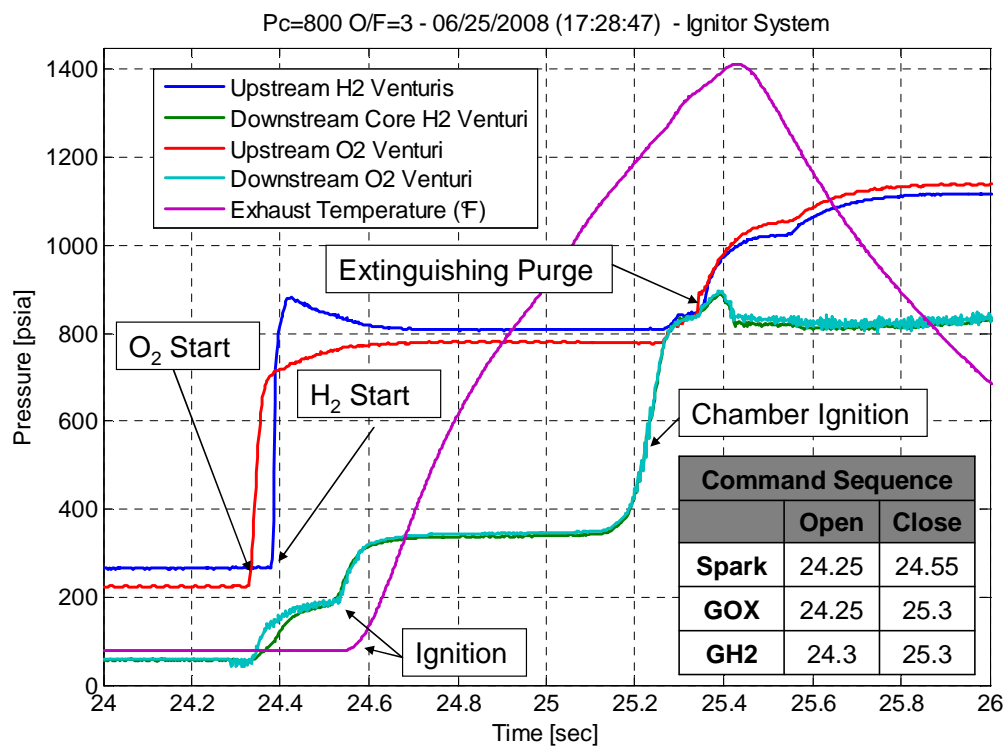|	Set Pressure	Venturi Dia	Mass Flow
	[psia]	[in]	[lbm/s]
Oxygen Flow	775	0.047	0.03263
H2 Core Flow	825	0.015	0.00088
H2 Sleeve Flow		0.047	0.00869

Figure 2.1: HOMEE Ignitor Operating Sequence

Nominal operation, shown in
Figure 2.1, has the O_2 commanded 0.05s before the H_2 to prevent any H_2 from entering the O_2 system. The spark is then commanded on at the same time as the O_2 to begin the

gas ionization process before the H_2 is introduced into the system. Ignition typically occurs when the core H_2 pressure exceeds the core O_2 pressure allowing the H_2 to flow into the spark chamber, typically about 0.15s after propellant flow begins. The spark remains on for a total time of 0.3s and is then turned off to allow for an abort check on the exhaust temperature thermocouple. Once ignition has been verified by the exhaust thermocouple the main propellants are turned on and the main chamber will ignite typically 0.2-0.4s later. High pressure N_2 is then flowed through the ignitor propellant lines as they are commanded off extinguishing the torch, and providing a buffer against main chamber gases entering the ignitor for the duration of the test.

The ignitor has demonstrated run times in excess of 10sec with no damage to the ignitor itself. Typical operation is for a 0.7-1sec hot fire to minimize damage to the opposing chamber wall. For the nominal case tests have shown up to a 1sec fire against a copper plate will result in no damage to the plate. Ignitor firing durations should not exceed 1sec if possible to minimize the potential for damage.

2.2. High Pressure Flow

The Purdue Preburner required a much higher set pressure for both propellants due to the high back pressure generated during startup in the preburner. As shown in Figure 2.2 the preburner chamber pressure rises rapidly and would exceed the nominal venturi upstream pressures before the preburner fuel is turned on. Initial testing of the preburner showed significant o-ring damage to the lower o-ring when this occurred. To solve this problem a brass washer was used to seal the lower sealing surface, and the viton o-ring was still used at the top sealing surface. The brass washer coupled with the higher set pressures eliminated all of the problems associated with the ignitor aborts and sealing. The coolant flow was also increased for the high pressure case to further reduce the overall O/F ratio to 2.07 while the core was increased to an O/F ratio of 40.67. The flow rates and venturis for the high pressure case are shown below in Table 2.2.

Table 2.2: Ignitor High Pressure Flow

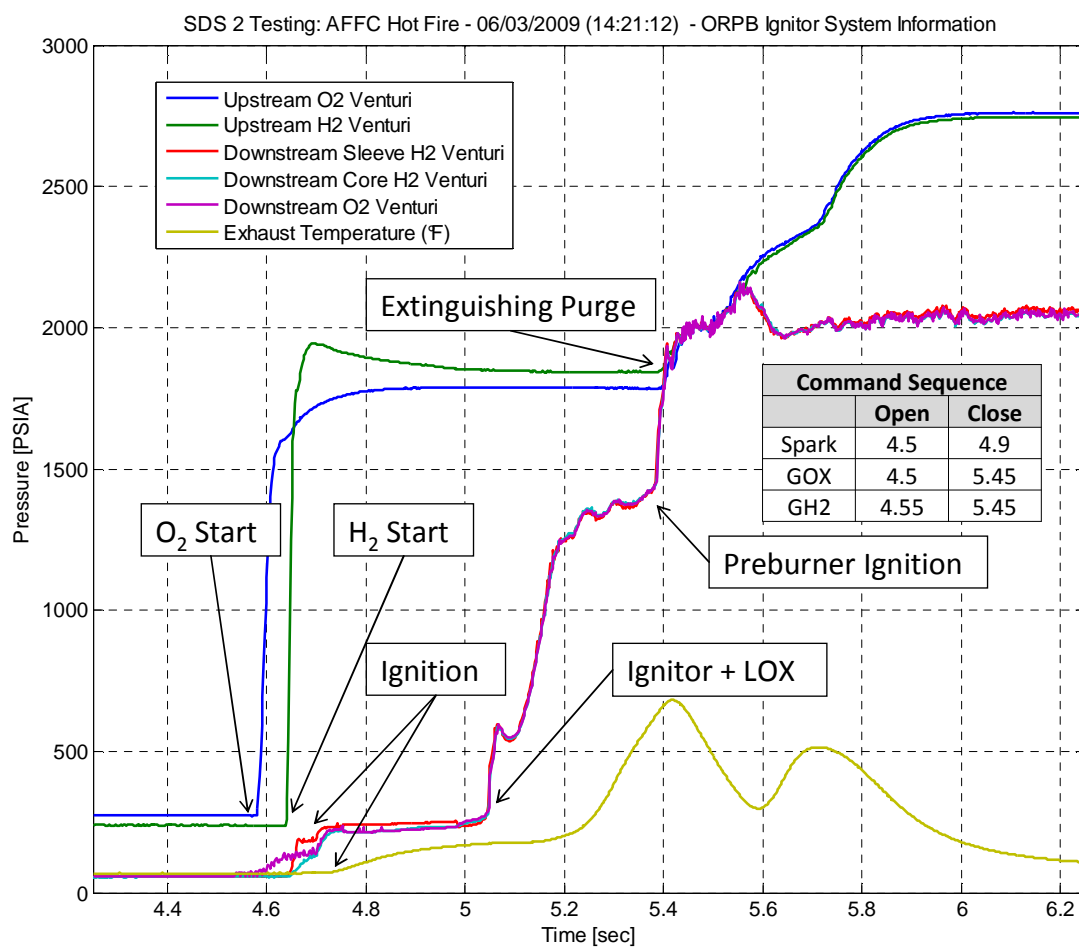|	Set Pressure	Venturi Dia	Mass Flow
	[psia]	[in]	[lbm/s]
Oxygen Flow	2000	0.028	0.0299
H2 Core Flow	2100	0.009	0.0007
H2 Sleeve Flow		0.037	0.0137

Figure 2.2: Preburner Ignitor Operating Sequence

The data plot shown in Figure 2.2 is similar to the nominal case with the exception of the higher pressures and the spark remaining on for 0.4sec instead of 0.3sec. Preburner operation has the LOX commanded on at 4.9sec while the GH_2 is not commanded until 5.25sec. With this timing sequence the ignitor lights the main LOX flow before the GH_2 is introduced into the system, which is shown in Figure 2.2.

2.3. <u>Low Flow</u>

The desire for ignition of a low flow rate preburner as well as various small scale LOX/LCH$_4$ combustors led to the desire for a lower flow rate ignitor. A low flow rate condition was testing in July, 2009 to verify operation at an approximate one-half flow rate. The detailed flow rates are shown below in Table 2.3 and represent a core O/F ratio of 40.47 and a final O/F ratio of 1.63.

Table 2.3: Ignitor Low Flow Rate

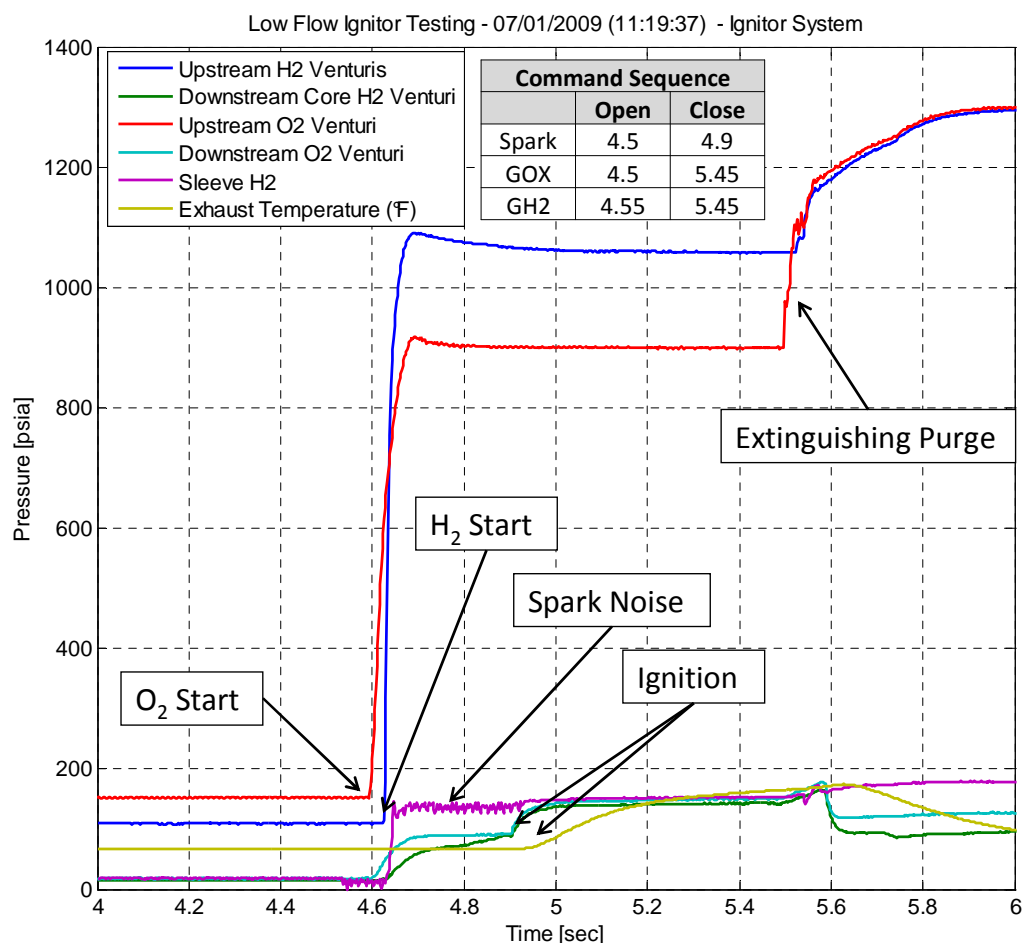|	Set Pressure	Venturi Dia	Mass Flow
	[psia]	[in]	[lbm/s]
Oxygen Flow	900	0.031	0.0165
H2 Core Flow	1055	0.009	0.0004
H2 Sleeve Flow		0.044	0.0097

Figure 2.3: Low Flow Ignitor Operating Sequence

The sequence is nearly identical to the previous tests with the exception of not having a chamber ignition. In this particular test the noise from the spark system is very evident in the downstream sleeve H_2 pressure measurement, however it is mostly absent from all other measurements. The much lower temperature shown on the exhaust thermocouple on this test is due to the lower O/F, lower mass flow rate, and the absence of a chamber. The low flow rate condition was also demonstrated at run durations of up to 10sec with no damage. An additional test was also completed with a flat copper plate 2.5in from the ignitor exit face and showed no damage up to a 2sec hot fire.

2.4. Operational Limits

There are several operation limits to the ignitor which were found empirically through various tests. The thermal limit on the ignitor core flow is equivalent to an O/F of 32, anything below that has been shown to melt the ignitor insert. O/F ratios on the fuel rich side have not been tested, but it is likely that there is a low O/F that is acceptable for use if desired. Core O/F ratios up to 55 have been tested largely through regulator drift over a test day. No issues have been found with higher O/F ratios, and the majority of tests are run in the low 40 range, sufficiently removed from the 32 limit.

Initial tests were run without any coolant flow and it was found that tests up to 0.5sec in length will allow the ignitor to run without coolant. A 1sec duration nominal was test and destroyed the ignitor insert, providing a known failure point.

The H_2 mass flow rate through the core is restricted based on the O/F detailed above. The actual ignition is dependent on the pressure in the manifold exceeding the pressure of the O_2 in the core. During the low flow rate testing this was not initially achieved resulting in several failures, and the new low flow rates were found to be the lower limit to achieve ignition. No high flow limit has been found, or investigated to date.

There is likely no limit on the final O/F ratio as the core flame is simply burning the excess H_2 coolant. The nominal case of 3.4 has been used substantially as well as a final O/F of 2.07, and has been tested up to an O/F of 8 (stoichiometric) and as low as an O/F of 1.6. No damage has been seen as a result of varying the final O/F ratio as this final mixing occurs at the ignitor exit or in the test chamber.

CHAPTER 3. PLUMBING INSTALLATION

3.1. <u>Installation Guidelines</u>

All three venturis need to be close coupled to the hardware. This has typically been done by installing the venturi into a fitting directly into the ignitor ports as shown in Figure 3.1. This was shown during some of the Rev 1 testing to reduce manifold oscillations and instabilities.
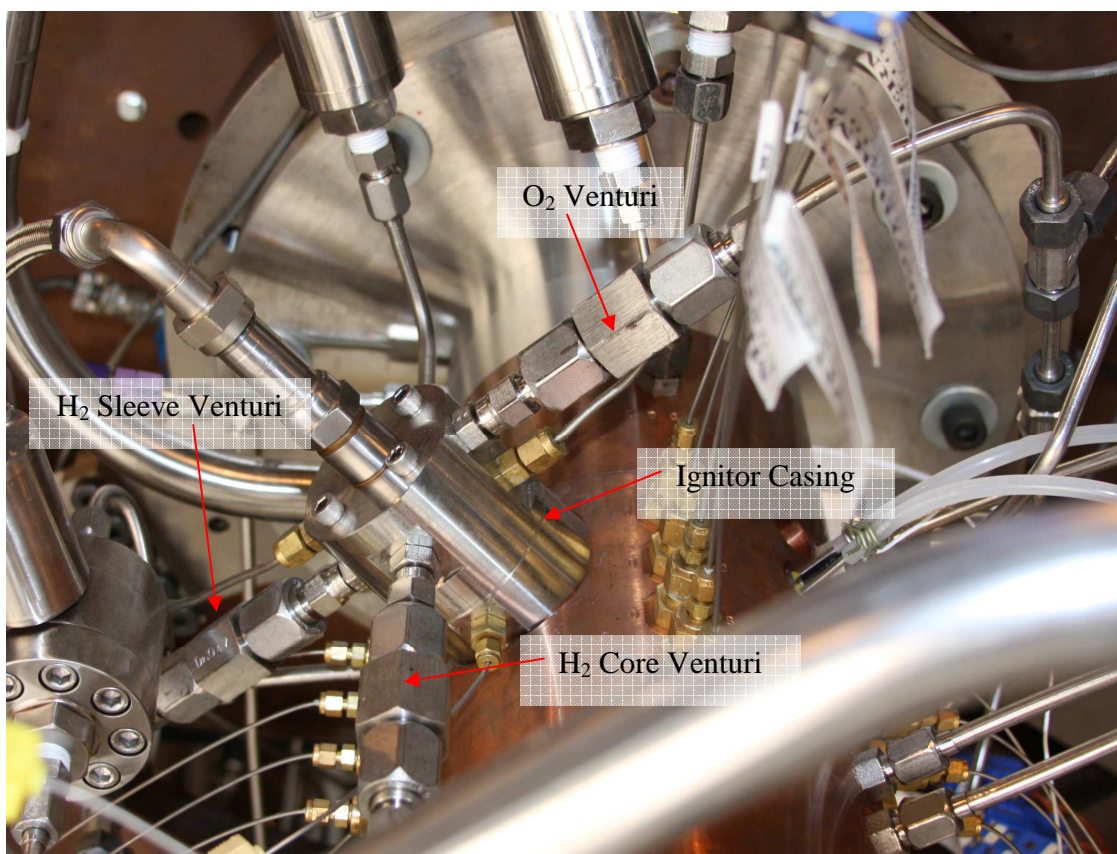

Figure 3.1: Ignitor R3.V2 Installation on Primary HOMEE Project – 7/28/2008

The double check valve on the ignitor fuel purge circuit, showin in Figure 3.2, is to prevent contamination of the O_2 system. The second check valve is for redundancy in the event the first one fails. A failure of both check valves would result in a potential back flow of H_2 or combustion gases into the O_2 feed system, and is to be avoided.

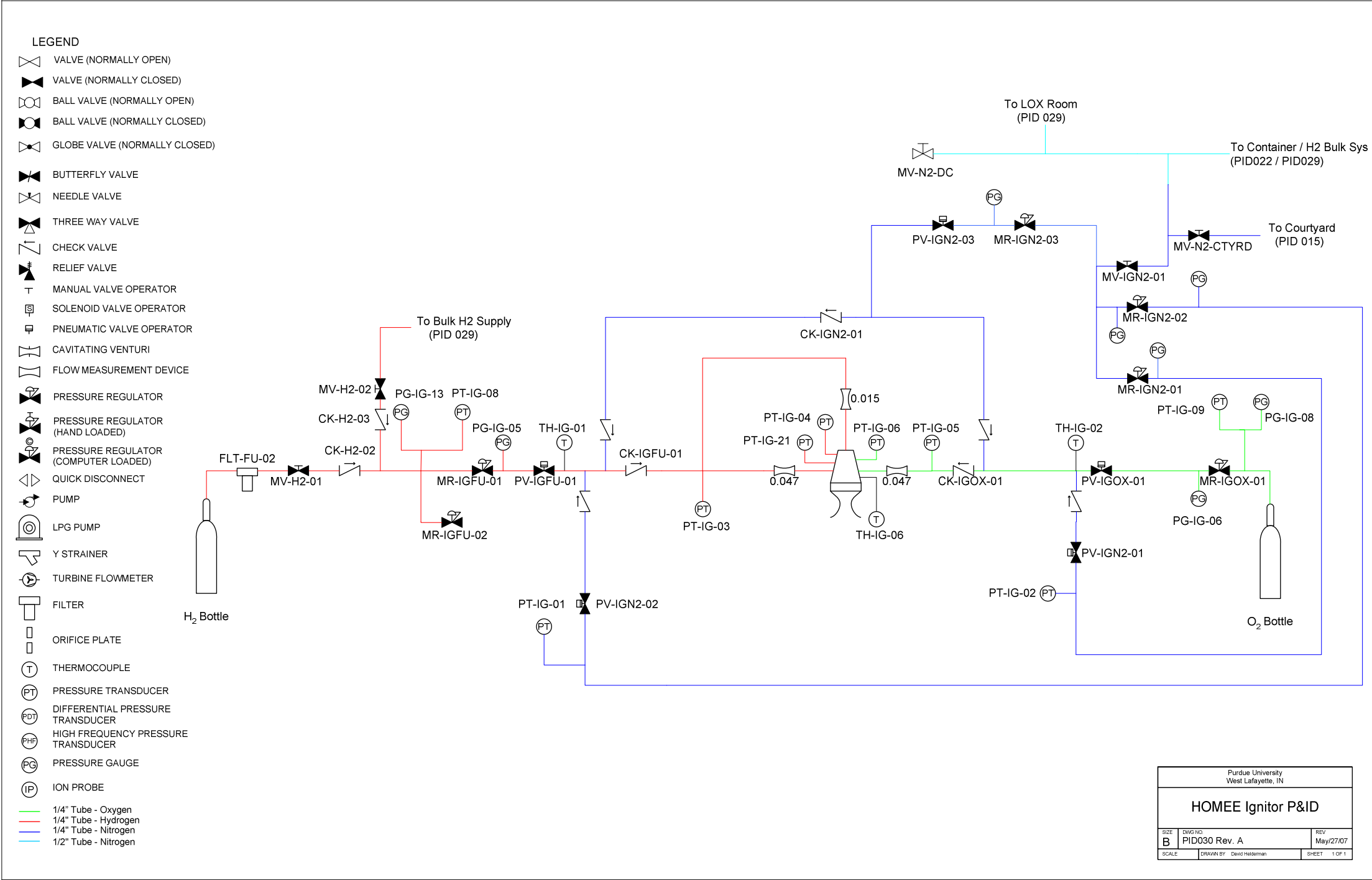## 3.2. Plumbing and Instrumentation Diagram (P&ID)

Figure 3.2: Purdue Ignitor P&ID

CHAPTER 4. IGNITION SYSTEMS

Several different ignition systems have been used with varying degrees of success throughout the various stages of the ignitor program. Initially an MSD high performance automotive ignition system was used, and was very reliable, but induced a lot of noise into the data. An Allanson furnace transformer was also used with a high degree of success and minimal induced noise. Additional alternative power supplies have been tested, but none have currently been used on the ignitor for an actual hot fire test.

4.1. Allanson Furnace Transformer

The Allanson furnace transformer used is a model 1092 Type N and outputs 6000V at 60Hz. This generates a 60Hz spark inside the ignitor which has been repeatedly demonstrated to be more than sufficient for ignition. Although the actual required voltage needed has not yet been determined, 6kV has also been shown to be sufficient.

4.2. MSD Ignition Coil

A two stage MSD automotive racing system ignition was used with a function generator to generate a 14Hz, 45,000V spark. This first stage is an MSD Digital 6-plus model 6520 step up transformer, which produces a pulsed 500V output. This output is then input to a MSD Blaster model 8207 to produce a 45kV pulsed output. This system has also been used repeatedly and performs well with the exception of the aforementioned noise issue.

4.3. <u>Spark Plug Cables</u>

Two different types of cables have also been used, both with a high degree of success. The first is an MSD heli-core 8mm wire (P/N: 3401) with a standard automotive end to connect to the MSD blaster coil. The spark plug end termination kit can be purchased from BG Systems (P/N: 21980-02). A cable can then be cut to length, and the end connectors installed for custom lengths. This is the cable and method preferred by Sierra Engineering, Inc. for their ignitor. It should be noted that the MSD cable has a very high resistance inherent to the design.

The second type of cable is manufactured by BG Systems and includes a metal braided overwrap for noise reduction. There are two different cables one for the Champion spark plug (P/N: 25638-108-18) and one for the Auburn spark plug (P/N: 25694-108-18). This cable had an appropriate end connection for the spark plug as well as a metal overwrap connected to the ignition system box with an unshielded section inside the box as shown in Figure 4.1. This cable has proven very reliable and has been used without problem with the Allanson furnace transformer. Because the cable has a very low resistance it should NOT be used with the MSD ignition system as the cable will rapidly deteriorate and begin sparking off the metal overwrap.
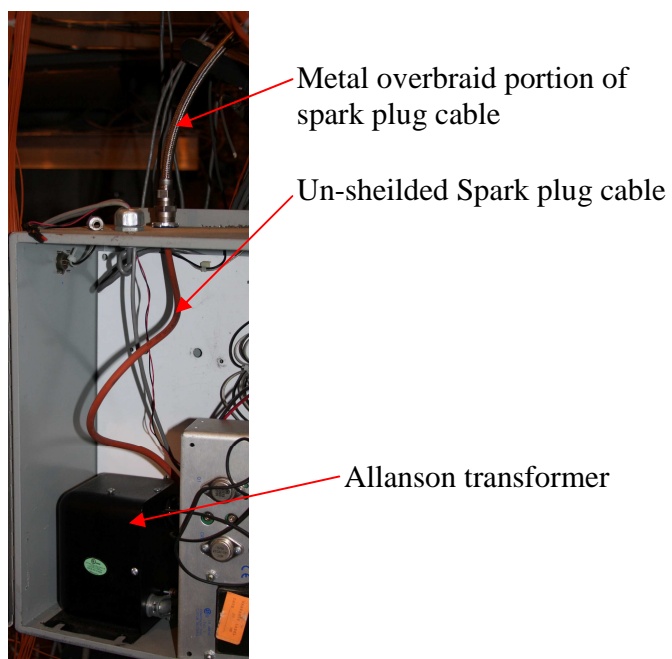
Figure 4.1: Preburner ignition box with Allanson transformer and BG Systems Cable

CHAPTER 5. CONCLUSIONS

5.1. <u>Future Design Opportunities</u>

There are several potential modifications that could be considered for improvement for a Rev. 4 design. The three that have the high potential near term applications are:

- The integration of the orifices into the ignitor casing to eliminate the need for venturis in the lines and simplify installation.

- The removal of all elastomeric O-rings and replace with metal seals/shims to allow for higher back pressure and temperature operation

- Develop or find inexpensive spark plug rated for high pressures to reduce overall cost of ignitor components

There are many additional design improvements that could be considered, however the three previously mentioned would provide significant tangible benefits to the project with minimal investment.

5.2. <u>Methane Redesign</u>

To facilitate the use of CH_4 as a fuel a slight redesign is required. A minimum core O/F ratio of 20 is required to prevent the insert from burning up. To achieve an O/F of 20+ the CH_4 flow rate must be substantially high to fill the core manifold and exceed the O_2 core pressure. With the current design this is not possible, as the exit holes from the manifold into the core are too large. These holes need to be shrunk to allow for a higher pressure rise in the manifold to get the impinging jet of CH_4 into the core O_2 stream.

5.3. <u>Acknowledgements</u>

LIST OF REFERENCES

[1] Repas, George. "Hydrogen-Oxygen Torch Ignitor." NASA TM 106493, 1994.

[2] Dambach, E., Helderman, D., Boopalan, A., and Kite, T., "Spark-augmented Torch Ignitor Part I," Purdue University Internal Report, West Lafayette, IN, Spring 2006.

[3] Nugent, N. J., Helderman, D. A., Boopalan, A., and Anderson, W. E., "Breakdown Voltage Determination for Gaseous and Cryogenic Propellants," AIAA Paper 2007-5440, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit,Cincinnati, OH, July 8-11, 2007.

[4] Nugent, N. J., Helderman, D. and Anderson, W. E., "Isolated Ground Return Electrode for Use in Gaseous and Cryogenic Propellants," AIAA Paper 2008-4758, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford, CT, July 21-23, 2008.

[5] Boopalan, Avanthi and Helderman, David, "Spark-augmented Torch Ignitor: Part II," Purdue University Internal Report, West Lafayette, IN, Fall 2006.

[6] Nugent, Nicholas, "Breakdown Voltage Determination in Gaseous and Near Cryogenic Fluids with Application to Rocket Engine Ignition," Doctoral Thesis, Purdue University, West Lafayette, IN, August 2009.

[7] Miller, Richard. Flow Measurement Engineering Handbook. Third Edition. Boston: McGraw-Hill, 1996.

[8] HTTP://WEBBOOK.NIST.GOV/CHEMISTRY

[9] Helderman, David A. "Measurement and Analysis in a Subscale Rocket Combustor," Masters Thesis, Purdue University, West Lafayette, IN, August 2009.

Appendix A. Installation Procedures

1) Inspect and clean ignitor casing and insert for oxygen service.
2) Clean ignitor casing surface with AK-225 (or similar) and inspect for scratches
3) Clean ignitor mounting surface, on main chamber, with AK-225 (or similar) and inspect for scratches.
4) Apply Krytox to metal o-ring and install into groove on the main chamber.
5) Inspect and clean ignitor casing for oxygen service.
6) Place ignitor casing onto main chamber, with thermocouple port in the downstream location.
7) Apply Krytox to 4 - 1/4"-20 x 3.25" bolts and insert into mounting holes of the ignitor casing. Torque to 10 ft-lb in the appropriate pattern.
8) Thoroughly inspect ignitor insert and clean for oxygen service.
9) Clean brass washer and slip around bottom of ignitor insert ensuring full contact.
10) Apply Krytox to Viton 2mm x 9mm o-ring and slip around bottom of ignitor until it rests against the bottom of the threaded section.
11) Liberally apply Krytox to ignitor insert threads and thread into ignitor casing using special 3-pin tool. 3-pin tool should be cleaned with AK-225 (or similar) before being used.
12) Measure depth of ignitor insert from the top surface of the casing to the top surface of the ignitor insert and ensure that the depth is 0.59" +/- 0.01".
13) Choose proper spark plug (Pc > 750 psia use Champion CH31887-3, Pc < 750 psia use Auburn S1-140 / I-33)
14) Trim electrode to 0.943" +/- 0.005" from sealing surface using a Dremel (or similar) tool.
15) Slide copper gasket of thickness 0.04" +/- 0.005" onto spark plug.
16) Apply Krytox to spark plug threads and install into ignitor casing ensuring compression of copper gasket. Torque to 17 ft-lb.
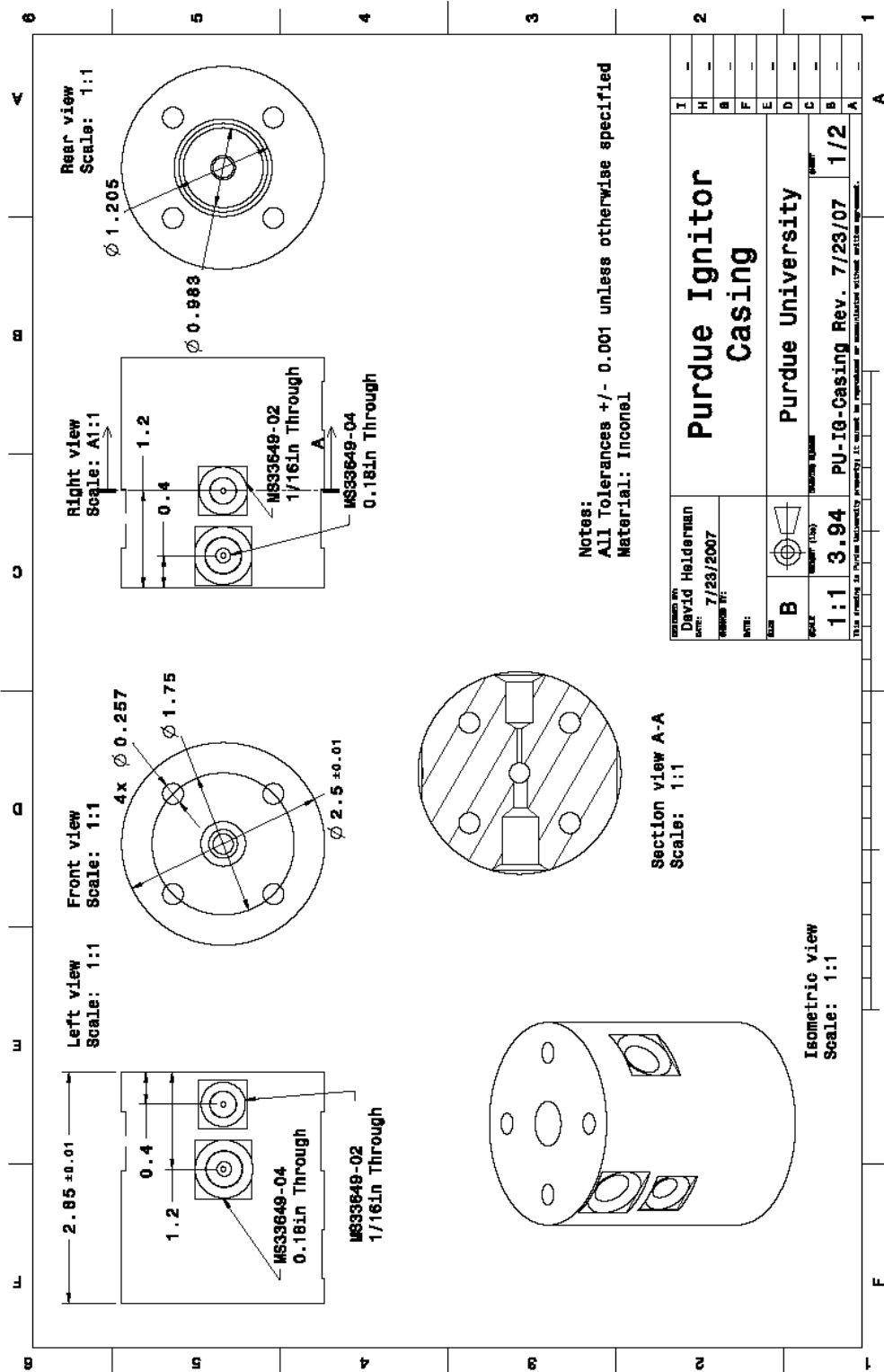
Appendix B. Design Drawings
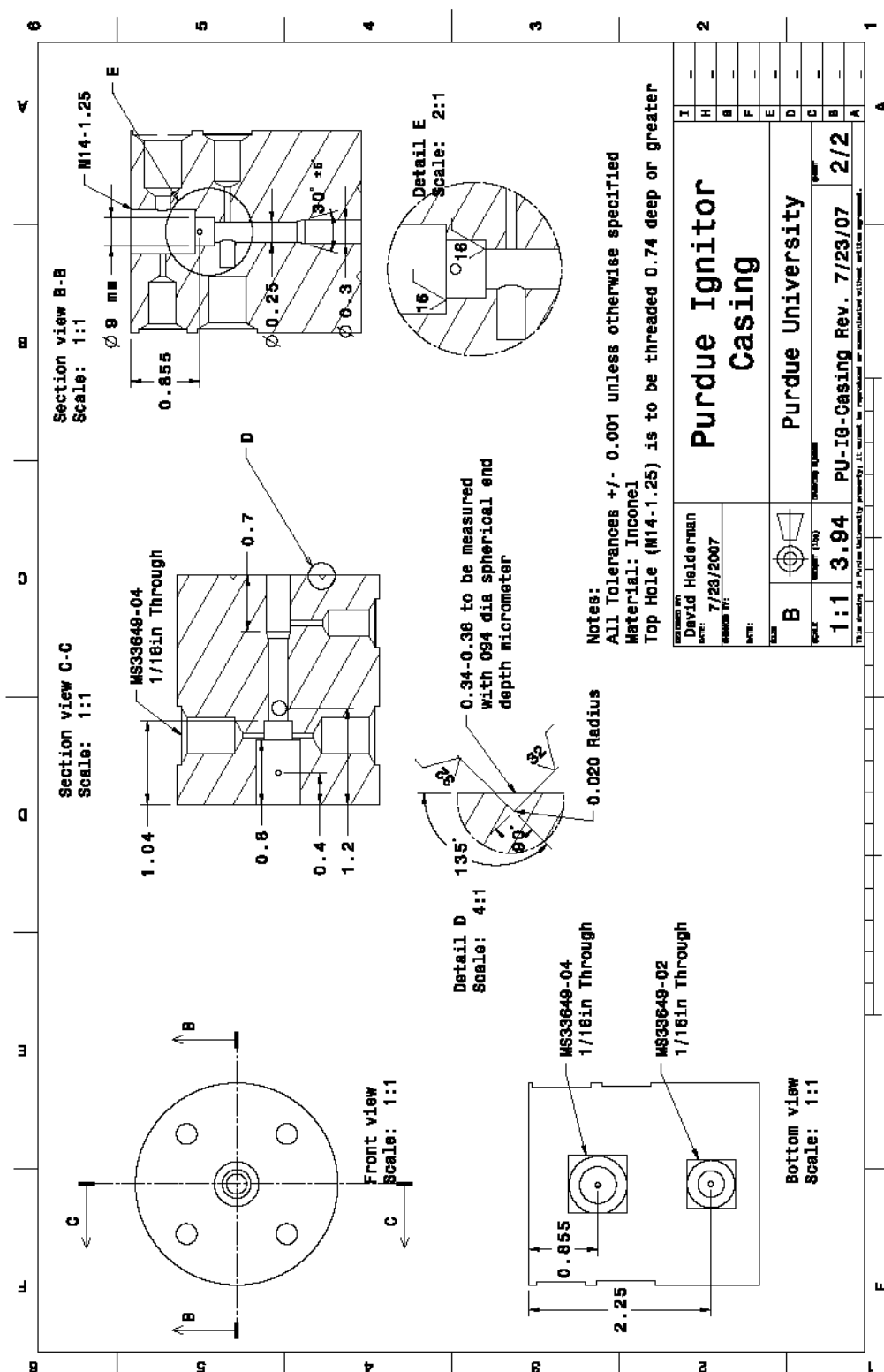

Figure B.1: Ignitor Casing (Page 1/2)
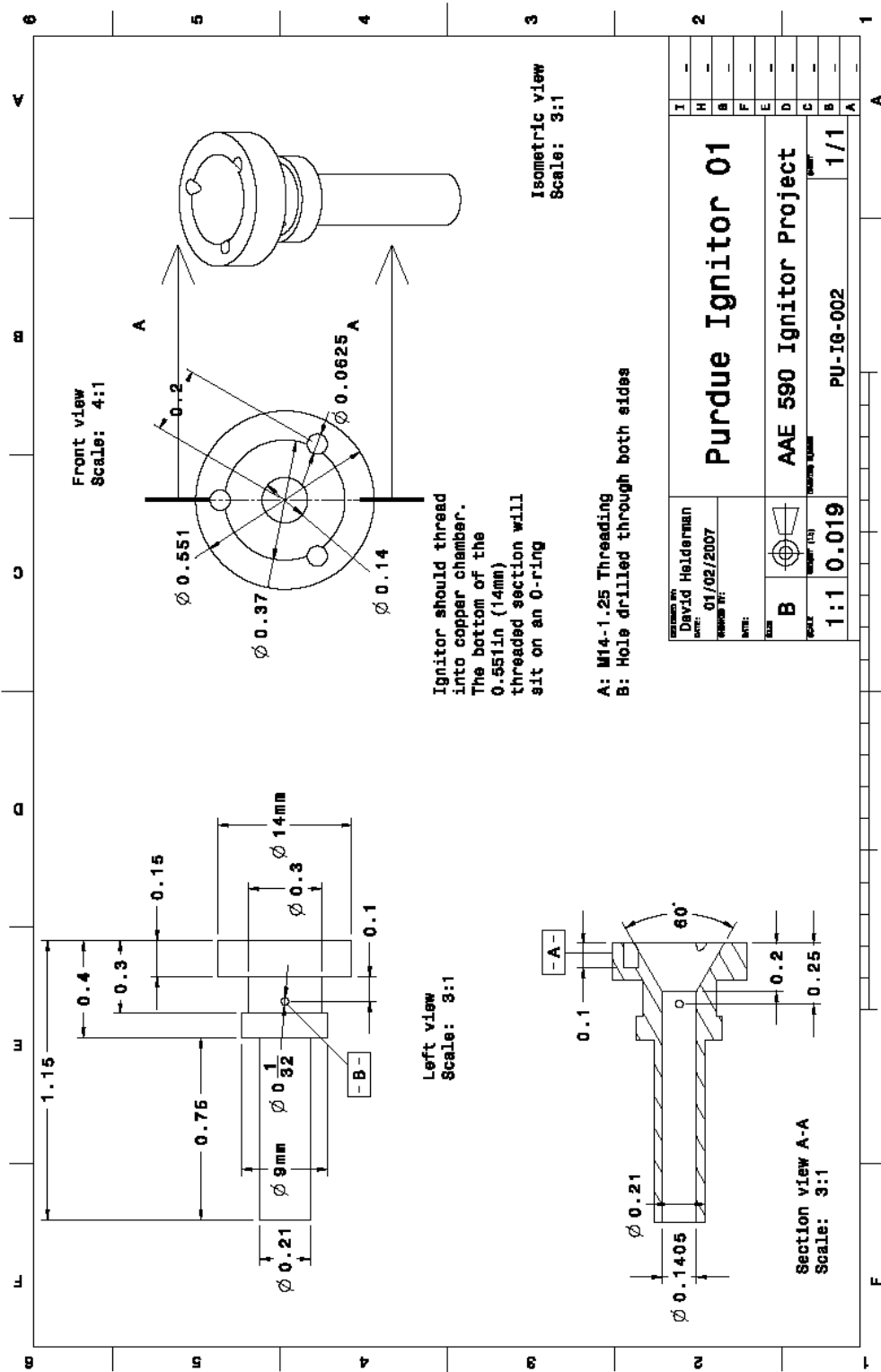
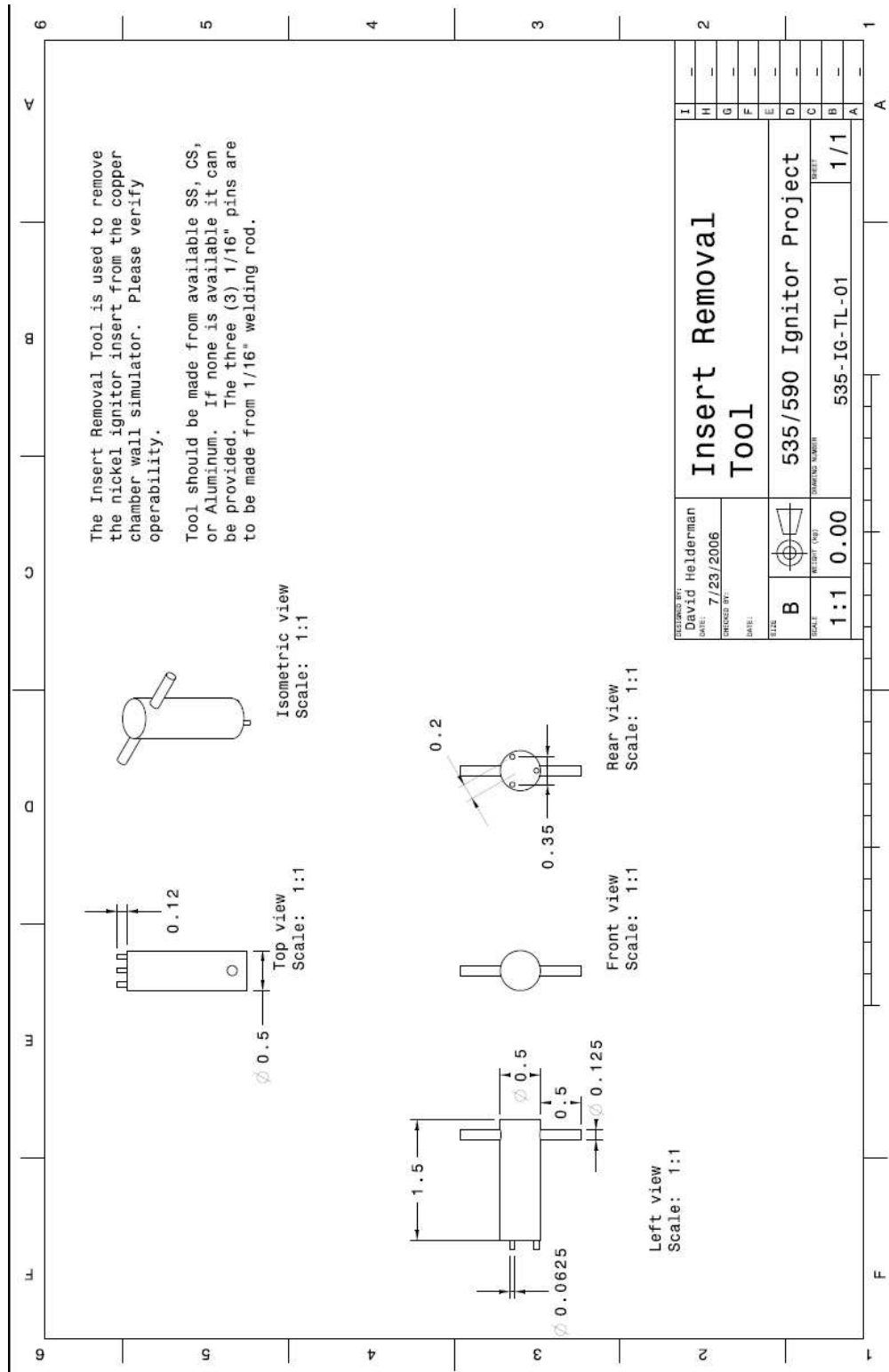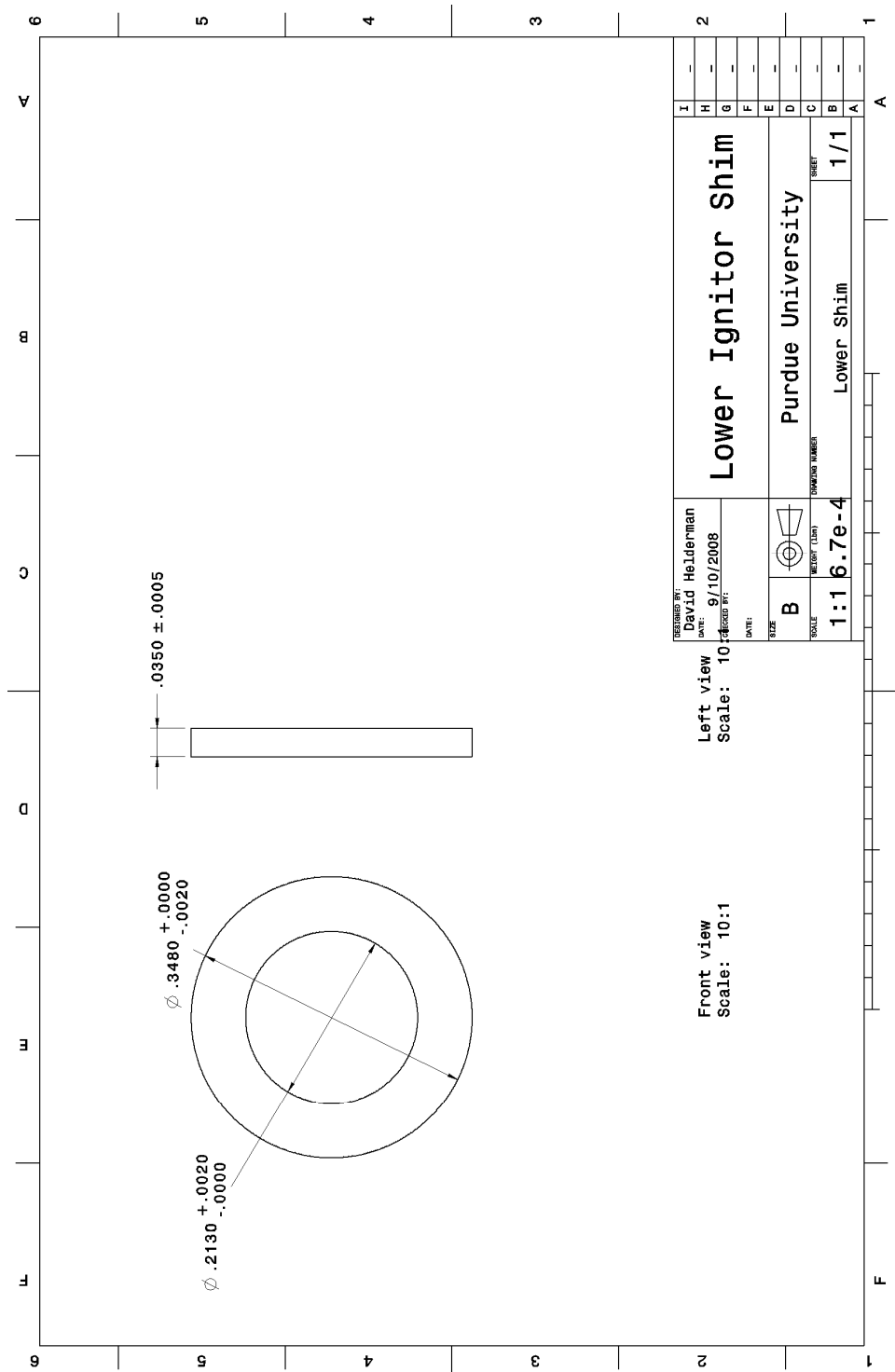Figure B.2: Ignitor Casing (Page 2/2)

Figure B.3: Ignitor Insert

Figure B.4: Ignitor Insert Removal Tool

Figure B.5: Ignitor Lower Sealing Washer