Failure Modes and Effects Analysis (FMEA)

RMTS Industries

Rocket Motor Test Stand

Program Manager Signature: ________________________

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Acronyms

Rocket Motor Test Stand ….. **RMTS**
Engineering Analysis Package ….. **EAP**
Failure Modes and Effects Analysis ….. **FMEA**
Direct Current ….. **DC**

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Purpose

The purpose of the Failure Modes and Effects Analysis (FMEA) document is to outline possible failures and their effects on the system. This document will also cover the likelihood of failures, counter measures, and reference the Engineering Analysis Package (EAP) where applicable.

This Failure Mode and Effects Analysis (FMEA) serves as an assessment by the RMTS industry of potential failures of the Rocket Engine Test Stand (RMTS) and their impact on the RMTS itself and surrounding personnel/objects. This information is crucial for ensuring the safety of personnel and property involved in rocket engine testing and operation.

The FMEA will identify high-probability events, describe the root causes of critical system failures, and propose mitigation measures to reduce the risk and/or impact of these failure modes.

Finally, by defining potential failure zones within the system, this document will also serve as a guide for developing test plans and procedures to accurately quantify risk factors and implement changes as necessary.

System Summary

RMTS Industries is contracted by University of Alaska (UAF) Aerospace Engineering Program to design and build the Rocket Motor Test Stand (RMTS).

Description

The RMTS is a test system compatible with National Association of Rocketry (NAR) 1/8A to Class I high-power motors. In terms of safety, it must withstand the thrust of 1/8A to Class I motors, with structural components employing a 5X safety factor to ensure protection for users and surrounding property in the event of an accident.The system's total weight must not exceed 500 pounds, with individual components weighing no more than 100 pounds, and it must be able to be assembled or deployed by one person within 30 minutes and be rapidly disassembled. The RMTS must be able to operate year-round outdoors in Alaska, including temperatures as low as -40 degrees Fahrenheit (40 degrees Celsius), and has a minimum 20-year operational lifespan with minimal maintenance requirements. The RMTS can be disassembled into seven components and transported using a 6.5-foot (1.98 m) pickup truck bed or a dedicated trailer for deployment to Poker Flat Research Range (PFRR), Kodiak Pacific Spaceport Complex (PSC), and remote areas.

Theory of Operation

This Failure Mode and Effects Analysis (FMEA) is a structured analysis based on the identified RMTS (Rocket Engine Test Stand) subsystem categories. The analysis outlines the causes and consequences of each potential failure mode, providing a thorough assessment of the inherent risks and probabilities in system operation. The analysis includes three quantifiable metrics from the FMEA standard: Severity (S), Occurrence (O), and Detectability (D), each ranked on a scale of 1-10. The product of these three ranks defines the Overall Risk Priority Number (RPN) for that failure mode, guiding the development of mitigation measures. The analysis also includes sections for "Consequences of failure" ,"Cause of failure", and "Countermeasures" to help reduce the risk of system failure.The ranks are described below.

Severity		
Severity Rank	Consequences	Definition
10		Threaten life safety and facility integrity
9	Very high	Not in compliance with regulations
8		Loss of all major functions during the design lifecycle
7	High	Degrade of all major functions during the design lifecycle
6		Loss of subsystem functionality
5		Degrade of subsystem functionality
4	Moderate	Some parts lose their functions, but the whole unit can work normally

3		Some parts degrade their functions, but the whole unit can work normally
2	Low	Minor fault, no impact on operation
1	Minor	No identifiable fault

Some examples of severity ratings include

Occurrence		
Occurrence Rank	Probability	Definition
10	Inevitable	New technology/design with no prior history to refer to. Unpredictable performance.Continuous failure.
9		New technology/design with no prior history to refer to. Prevention controls cannot meet the performance requirements.
8	Very High	New technology/design with no prior history to refer to. Existing experience cannot be applied to current products. Preventive controls cannot reflect field performance.
7		New design based on legacy products for which no validation has been performed. Standards and design rules apply to legacy products. Preventive controls reflect limited performance indicators.
6	High	New designs based on experience with older products. Design and operational experience. Standards and design rules are not comprehensive. Preventive controls can provide some ability to prevent the cause of failure.
5		New designs based on proven technology and experience. Products are evaluated using standards and design rules based on design and operational experience, but are not validated. Preventive controls provide the ability to prevent the cause of failure and provide some performance indicators.
4	Moderate	Optimize and improve existing designs based on short-term operational experience. New designs comply with standards and design rules. Preventive control measures can identify defects related to failure causes and provide performance indicators.
3	Low	Optimize and improve upon a proven design. New designs comply with standards and design rules. Preventive controls can identify defects related to failure causes and predict production consistency with design.
2	Very Low	Design based on long-term operational experience. Design complies with standards and design rules. Preventive control measures can identify defects related to failure causes and provide stable and predictable production and design

		consistency.
1	Minor	Preventive controls can virtually eliminate the cause of a failure.

Some examples of occurrence ratings include

Detection			
Detection Rank	Detection capabilities	Detection method maturity	Methods for Detection
10		Test procedures have not yet been developed,Test methods not yet defined.	None
9	Very Low	The detection methods are not specifically designed for failure modes and causes	Pass/fail testing, Failure testing, Burn-in testing
8		New test method, not validated.	Pass/fail testing, Failure testing, Burn-in testing
7	Low	Proven test methods. These methods are used to verify functionality and confirm design specifications. Insufficient test planning time. Failure to complete the test will impact progress.	Pass/fail testing
6			Failure testing,
5	Moderate		Burn-in testing
4		Proven test methods. These methods are used to verify functionality and confirm design specifications. The test plan has sufficient time. Test failures do not affect progress.	Pass/fail testing
3			Failure testing,
2	High		Burn-in testing
1	Very High	The test method can always detect the failure mode and cause of failure.	

Some examples of detection ratings include

Analysis Results

Detailed results of analysis are in the EAP document. The following sections will briefly show analysis related to overall rating levels of core systems. See the attached table in the appendix for a detailed FMEA form.

Failure Modes

Electrical Subsystem

Power Risks						
Failure	Cause	Effect	Prevention	Probability	Severity	Risk
Power interruption, brownout, or voltage fluctuations	Bad battery or power converters, electronics using more current than expected	Electronics could be damaged, data could be inaccurate or corrupted	Calculate a theoretical power budget, verify current consumption by testing components before installing them, test the fully integrated system, monitor for power issues during RMTS use	5	5	25
Wire short circuit	Loose bare wires, vibration from motor, improper connections	Person gets shocked, fire, damaged electronics, inaccurate or corrupted data	Ensure proper connections when installing components, setting up the RMTS, and between rocket motor tests	3	10	30
Siren and light failure	Insufficient voltage or amperage	No warning of rocket ignition	Test the fully integrated system, monitor for power issues during RMTS use, stop the ignition countdown if the siren or	3	9	27

			light do not work			

Data Risks						
Failure	Cause	Effect	Prevention	Probability	Severity	Risk
Test data corruption	Bad analog to digital converter measurements, errors during RS232 or RS485 transmission, the load cell not working or incorrect wiring	The test data cannot be used or is misleading	Test the load cells with bench equipment and the Arduino's analog to digital converter, test the TTL to RS485 using the Arduino and Raspberry Pi, monitor the data to see if there are errors	5	7	35
Arduino or Raspberry Pi corruption	Electrostatic discharge, data incorrectly written to Arduino's storage or the Raspberry Pi's microSD card	Data gathering software does not work	Test the Arduino and Raspberry Pi while setting up the RMTS and reprogram them if needed	2	8	16
IT problems	Mouse, keyboard, or monitor have dead batteries, break, or won't connect to the Raspberry Pi	The data gathering software cannot be controlled or the data cannot be viewed	Ensure the mouse, keyboard, and monitor are working while setting up the RMTS	4	5	20

			and replace batteries, re-pair Bluetooth connection, or swap peripherals as necessary			

Ignition Risks						
Failure	Cause	Effect	Prevention	Probability	Severity	Risk
The rocket motor cannot be ignited because of insufficient voltage or current	A drop in voltage due to the length of the cable or the battery not supplying the needed current	The rocket motor cannot be tested	Calculate a theoretical power budget, test the fully integrated system, monitor for power issues during RMTS use	5	8	40
Premature ignition	Voltage and current are applied to the ignition circuit early	The rocket motor will ignite, potentially with people too close	Check ignition wiring while setting up the RMTS and inserting the rocket motor, follow all rocketry rules about when the interlock key can be inserted and the rocket motor ignited	2	10	20

The biggest risks for the electrical subsystem are related to a failed test, either due to an ignition issue, bad data, or a power issue. These problems can be successfully mitigated by thorough testing of individual components and by testing the whole RMTS system using realistic conditions. Unfortunately, this testing cannot be done before the components arrive, so the risk could not be mitigated until late in the semester. Additionally, many of the other risks can be mitigated by carefully inspecting wires and connections when the RMTS is being set up and between tests, adhering to rocket safety guidelines, and bringing spare batteries.

Sample Calculations

The power consuming components within the RMTS control “suitcase” are the Raspberry Pi 4, TTL to RS485 driver board, portable monitor, keyboard with integrated mouse, and dual relay module. All will use 5 V DC power, except for the keyboard/mouse, which is powered by an internal battery. The Raspberry Pi 4 is expected to need about 2.5 A (Link), the portable monitor is expected to need about 2 A (Link), the dual relay module (only one relay will be used) will need a maximum of about 0.1 A when switching (Link), and, based on researching similar RS485 drivers, the TTL to RS485 driver board will likely need about 0.06 A (Link). This adds up to a current of 4.66 A at 5 V DC. Two 12/24 V DC to 5 V, 3 A USB-C converters will be used to supply this power. The converters are about 96% efficient (Link). The total current draw from the battery can be calculated using the equation $I_{suitcase}V_{suitcase}=I_{battery}V_{battery}E_{converter}$, where $I_{suitcase}$ is the total current used by the suitcase components, $V_{suitcase}$ is the voltage used by the suitcase components, $I_{battery}$ is the current drawn from the battery, $V_{battery}$ is the voltage supplied by the battery, and $E_{converter}$ is the efficiency of the converter. For a 12 V battery, the total expected current is about 2.02 A.

The power consuming components within the test stand are the Arduino Uno R4, TTL to RS485 driver board, load cell amplifier/transmitter, flasher/siren, relay module, and ignition circuit. The Arduino R4, the TTL to RS485 driver board, and the dual relay module will use 5 V DC current, provided by the Arduino’s built in converter, which will be supplied with 12 V DC current from the cable bundle. The Arduino R4 consumes about 0.093 A while continuously sampling analog values during testing (Link), and as stated above, the TTL to RS485 driver board will probably need about 0.06 A, and the dual relay module will need a maximum of about 0.1 A, for a total 5 V current draw of about 0.253 A, which will require 0.111 A at 12 V DC to supply, assuming the Arduino’s converter has an efficiency of 95%. The load cell amplifier/transmitter requires an input current of up to 0.02 A at 24 V DC (Link) and the flasher/siren requires an input current of 0.075 A at 24 V DC (Link), resulting in a 24 V DC current of 0.095 A. The 12 V to 24 V converter that will be used has an efficiency of about 95% (Link), so the 24 V components will require 0.2 A from the 12 V source in the cable bundle. Based on the available rocket motor initiator specifications, the ignition circuit will likely need up to 2 A (Link) at 12 V. This results in a total 12 V current draw over the RMTS cable of about 2.311 A.

The power will be passed to the test stand over 14 AWG wire, which has a resistance of about 2.58 Ohms per 1000 ft (Link). This equates to a resistance of 0.3225 Ohms over the 125 ft cable. Passing 2.311 A over a cable with 0.3225 Ohms of resistance will result in a current drop of about 0.745 V, so the voltage reaching the converter will be about 11.255 V. Obviously this is not ideal, and the reduced converter input voltage will actually mean the test stand needs slightly more current than 2.58 A. However, the 12 V to 24 V converter is rated for input voltages as low as 10 V and the Arduino needs a minimum of just 5 V, so the system should function as expected during testing.

Mechanical System

Potential failure modes	Consequences of failure	Cause of failure	Countermeasures	S	O	D	RPN
Motor shakes itself out/Rips itself apart	Equipment damage, People injuries	Faulty motor, Not Tightened enough	Testing procedure makes sure motor is affixed properly, follow stand off distance	8	4	2	64
Chuck jaw gets stuck	Test interruption	Bad Lathe Chuck/Corrosion	Regular inspection, lathe chuck must be oiled on a schedule	3	3	1	9
Chuck jaw breaks	Test interruption, Equipment damage	Bad Lathe Chuck	Testing of parts before motor test	4	1	10	40
Falls over	Equipment damage, People injuries	Not set up correctly	Make sure stand is on a level surface and attach stabilization legs if needed	5	3	5	75
Breaks	Equipment damage, People injuries	Used with a motor that is too powerful	Remove blast protection and increase standoff distance	5	1	5	25
Becomes shrapnel	Equipment damage, People injuries	Used with a motor that is too powerful	Remove blast protection and increase standoff distance	9	1	7	63
Motor mount plate collapses	Equipment damage, People injuries	Bad motor mount plate	Testing of parts before motor test	7	1	10	70
Frame warps	Test interruption, Equipment damage	Excessive force applied	Testing of parts before motor test	4	1	10	40
Welds break	Equipment damage, People injuries	Bad weld/ excessive force applied	Testing of parts before motor test	7	1	10	70
Structure tips over	Equipment damage, People injuries	Large off axis burn	Stabilization legs	7	1	7	49
Damage container	Equipment damage, People injuries	Container located too close to stand	Remove stand from container and place it a safe distance away	6	1	10	60
Damage motor mount	Test interruption, Equipment damage, People injuries	Explosive force	Good documentation for replacement parts	4	2	10	80
Damage frame	Test interruption,	Explosive	Good documentation for	6	1	10	60

	Equipment damage, People injuries	force	replacement parts				
Damage to load cells	Test interruption, Equipment damage, People injuries	Explosive force	Good documentation for replacement parts	7	3	10	210
Damage to arduino	Test interruption, Data loss, Equipment damage, People injuries	Explosive force	Good documentation for replacement parts	4	1	10	40
Damage to RMTS mounted lights and sirens	Test interruption, Equipment damage, People injuries	Explosive force	Good documentation for replacement parts	4	2	10	80
Damage Most RMTS part	Test interruption, Data loss, Equipment damage, People injuries	Explosive force	Good documentation for replacement parts	9	1	10	90
Off-axis burn	Equipment damage, People injuries	Stability loss	Stabilization legs	7	1	7	49

Operational

Potential failure modes	**Consequences of failure**	**Cause of failure**	**Countermeasures**	**S**	**O**	**D**	**RPN**
Ignition before safety area is clear	Personnel injury	Improper safety procedures	Lights and sirens begin 5 seconds prior to allowing ignition or rockets	9	4	2	72
Accidental ignition	Personnel injury, Equipment damage	Improper operations procedure	Lights and sirens begin 5 seconds prior to allowing ignition or rockets, covers over ignition buttons, keyed power	9	4	3	108
Incorrect standoff distance	Personnel injury	Misunderstood motor size/improperly measured distance	Safety training, operations training	9	3	3	81
Flammable materials	Location damage	Standoff distance not cleared	Safety training, field inspection prior to ignition/mounting motors	9	2	2	36

Air ventilation	Personnel injury, Location damage	Improper location for test	Safety training, operations training, ignition location inspection	9	3	3	81
Weather	Equipment damage	Rain entering motor	Operations training, location inspection, weather brief prior to test	9	2	1	18
Incorrectly mounted motor	Equipment damage	Improper operations training	Operations training	9	4	3	108
Incorrectly placed blast protection	Personnel injury	Misunderstood motor size/improperly measured distance	Safety training, operations training	9	4	3	108
Install engine backwards	Equipment damage	Improper motor mounting	Operations training	9	3	2	54

References

Appendix

(include any supporting calculations, test data, drawings, etc.)

FMEA based on circuit components

Functions/Components	Potential failure modes	Consequences of failure	Cause of failure	Countermeasures	S	O	D	RPN
12V battery	No power	Need external power supply, Test interruption	Battery aging, overcharge, overdischarge, extreme temperature	Regular inspection and maintenance	6	4	2	48
Battery Charger	Charging failure	Shortened Battery Life, Test interruption	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	7	4	2	56
5V PSU	Output failture	Raspberry Pi not working	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	4	3	96
Power System(AC)	Power Interruption	Test interruption	Power outage, Line failure	Backup battery	5	3	2	30
Power System(AC)	Power Brownout	Test interruption, Data loss, Equipment damage	Power grid , Line failures	Regulated power supply, Backup battery	5	3	2	30

Power System(AC)	Voltage fluctuations	Equipment damage	Power grid	Regulated power supply, Backup battery	5	3	2	30
Power System(AC)	Unable to find acceptable power source	Test interruption	Test site issues	Backup battery	5	3	2	30
Power System(AC)	Generator unable to perform	Test interruption	Low fuel, Mechanical failure	Monitor, Maintain regularly, Replace if necessary	4	3	2	24
Raspberry Pi	Corruption	Test interruption	Software failure	Improved Software	8	7	3	168
Raspberry Pi	Interface freezes	Test interruption	Software failure	Improved Software	5	7	3	105
Raspberry Pi	Monitor connection failure	Unable to monitor system status	Loose interface, Equipment failure	Regular inspection, replacement if necessary, and provision of spare parts	5	3	2	30
Raspberry Pi	Mouse conne	Unable to control system status	Loose interface, Equipment failure	Regular inspection, replacement if necessary, and	6	3	2	36

	ction failure			provision of spare parts				
Raspberry Pi	Does not store data	Wrong data/Missing data	Poor communication,Sensor damaged	Regular inspection, replacement if necessary, and provision of spare parts	5	6	3	90
USB-C hub	Poor port contact	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	2	3	30
USB-C hub	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	2	3	48
USB cable	Poor port contact	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	2	3	30
USB cable	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	2	3	48
TTL to RS485	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	3	4	96
8-pin MIL-STD	Poor port	Test interruption,	Parts failure	Regular inspection, replacement if necessary, and	5	4	4	80

connector	contact	Operation failure		provision of spare parts				
8-pin MIL-STD connector	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	3	4	96
Cable Boundel	Poor port contact	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	2	4	40
Cable Boundel	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	2	4	64
Cable Boundel	Unstable communication	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	2	4	40
Relay Module	Abnormal working	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	4	2	64
Key Switch	Unstable connection	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	3	2	30
Key Switch	Key mech	Test interruption, Operation	Parts failure	Regular inspection, replacement if necessary, and	8	2	2	32

	anism failure	failure,Safety hazards		provision of spare parts				
Push Button	Unstable connection	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	3	2	30
Push Button	Mechanism failure	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	2	2	32
Monitor	No Display	Test interruption, Unable to monitor status	Parts failure	Regular inspection, replacement if necessary, Use other methods of control and monitoring	5	2	2	20
Keyboard/Mouse	Loss Control	Test interruption, Operation failure,Safety hazards	Parts failure	Regular inspection, replacement if necessary, Use other methods of control and monitoring	5	2	2	20
Screw Terminal Block	Poor port contact	Test interruption, Operation failure,Safety hazards	Socket loose, Parts failure	Regular inspection, replacement if necessary, Use other methods of control and monitoring	7	3	3	63
Arduino	Corruption	Test interruption	Software failure	Improved Software	8	7	3	168
Arduino	Broken lines	Test interruption	External impact,	Regular inspection, replacement if necessary, and	8	4	3	96

			Corrosion, Aging	provision of spare parts				
Arduino	Failure to perform	Test interruption	Software failure, Power supply failure	Regular inspection, replacement if necessary, and provision of spare parts	6	7	3	126
Load Cell Amp	Not reading	Missing data	Losseing wire,Parts damaged	Regular inspection, replacement if necessary, and provision of spare sensors	8	3	4	96
Load Cell Amp	Broken	Missing data	Parts damaged	Regular inspection, replacement if necessary, and provision of spare sensors	8	3	4	96
Load Cell Amp	Incorrect readings	Wrong data	No calibration,Part damaged	Regular inspection,Calibration sensors	6	3	3	54
Load Cell Amp	Not plugged in	Missing data	Losseing wire	Regular inspection	8	3	2	48
Load Cells	Not reading	Missing data	Losseing wire,Sensor damaged	Regular inspection, replacement if necessary, and provision of spare sensors	8	3	4	96
Load Cells	Broken	Missing data	Sensor damaged	Regular inspection, replacement if necessary, and provision of spare sensors	8	3	4	96

Load Cells	Incorrect readings	Wrong data	No calibration,Sensor damaged	Regular inspection,Calibration sensors	6	3	4	72
Load Cells	Not plugged in	Missing data	Losseing wire	Regular inspection	8	3	2	48
4-pin MIL-STD connector	Poor port contact	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	5	2	3	30
4-pin MIL-STD connector	Disconnection	Test interruption, Operation failure	Parts failure	Regular inspection, replacement if necessary, and provision of spare parts	8	2	3	48
Ignition	Improper procedure prior to key	Abnormal ignition	Human error	Training	9	3	5	135
Ignition	Power wire broken	Abnormal ignition	Overcurrent, Loose, Corrosion	Regular inspection,Use fuse or overcurrent protection	8	5	4	160
Ignition	Power wire melts/ fries	Abnormal ignition	Overcurrent, Loose, Corrosion	Regular inspection,Use fuse or overcurrent protection	8	5	4	160
Ignition	Igniter not working	Abnormal ignition	Plug Looseness, Wire Corrosion	Wait for a certain period of time,Regular inspection, Training	8	7	5	280

	prope rly							
Siren /light failur e	Fail to activa te	No warning,Acc idents may occur	Circuit failure, Component failure	Regular inspection and Test	5	3	3	45
Siren /light failur e	Activa ting at impro per times	False alerts	Circuit failure, Component failure	Regular inspection and Test	5	3	3	45
Siren /light failur e	Light break s	No light warning	Circuit failure, Component failure	Regular inspection and Test	4	3	3	36
Siren /light failur e	Siren speak er break s	No sound warning	Circuit failure, Component failure	Regular inspection and Test	4	3	3	36