Trevor Zinky
Dylan Potter
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ME 102B: Mechatronics Design
Professor Hannah Stuart

Pyrovalve Report

1. Opportunity

A pyrovalve is used to control fluid flow and is most commonly used in the aerospace industry; the pyrovalve differs from other mechanically actuated valves by generating pressurized gases, usually via an explosive charge, to move an internal plunger to permit flow, as discussed in greater detail in the device strategy section of the report. This method of actuation, while only permitting a single-time use, creates a higher degree of reliability compared to other valve options, especially in a zero-G environment, and thus makes it a popular option for non-reversible systems (e.g. primary launch stages, pneumatically controlled stage separation, etc.); additionally, pyrovalves are consistently cheaper and smaller than other mechanical valves of comparable performance, such as a solenoid or ball valve. As a final advantage, pyrovalves generally possess lower power requirements than comparable mechanical valve options.

As such, creating reliable pyrovalves has broad applicability in the aerospace industry. Currently, there is a growing subsector of the aerospace industry and academia pursuing rocket miniaturization, specifically for sensing applications. Therefore, there is a demand for the miniaturization of supporting equipment, specifically valves, to advance this pursuit. This project was conceptualized in this context, with the intention of creating a miniature pyrovalve that could provide the reliability of current commercial pyrovalve options, except at a smaller scale. This project was an exciting opportunity both to gain a deeper understanding of the internal functionality of valves as well as applying useful course concepts to devise an appropriate state machine, properly size and source fittings, including bolts and washers, interface with analog and digital inputs, design locating features, and ensure the custom-made actuator fulfilled performance requirements.

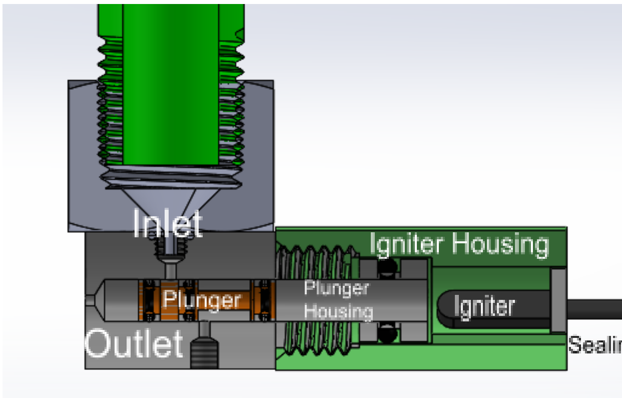
Project Required Components:

- Moving parts - Internal plunger. Difficulty arises not from the scale of motion, but rather the requisite precision of motion.
- Actuator - Project revolved around creating and utilizing a custom actuator from scratch
- Analog input - Load cell
- Digital input - Two buttons
- Microcontroller - ESP32
- State machine using event driven programming - Implemented state machine with event driven programming

Course components used: State machine programming, sourcing appropriate parts, choosing appropriate fittings, locating features. Also gained extensive experience in manufacturing and tolerancing, as well as sizing and installing O-rings.

2. Device Strategy

In a pyrovalve, fluid flow is controlled by moving an internal plunger from the closed to open configuration. In the closed configuration, the plunger is aligned such that the inlet is bounded between two sealing O-rings and the large-diameter section of the plunger (figure 1), thus preventing any fluid flow from the inlet. Upon actuation, gases are created to push the plunger out of the closed configuration.



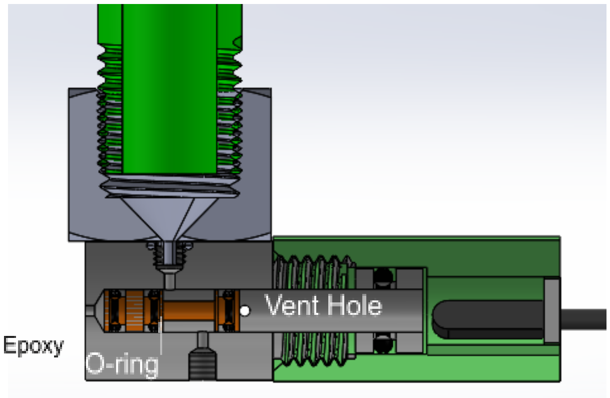


Fig. 1: Closed Configuration **Fig. 2: Open Configuration**

For the purposes of this project, an igniter was used to generate the necessary gases; it was chosen since it is the safest to handle and has little explosive power. The primary safety concern surrounding igniters is that they should only be used in a well-ventilated area since the created gases are not safe for inhalation; this was addressed by conducting all tests outdoors. Additionally, it is necessary that the igniter housing be airtight such that all energy associated with the created gases is used toward moving the internal plunger. This proved challenging in the development of this project, requiring approximately 12 tests featuring different iterations of the igniter housing and plunger housing before a reliable design was achieved.

Once the plunger moves, the inlet is aligned with a smaller-diameter portion of the plunger such that flow can occur around it (figure 2), thus connecting the inlet and outlet and allowing flow through the valve. In this open configuration, the igniter housing is exposed to a small vent port after the plunger has moved such that the generated gases can escape. There is a physical locating feature at the end of the internal plunger housing to stop the plunger motion and ensure the inlet and outlet are aligned appropriately. The inlet also acts as a locating feature for the closed configuration.

Compared to our original design ideas in previous project submissions, this design is much smaller than our first prototype as we were able to successfully reduce the size of the device. It also does incorporate all the basic features of the valve as desired in previous submissions with the addition of other physical features (such as the addition of the o-ring grooves on the plunger housing) which have been added to improve the project functionality.

3. Integrated Physical System and Function Critical Decisions

In creating the valve, there were several fundamental design considerations that ultimately shaped the final design. Firstly, the manner in which the igniter is electrically actuated needed to be determined. A transistor was considered to control this actuation, but the available lab kit transistor (i.e. the MOSFET) had insufficient maximum amperage restrictions. The igniter draws 1 A of current, while the lab kit transistor has a maximum drain current of 500 mA; this amperage was tested, but it was insufficient to actuate the igniter. A relay was then used due to its high amperage capacity.

Additionally, the minimum attainable size (since the project objective was miniaturization) was constrained by the smallest commercially available O-rings (2mm ID, 4mm OD). This determined the dimensions of the internal plunger housing, which all other features referenced; thus, relative to this internal housing, the other valve features' dimensions were determined appropriately. The internal housing dimension was based upon the principle that the O-ring needs to be stored in compression, but no more than 3% of the outer diameter of the O-ring.[1] As such, we decided to store the O-ring in 0.5%

compression, which translated to an internal diameter of 3.98mm for the internal plunger housing. This was later empirically confirmed to be an appropriate compression for full sealing. Also, upon installation, lubrication was used such that the plunger with the O-rings installed could be pushed into the correct position in the valve body. One primary challenge that arose was reaching appropriate manufacturing tolerances such that the 3.98 mm ID could be realized to sufficient accuracy to maintain the airtight sealing of the plunger. This required many iterations, but it was eventually successfully attained. An additional sealing challenge was the connection point of the charge holder to the valve body. This was addressed by utilizing teflon tape around the threads to provide additional sealing.

As the igniter has limited information about what type of pyrogen it contains and how much gas it uses, calculations could not be easily completed for the force or pressure generated by the igniter; therefore, working conditions were determined empirically.

4. Circuit and State Transition Diagram

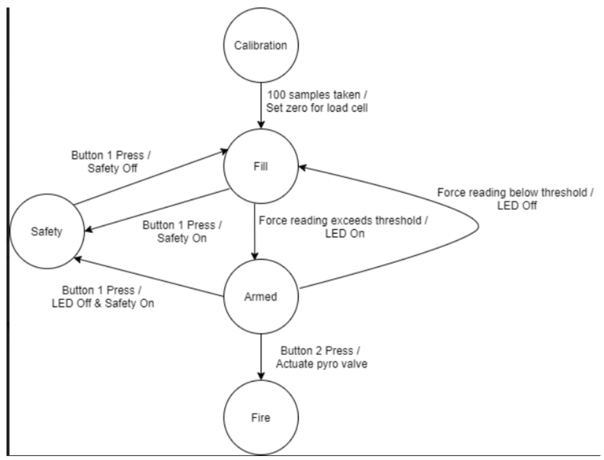


Fig 3: State Transition Diagram

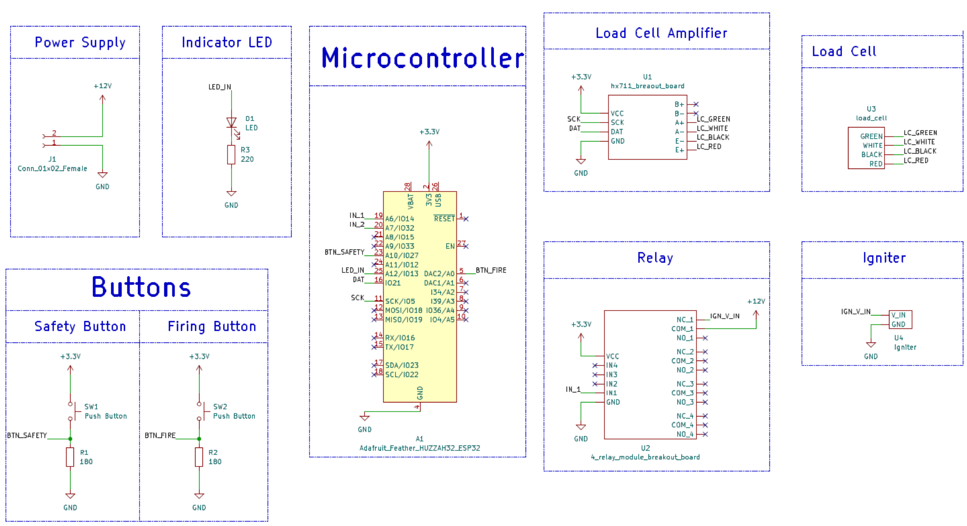


Fig 4: Circuit Diagram

5. Reflection

This project was successful overall. Creating a prototype early which could be iterated on many times worked very well for us and allowed us enough time to design, order, and manufacture updated parts after previous iterations didn't work. If doing this project again, we would buy a 3d printer because one of the most challenging parts of this project was dealing with very long lead times and inconsistent print quality from the Jacobs Project Support.

References

[1] *Eriks NV - O-Ring Technical Handbook - O-Ring assembling* . Eriks. (n.d.). Retrieved December 12, 2021, from https://o-ring.info/en/o-ring/technical%20handbook/15%20-%20eriks%20nv%20-%20o-ring%20technical%20handbook%20-%20o-ring%20assembling%20conditions.pdf.

Appendix A: State Machine Code

state_machine

```
#include <Arduino.h>
#define BTN 27  // declare the button ED pin number
#define BTN2 26  // declear the speaker pin number
#define LED_PIN 13 // dlclare the builtin LED pin number
#define POS 32
//#define POS2 21
#include "HX711.h"

float THRESH = 12500;
float zero;
hw_timer_t* timer = NULL;

//Setup variables ------------------------------------
const int freq = 5000;
const int pwmChannel = 0;
const int resolution = 8;
int state = 1;
float runningSum = 0;
int numElements = 0;
unsigned long runningTime = 0;

HX711 scale;
const int LOADCELL_DOUT_PIN = A2;
const int LOADCELL_SCK_PIN = A1;

//Initialization ------------------------------------
void IRAM_ATTR isr() {  // the function to be called when interrupt is triggered
  unsigned long currentTime = millis();
  if ((state == 1 || state == 2) && (currentTime - runningTime) > 350) {
    state = 3;
    runningTime = currentTime;
    digitalWrite(LED_PIN, LOW);
  } else if (state == 3 && (currentTime - runningTime) > 350) {
    state = 1;
    runningTime = currentTime;
    digitalWrite(LED_PIN, LOW);
  }
}

void IRAM_ATTR isr2() {
  if (state == 2) {
    state = 4;
    actuate();
    //digitalWrite(LED_PIN, LOW);
  }
}
```

state_machine

```
void setup() {
  // put your setup code here, to run once:
  pinMode(BTN, INPUT);  // configures the specified p
  pinMode(LED_PIN, OUTPUT);
  pinMode(POS, OUTPUT);
  pinMode(BTN2, INPUT);
  attachInterrupt(BTN, isr, RISING);
  attachInterrupt(BTN2, isr2, RISING);
  Serial.begin(57600);


  //ledcSetup(pwmChannel, freq, resolution);
  //ledcAttachPin(SPK, pwmChannel);
  digitalWrite(LED_PIN, LOW);
  digitalWrite(POS, HIGH);
  Serial.println("POS LOW");
  //digitalWrite(POS2, HIGH);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  //scale.set_scale();
  //scale.tare();
  zero = 0;
  zero = calibrate();
  //zero = 0;
}

void loop() {
  // put your main code here, to run repeatedly:
//  ledcWriteTone(pwmChannel, 440);
  // delay(100);
  switch (state) {
  // State 1 is filling
  // State 2 is armed
  // State 3 is safety
  // State 4 is firing
  case 1:
    pollingState();
    break;
  case 2:
     pollingState2();
     break;
  case 3:
     break;
  case 4:
     break;
  }
}
```

Case 3 does not have an event checker since the interrupt attached to the safety button performs this function and case 4 does not have an event checker since it is a terminal state

state_machine

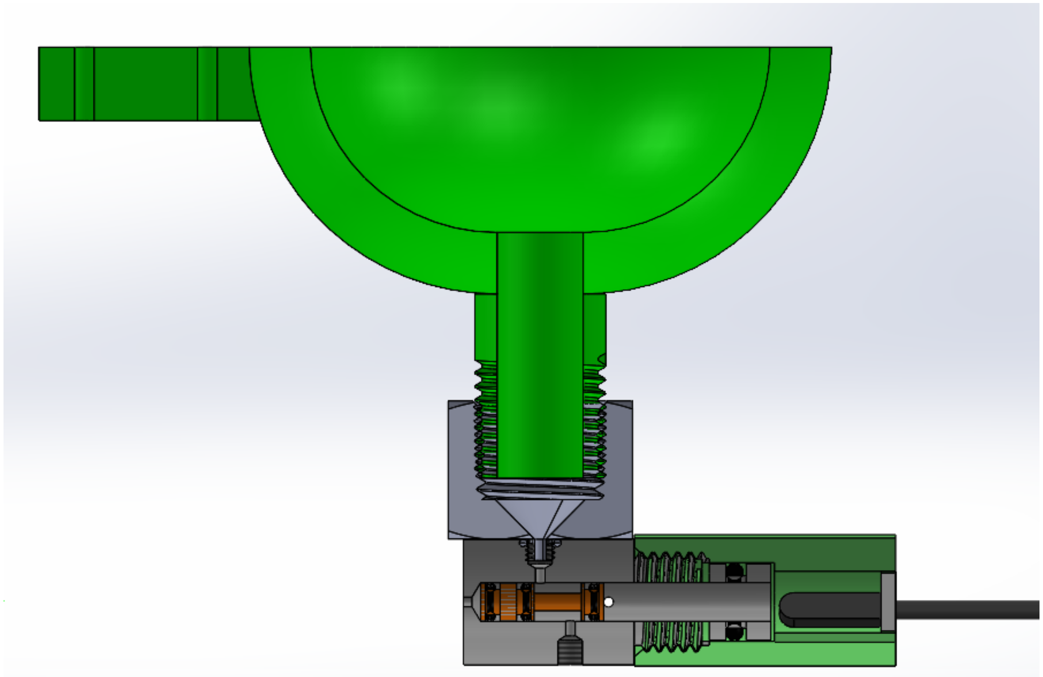
```
void pollingState() {
  if (scale.is_ready()) {
    float currReading = getReading();
    if ((currReading - zero) >= THRESH) {
      digitalWrite(LED_PIN, HIGH);
      state = 2;
    }
  }
}

void pollingState2() {
  if (scale.is_ready()) {
    float currReading = getReading();
    if ((currReading - zero) < THRESH) {
      digitalWrite(LED_PIN, LOW);
      state = 1;
    }
  }
}

// Reads analog input
float getReading() {
  // ADD LOGIC
  float reading = abs(scale.get_units());
  Serial.println(reading - zero);
  return reading;
}

// Use IRAM_ATTR to force use of RAM memory, which is
// accessible in constant time. This is faster than
// resorting to flash memory. Since this is an ISR, we
// want fast performance
void IRAM_ATTR onTime() {
  if (scale.is_ready()) {
    runningSum += getReading();
    numElements+=1;
  }
}

float calibrate() {
  // Create timer
  // Take 100 samples
  // Average all readings
  // Return average (represents zero)
  //timer = timerBegin(0, 80, true);
  //timerAttachInterrupt(timer, &onTime, true);
```

state_machine

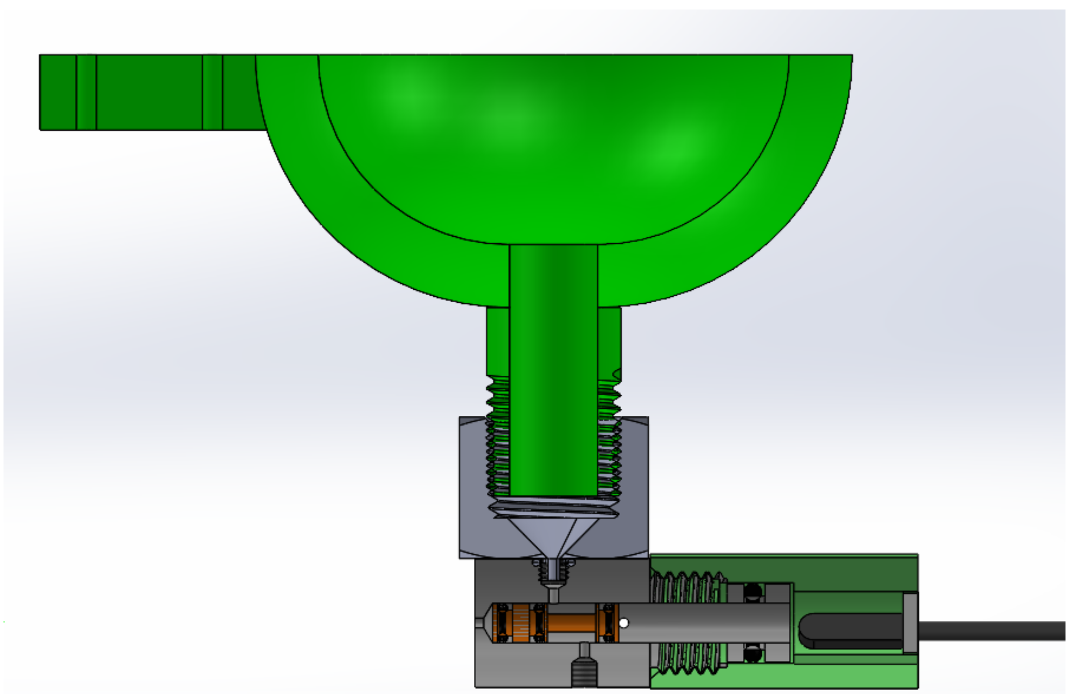
```
  Serial.println(reading - zero);
  return reading;
}

// Use IRAM_ATTR to force use of RAM memory, which is
// accessible in constant time. This is faster than
// resorting to flash memory. Since this is an ISR, we
// want fast performance
void IRAM_ATTR onTime() {
  if (scale.is_ready()) {
    runningSum += getReading();
    numElements+=1;
  }
}

float calibrate() {
  // Create timer
  // Take 100 samples
  // Average all readings
  // Return average (represents zero)
  //timer = timerBegin(0, 80, true);
  //timerAttachInterrupt(timer, &onTime, true);
  // 20 readings/second
  //timerAlarmWrite(timer, 50000, true);
  //timerAlarmEnable(timer);
  while (numElements < 100) {
    //Serial.print("Num Elements: ");
    if (scale.is_ready()) {
      Serial.println(numElements);
      runningSum += getReading();
      numElements++;
    }
  }
  Serial.println("Calibration complete");
  //timerStop(timer);
  return runningSum / 100;
}

void actuate() {
  //ledcAttachPin(SPK, pwmChannel);
  digitalWrite(POS, LOW);
    Serial.println("ACTIVATE");
  digitalWrite(LED_PIN, LOW);
}
```

Appendix B

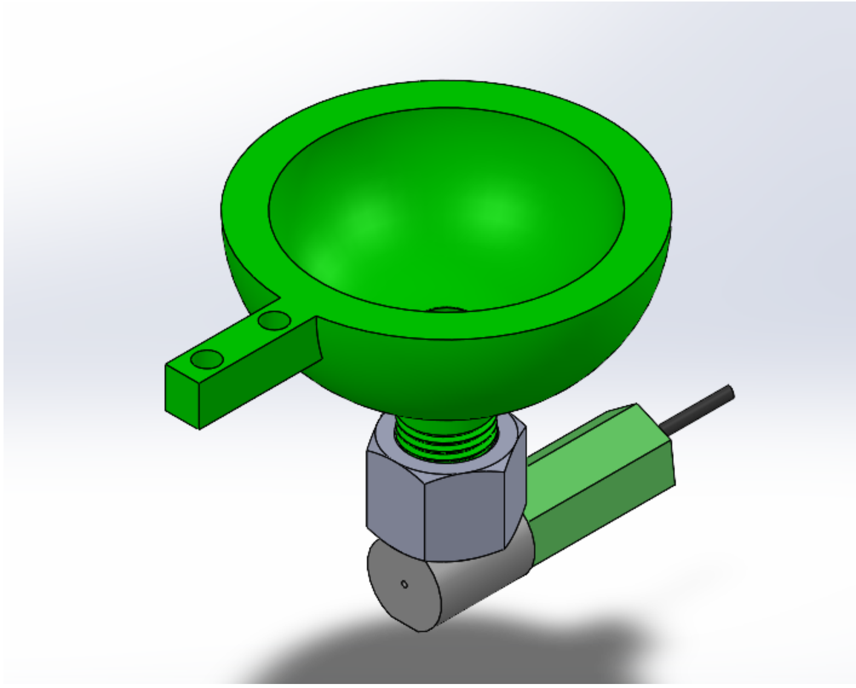
Appendix B contains additional full-size images of the CAD along with pictures of the final design and prototype designs



Valve in the closed position



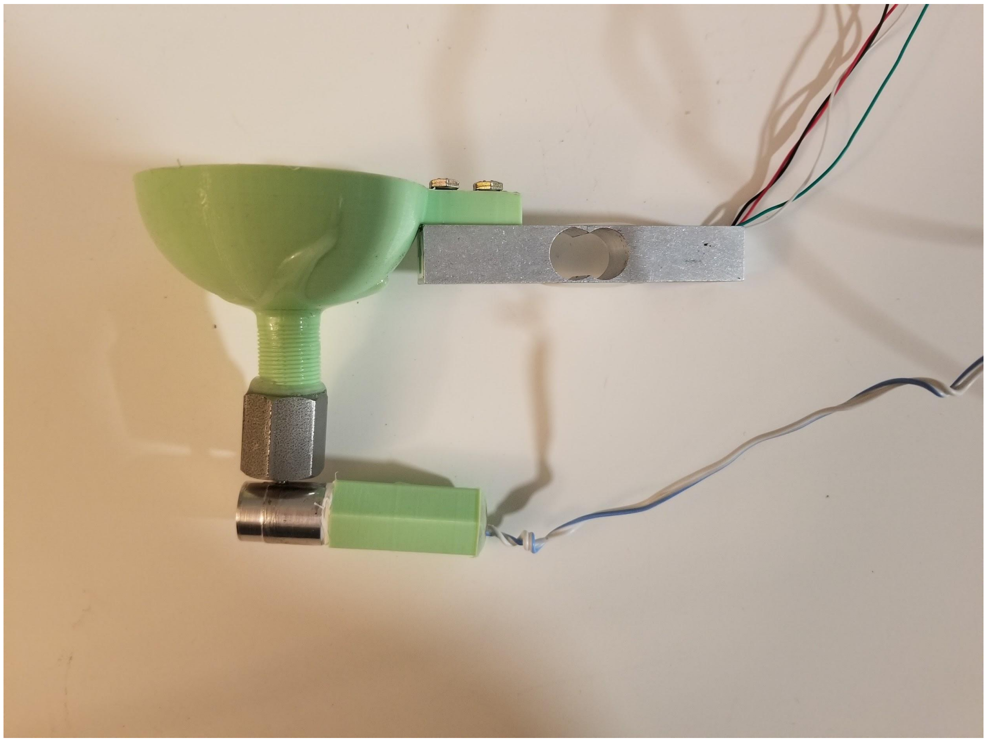
Valve in the open position



Isometric view of the valve assembly

Valve body and plunger with a dime for scale

Pyro valve body prototypes and final design



Integrated design

Appendix C

Appendix C shows the updated bill of materials for the pyro valve

									Total (Projected):	$ 157.63
Item Name	**Description**	**Purchase Justification**	**Serial Number / SKU**	**Price (ea.)**	**Quantity**	**Vendor**	**Link to Item**	**Notes**	**Subtotal**	
Aluminum Rod	6061 Aluminum Rod 9/16"	Used for machining housing for valve, and reservior	8974K46	$3.51	1	McMaster Carr	https://www.m		$ 3.51	
O-ring	-008 Viton O-rings	Seals the pyro valve charge holder	9464K13	$6.87	1	McMaster Carr	https://www.mcmaster.co		$ 6.87	
O-ring	2 mm ID O-rings	Seals the pyro valve	1295N112	$5.95	1	McMaster Carr	https://www.mcmaster.co		$ 5.95	
Miniature Medium-I	Pipe fitting adapters for valves	Allows connection of the pyro valve	2684K214	$23.97	2	McMaster Carr	https://www.mcmaster.co		$ 47.94	
Krytox Grease	Krytox Lubriant Grease	Lubricates O-rings for instalation and sealing		$22.98	1	Amazon	https://www.ar		$ 22.98	
PTFE Tape	Inducstrial Sealant Tape	Seals threads on charge holder connecyion		$2.65	1	Amazon	https://www.ar		$ 2.65	
Epoxy	JB Clear Weld 5 Minute Expoxy	Seals the end of the charge holder		$17.81	1	Amazon	https://www.amazon.com		$ 17.81	
Igniters	Previously purchased	Actuator for the pyro valve		$1.50	20	Previously purc	https://www.py		$ 30.00	
Relay	ELLEGO 4 Channel Relay	Controls igniter actuation		$9.99	1	Amazon	https://www.ar		$ 9.99	
Screws	Hex head 8-32, 1" long (5 pack)	Secures reservoir to load cell		$9.93	1	McMaster Carr	McMaster-Carr		$ 9.93	
Aligator clips	Previously purchased	Connecting loose leads to microcontroller		$0.00	2	Previously purchased			$ -	
12 V/ 2 A	Previously purchased	Higher voltage and current supply for actuating igniter		$0.00	1	Previously purchased			$ -	
ESP32	From lab kit	Microcontroller for electonic control		$0.00	1	From lab kit			$ -	
Breadboard	From lab kit	Connections for components		$0.00	1	From lab kit			$ -	
Leads	From lab kit	Connecting components together		$0.00	1	From lab kit			$ -	
Load Cell	From lab kit	Analog input sensor		$0.00	1	From lab kit			$ -	
Strain gauge ampli	From lab kit	Allows the microcontroller to read the pressure transduce		$0.00	1	From lab kit			$ -	
Button	Standard pushbutton	Digital input for control of state machine		$0.00	2	From lab kit			$ -	
Diode	Standard diode	Indicates system state		$0.00	1	From lab kit			$ -	

Bill of materials for the pyro valve