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FMECA-Based Risk Assessment in Monopropellant Hydrazine Propulsion System

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Abstract

The Monopropellant Hydrazine Propulsion system is one of the most widely used types of single-agent propulsion systems to control the position or correction of satellites in orbits. This system consists of combustion chamber subsystems (catalyst bed, catalyst, nozzle, and cap), fuel and fuel tank, high-pressure tank, control valves, and interface pipes. In this paper, the MPHP system (as a case study) is described in detail, and then critical risks are identified by creating FMECA tables on the case study in the design phase. Based on the proposed FMCEA flowchart, potential failure modes are identified. In the next step, decisions and corrective actions are formulated regarding the inherent failures of the system. Finally, the necessary measures to reduce the risks will be taken according to the system's failure modes, and the reduction of the identified risks to an acceptable level is presented. The attained results show that the catalyst decomposition chamber, catalyst bed, inlet flow control valve, and propellant management facilities units have the highest risk index values (RPN), respectively. For this purpose, corrective measures have been suggested for each of these.

Keywords: Monopropellant hydrazine, Risk assessment, FMECA, Expert opinion, Failure modes

Nomenclature and Units

D	Detectability
O	Occurrence
S	Severity
CA	Corrective Action
FMEA	Failure Modes, Effect Analysis
FMECA	Failure Modes, Effect & Critically Analysis
MPHP	Mono Propellant Hydrazine Propulsion
RPN	Risk Priority Number

Introduction

Despite more than five decades of effort to develop space projects worldwide, there is still the idea of reducing risk in space missions. While there are still serious challenges in reducing development costs as well as many technical challenges to cost savings, mission and product assurance are also of paramount importance. Since the early 2000s, NASA and the Department of Defense have decided to focus on new spacecraft development plans for manned exploration of the moon and Mars and having disposable space carriers for operational launches and the current needs of their space transport fleet. Hence, the issue of risk reduction increased safety, and product assurance in space programs became more important than ever [1]. In recent years, there has been a paradigm shift in the design

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and development of space carriers. In addition, space exploration, demonstration of technological capabilities for access to space, as well as access to global Earth studies are the motivation behind the design [2]. At present, the issue of product and mission guarantees is the main factor in developing space carrier technologies. The success based on minimizing probable risks of the space carrier with new advanced technology is guaranteed to be economical in use. Also, suitable carriers for launching unmanned cargo are multi-stage disposable space carriers [3, 4]. In the field of liquid fuel propellants, the modifying of existing engines to achieve next-generation space carriers is presented. It also introduces five factors for selecting and modifying its propulsion system: efficiency, operation, reusability, reliability, and manufacturing capability [5]. It also improves the crew's reliability and safety and centrally reduces costs [6]. It has been proposed to invest in existing technology and adapt methods for advanced space transportation systems [7]. In this regard, NASA has submitted a report on the evaluation of large industrial projects in the field of space carriers and the required infrastructure [8].

One of the most widely used types of propulsion systems in space carriers is the Monopropellant Hydrazine Propulsion (MPHP) system used to control the position or correction of satellites in orbits [9]. The reason for its widespread use is the low cost and simplicity of the technology used and the high specific impact as well as its long-term storage capability without losing its purity [10]. Numerous parameters and variables are involved in the optimal design of monopropellant propulsion systems. In order to optimally design this type of system, to minimize the mass and maximize the total impact in the multidisciplinary design optimization method framework, several studies have been conducted [11-14], and a genetic algorithm has been used to optimize [15].

The remainder of this paper is structured as: the 2nd section defines the problem. It states the research subject as research background, and the research on FMEA and propulsion system construction is described and introduced. In the 3rd section, the proposed method of FMEA in-space propulsion systems is presented. In this section, due to the complexity of the propulsion system and the need for an applicable method to implement the product guarantee in this propulsion system, the FMECA method has been used. In the 4th section, the method is implemented, and the risk assessment is done in the propulsion system. In this section, FMEA tables have been completed based on the method proposed in section 3 and have been evaluated and validated according to designers' technical knowledge and experience in this field. Finally, the attained tabulated tables based on FMECA are extracted, and respective correction actions to eliminate or decrease the risks of the system are demonstrated and mentioned.

Research Background

So far, various methods and techniques have been used to guarantee the product. The most efficient of these methods are FMEA, FTA, Markov chain, FMECA, etc. Given the complexities of propulsion systems, a method should usually be chosen that does not have restrictions on implementation on complex systems. According to this view, the FMEA method has been used in its risk assessment and product assurance propulsion system. FMEA is a technique first used in the US military. The MIL-P-1629 Military Standards were published on November 9, 1949, entitled (failure/fault analysis method [16], related impacts as effect analysis [17], and importance). In this standard, faults or failures are classified according to their impact on the final goal and the level of safety of personnel and equipment.

FMEA in design is an analytical method used by the engineering team in charge of design to identify and investigate faulty cases and related causes. DFMEA usually comes with steps, including elements, components, subsystems, or assembled collections. DFMEA is an evolutionary process that uses technologies and methods to design, develop, and create a new product effectively. In DFMEAs, the cause of the error is a design defect that results in failure modes [18]. FMEA is a systematic tool based on teamwork used to define, identify, evaluate, prevent, eliminate or control the causes and effects of potential faults in a system, process, design or service, before the product or service reaches the customer. In other words, FMEA is an analytical method in risk assessment, which tries to identify and score as much as possible the potential risks in the areas where the risk assessment is performed and the related causes and effects. Experience has shown that the FMEA method is one of the most useful methods for identifying, classifying, analyzing failures, and evaluating the risks and risks arising from them. With the help of this method, the rate of failures can be rooted out and prevented from occurring. Predicting failures and finding the cheapest solution to prevent them is another reason to use the FMEA method.

Reducing the risk, increasing the reliability, and consequently guaranteeing the product is complete order in the study, planning, and execution of activities [16, 19-23]; In order to ensure that the design, control, methods, and techniques of the project will lead to a result at an acceptable level of expected product quality. This article aims to bring the product capability to the desired functions of the product, which, based on previous experiences, estimates the reliability of product performance in the future to identify product weaknesses and reinforce this weakness in the early stages of hydraulic mono-propellant propulsion system product design. The system consists of three subsystems: combustion chamber, fuel tank, and high-pressure gas tank, and uses a chemical as a source of energy and fuel. The most common fuel is hydrazine (N2H4) single-component systems, which decompose in the presence of a catalyst [24]. The aim is to design models that provide safety and protection against uncertainty.

Since the FMEA method is one of the fundamental methods in the analysis of engineering systems in order to control the risk of elements and items and have basic steps for qualitative and quantitative analysis. In this paper, in order to examine the tables related to FMEA, a proposed flowchart with a repetitive process (Figure 5) based on the existing critical items has been used, which using the experts opinions tries to identify supercritical elements and is able to reduce the potential risks that has not been conducted in previous and no findings have been made on a case study involving the MPHP space propulsion system.

MPHP as an Application Example

Monopropellant Hydraulic propulsion system is one of the most widely used types of single-component propulsion systems used to control the position or correction of satellites in orbits. The reason for its widespread use is the low cost and simplicity of the technology used and the high specific impact as well as its long-term storage capability without losing its purity. Numerous parameters and variables are involved in the optimal design of single-component propulsion systems. For this purpose, in previous studies, the optimal conceptual design of a single-component hydraulic propulsion system to minimize mass and maximize the total impact in the multi-theme design optimization method framework has been studied [25]. This system consists of different subsystems: combustion chamber (catalyst bed, catalyst, nozzle, and cap), fuel and fuel tank, high-pressure tank, etc. These are designed by multi-thematic optimal design methods and design methods. This system has been examined in this research to examine from the point of view of product guarantee. **Fig. 1** shows the formal schematic of the MHP system with its elements and components consisting of three subsystems: combustion chamber, fuel tank, and high-pressure gas tank. The combustion chamber structure is made of steel, the fuel tank is made of aluminum alloy, and the high-pressure tank is made of titanium.

In order to investigate the risk in this system, it is assumed that the system has two main sets, including the thrust unit and the pressurized and transmission unit of thrust. The components and accessories of these two units are shown in **Fig. 2**.

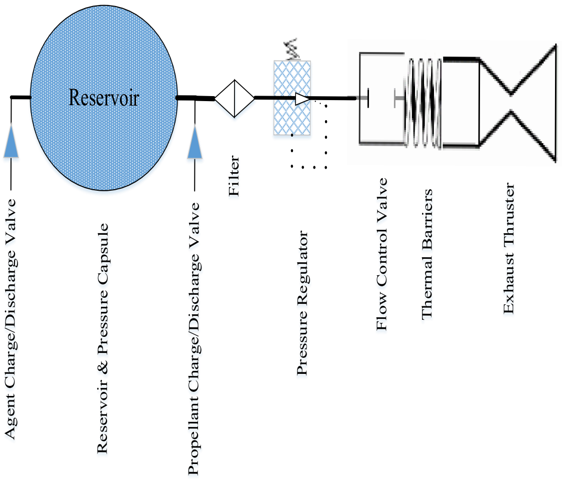


Fig. 1. Components of the Mono-propellant Hydrazine Propulsion System [24]

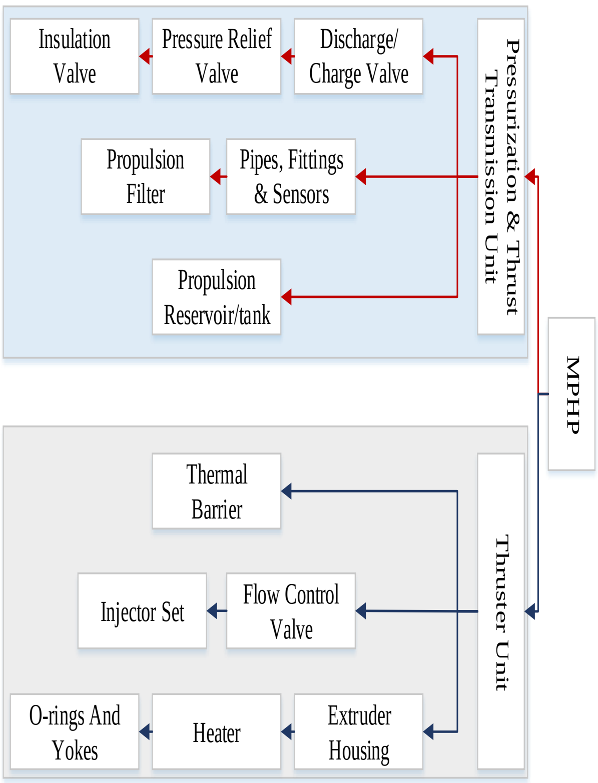
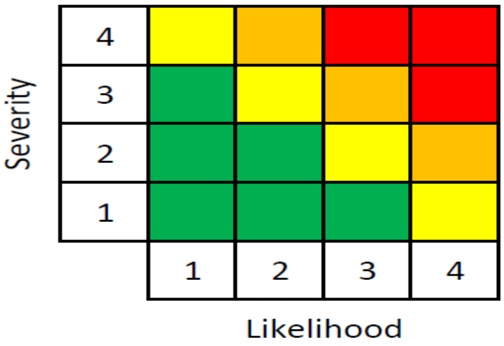


Fig. 2. MPHP components first stage breakdown suitable for the design phase [24]

It should be noted that the level of breakdown is due to the study in the design phase, and for a more detailed study, the smallest elements must be considered and entered. The extruder housing in the thrust unit itself contains the combustion chamber and nozzle. The combustion chamber consists of a catalyst, a catalyst bed, and a nozzle. The amount of trust and specific impulse depends on the size and characteristics of the thruster. The material of this subsystem is usually made of steel. The catalyst is one of the most important parts of this propulsion system, responsible for the decomposition of hydrazine and its conversion into a hot stream of nitrogen and ammonia gases. Fuel tanks/reservoirs are made of spheres or cylinders. Cylindrical fuel tanks are smaller and easier to build but weigh more than spherical ones. These tanks are designed to reduce the mass of aluminum or titanium. Besides these, the pressurized unit is responsible for providing proper pressure using high pressure and generally ineffective gases. If constant pressure is required, a regulator is used. This subsystem includes connecting pipes, tank, regulators, valve, and high-pressure gas.

FMECA Implementation on MPHP

Most of the time, when management is applied to a risk project, the employees in charge of each section identify their work risk list. This list should be reviewed periodically to determine which actions have been taken to reduce the risk. Newly identified risks are added to these reviews, and sometimes some of the identified risks are combined if they are closely related. To help the project manager delete the detailed information in this list, the identified risks are sometimes color-coded to attract attention. The color scheme of the risk (as shown in **Fig. 3**) based on the event severity and likelihood is as follows: Red indicates unresolved, most probable, and very serious impact risks; Orange: Has a high potential for destructive impact and a growing potential risks; Yellow: The probability and impact of the risks are less and small; Green: Eliminated risks that are no longer a threat.



Severity				
4	🟨	🟧	🟥	🟥
3	🟩	🟨	🟧	🟥
2	🟩	🟩	🟨	🟧
1	🟩	🟩	🟩	🟨
	1	2	3	4
	Likelihood			

Fig. 3. Color Scheme of the Risk by Event's Severity & Likelihood [29]

The most appropriate time to start risk assessment is in the design phase. The purpose of risk management in a spacecraft project is to reduce the risks over the life of the project to deliver the final product within the required standards and despite time and financial constraints. One of the most useful and effective techniques in risk assessments is the FMEA tool. FMEA is a systematic tool based on teamwork used to define, identify, evaluate, prevent, eliminate or control the causes and effects of potential failures in a system, process, design, or service. In other words, FMEA is an analytical method in risk assessment, which tries to identify and score as much as possible the potential risks in the areas where the risk assessment is performed and the related causes and effects. These processes are performed in the order of the tasks shown in **Fig. 4**. In the case of FMEA tables, the most commonly used parameters are Severity (S), Detectability (D), and Occurrence (O) or likelihood probability for each event. How to score for each element and the range of values each of them can assign to themselves.

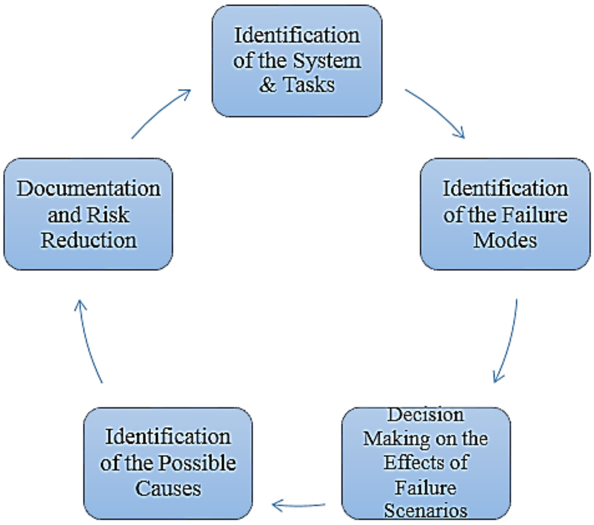


Fig. 4. Process of the Proposed System's Risk Assessments

The Risk Priority Number (RPN) can be calculated from the above parameters and found in abundance in previous documentation and research [26-29]. Identifying risk assessment is a logical method for determining quantitative and qualitative risk size and examining potential consequences of the events based on SOD ($RPN =< S * O * D >$) parameters.

There are three strategies for obtaining probability weight or consequence intensity weight: quantitative, qualitative, and semi-quantitative. The RPN is from 1 to 1000 to classify the corrective actions needed to reduce or eliminate the potential failure pattern. Failure patterns that have the highest RPN score should be considered first. It is very important to pay attention to the issue of class intensity. If the severity of the categories is 9 or 10, regardless of the RPN, the cause should be investigated immediately. The proposed flowchart to assess the risk of the system based on the failure modes, effects, and critical analysis aiming to reduce the potential risks is demonstrated in Fig. 5.

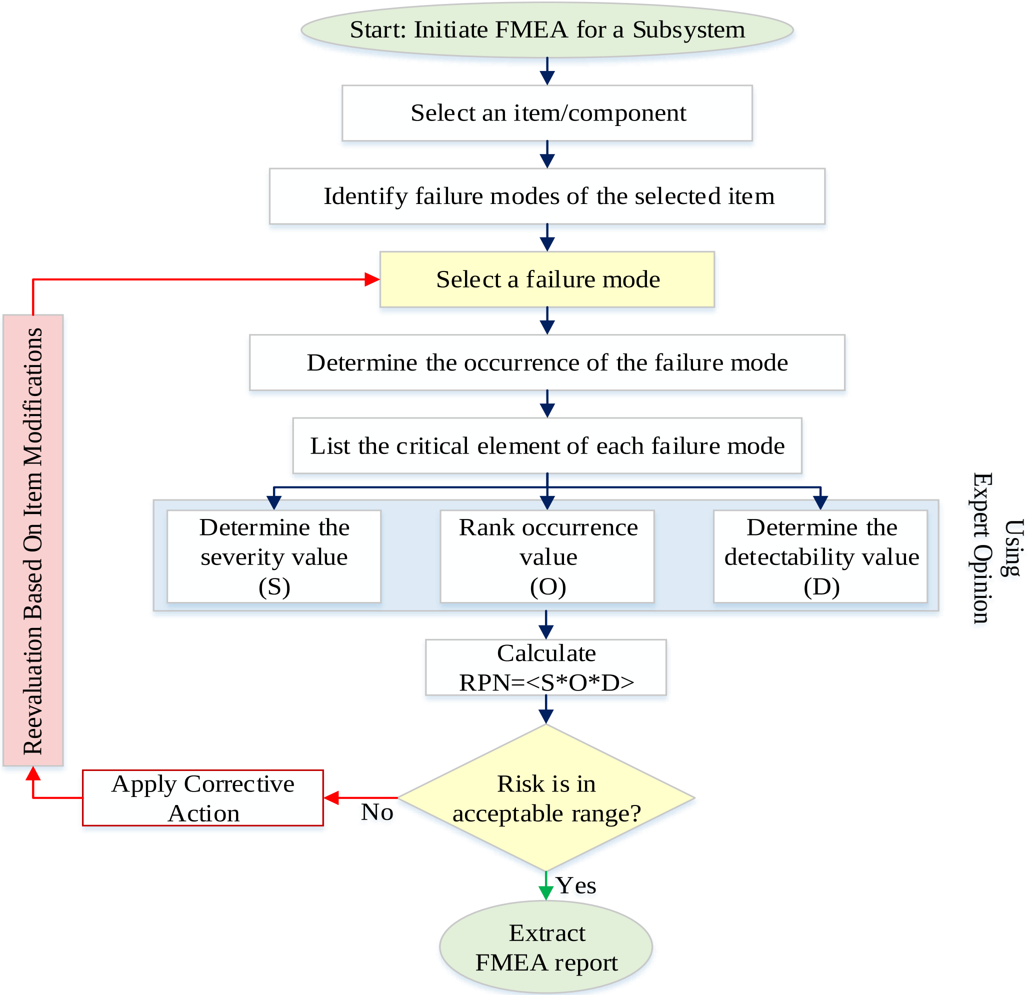


Fig. 5. Proposed FMECA Flowchart based on RPN Values

Based on the proposed steps for risk assessment of the MPHP system, by using the expert opinions, the respective FMECA tables are completed, and based on the allocated values for severity, occurrence, and detectability, the RPN values for each of the elements are estimated. The elements with a high value of RPN are selected as critical elements, and consequently, corrective measures have been proposed to reduce the risk and RPN index on them. Then, based on these measures, the relevant calculations are repeated and performed as far as possible to reduce the risk. An example of an implemented table for some subsystems and elements is shown in **Table 1**. As shown in the table, the MPHP system consists of 5 subsystems. These subsystems are flow control valve assembly, injector set, insulator unit, extruder housing or combustion chamber unit, reservoir or propellant tank, and the pressurization and transmitting unit (1st column of the table). The 2nd column lists the elements and items used in each subsystem. 3rd column represents the task and function assigned to each of these elements. Then the failure modes, the causes for the failure of the element, and the effect of the failure of that element on the entire system are listed in the next columns, respectively. The 7th column demonstrates the initial value of the risk index, which is estimated and averaged based on expert opinions. Here, experts assign values for each element for severity, occurrence, and detectability. Based on these values, the value of the RPN index, which is the product of the values of the above three indices, was calculated and is given as the initial RPN value. These measures are essential for items with a high degree of risk criticality to reduce or eliminate the amount of risk to an acceptable level as much as possible.

Fig. 6 shows the values calculated based on the FMECA tables for each subsystem element. **Fig. 7** also shows among all the items the elements that have a more critical degree of risk (higher RPN number) than the other items. As it turns out, these items are the catalyst, catalyst bed, valve, propellant management facilities, pressure regulating valve, pipe/fitting/sensors, combustion chamber-evaporation zone, adaptor, charge/discharge ports, and finally shell and body.

Table 1. Extracted FMECA table for MPHP system

Unit	Component	Function	Failure Modes	Failure Cause	Failure effects	Initial Risk Priority Number				Corrective Actions
						S	O	D	RPN	
Flow Control Valve	Valve	Control of input stream to thruster	Problem in opening/closing of the valve	Loss of magnetic siege property	Unable in adjusting the flow & consequently improper thrust	9	3	7	189	1- Selecting parts with appropriate quality 2- Putting valve before heat retaining 3- Performing environmental tests
	Spring	Restore the valve to its original state	fails to return to original state	Loss of spring Failure Rusty	Impossibility of regulating the flow and consequently improper trust	8	3	2	48	1- Selecting the appropriate spring material 2- Putting valve before heat retaining 3- Using step motor
	Valve Core	Rotation of valve	Expansion and contact with the coil, Softness and torsion intolerance	Intolerance to high temperature	Flow regulation disorder	8	3	2	48	1- Selecting parts with appropriate quality
	Valve Body	Maintain the set and withstand pressure differences	Malfunction of the set	Casting bubbles Fatigue Rusty	Flow regulation disorder	8	1	2	16	1- Selecting parts with appropriate quality 2- Performing environmental tests
	Elec. Port	Connect the solenoid to the battery current	Lack of electrical current in the coil and valve operation	To be sulfated	Loss of thrust adjustment valve	7	3	3	63	1- Selecting the material according to the temperature and operating conditions
	Spool	Create a magnetic field and rotate valve	Lack of valve and thrust adjustment	Short circuit Burns	Improper Thrust	8	4	2	64	1- Select the wire material to fit the maximum electric current 2- Select the appropriate case
Injector Set	Adaptor	Adjust the input flow to the valve	Improper current input to the solenoid valve	Burn Internal interrupt	Burning or malfunction of solenoid valve	8	3	3	72	1- Performing environmental tests
	Inj. Core	Adjust fuel flow in the thruster	Fails to send proper fuel	Failure Resize due to corrosion	Improper thruster function Thruster choking	6	2	5	60	1- Selecting parts with appropriate quality 2- Performing environmental tests
Insulator	Heat absorber blade	Heat transfer to the surrounding environment	Heat dissipation and temperature decrease	Wear Corrosion Crack	Increase system temperature	4	3	3	36	1- Selecting parts with appropriate quality 2- Performing environmental tests 3. Calculation required temperature and heat transfer
	Resilient tube	Heat absorption of parts	Heat dissipation and temperature decrease	Fatigue Corrosion Crack	Increase system temperature	4	3	3	36	1- Selecting parts with appropriate quality 2- Performing environmental tests 3. Calculation required temperature and heat transfer
Extruder housing	Nozzle	Adjust the output current profile And create the required thrust	Disruption in creating thrust and changing the flow of exhaust gases	Burning Deformation Crack	Fails to provide the required thrust	8	2	3	48	1- Selecting parts with appropriate quality 2- Performing environmental tests 3. Calculation required temperature and heat transfer
	Heater	Increase the temperature to start the reaction	Fault in heater and malfunction	Fails to flow and failure	No reaction	6	2	5	60	1- Selecting parts with appropriate quality 2- Performing environmental tests

Unit	Component	Function	Failure Modes	Failure Cause	Failure effects	Initial Risk Priority Number				Corrective Actions
						S	O	D	RPN	
	Decomposition chamber - evaporation zone	Increase pressure and readiness and perform combustion	Failure to provide the required thrust	Crack Excessive expansion Corrosion	Fails to provide the required thrust Intolerance and loss of pressure	8	3	3	72	1- Selecting parts with appropriate quality 2- Performing environmental tests
	Decomposition chamber - lattice surfaces	Cooling and engineering of high pressure flow inside the chamber	Increased chamber temperature and turbulence of the flow inside the chamber	Eclipse Leak Failure	Fails to provide the required thrust	8	2	3	48	1- Selecting parts with appropriate quality 2-Performing environmental tests 3- calculate the required temperature and heat transfer
	Decomposition chamber - Catalyst bed	Catalyst maintenance over time	Unbalancing in combustion	Inhomogeneity	Failure to provide the required or excessive thrust	8	4	7	224	1- Selecting the appropriate substrate and approved suppliers
	Decomposition chamber - catalyst	Combustion and reaction	No proper combustion	impurity	Fails to provide the required thrust	8	6	7	336	1- Selecting the appropriate catalyst from approved suppliers
	O-ring and fasteners	Sealing parts and housings	Leaks and system malfunctions	Expand Drying Powdering Crush	Severe leakage and breakdown of parts size	5	1	6	30	1- Selection of approved suppliers 2- Performing environmental tests
Reservoir	Shell or body	Maintenance of propellant fluid in ideal conditions	Leakage	Crack, Fluid pressure intolerance, Deformation due to the forces applied to the surrounding structure	Explosion	10	1	7	70	1-Calculation of incoming forces and internal pressure 2-Use construction methods with high reliability
	Charge/ discharge ports	injection and adjusting the spraying method according to the flow profile	Dispersion in spraying profile	Clogging due to improper filters, Faults	Lack of flow and disconnection of propellants	7	2	5	70	1- Preparation of high purity propellants 2- Prepare a filter with the correct ratio of fluid 3- Reputable suppliers 4- Performing environmental tests
	Propulsion Manag. facilities	Adjust the amount of thrust	Failure to enter the propellants as needed	Lack of proper design of control system	Lack of thrust control	8	6	3	144	1- Performing control simulation
	Installation pad	Keep the internal parts in place	Fault	Crack Rupture	Displacement of components and change of center of mass and loss of control	6	1	7	42	1- Selecting parts with appropriate quality 2- Performing environmental tests

Unit	Component	Function	Failure Modes	Failure Cause	Failure effects	Initial Risk Priority Number				Corrective Actions
						S	O	D	RPN	
Pressurize and transmit unit	Charge/ discharge valve	Propulsion fluid flow	Stop fluid flow	Internal parts failure; Obstruction	Failure to successfully charge or drain tanks	6	2	4	48	1- Performing environmental tests
	Pressure regulating valve	Adjust operating fluid flow	Lack of proper flow control	Internal component failure Magnetic interference of adjacent equipment	Inability to control the thrust and guide the device	6	4	5	120	1-Approved suppliers 2-Use of qualified materials
	Driven filter	Removal of micro-harmful propellant particles	Closing the filter holes	Closure of holes due to impurities in the propulsion or non-standard filter	Lack of flow and disconnection of propellants	6	1	2	12	1- Preparation of high purity propellants 2- Prepare a filter with the correct ratio of fluid 3- Reputable suppliers
	Pipe fittings and sensors	Maintain and steer propulsion	Clogging and cut-off	Unable to transfer flow to the propulsion chamber	Crack Choking Reduce pressure Reduction and or loss of required of propulsion	6	3	4	72	1-Accurate calculation in design
	Insulation valve	Creating a magnetic field to rotate the valve core	Current interruption	Short circuit Disconnected connectors	Lack of valve opening and lack of sufficient propulsion	8	4	2	64	1- Selecting parts with appropriate quality 2- Performing environmental tests

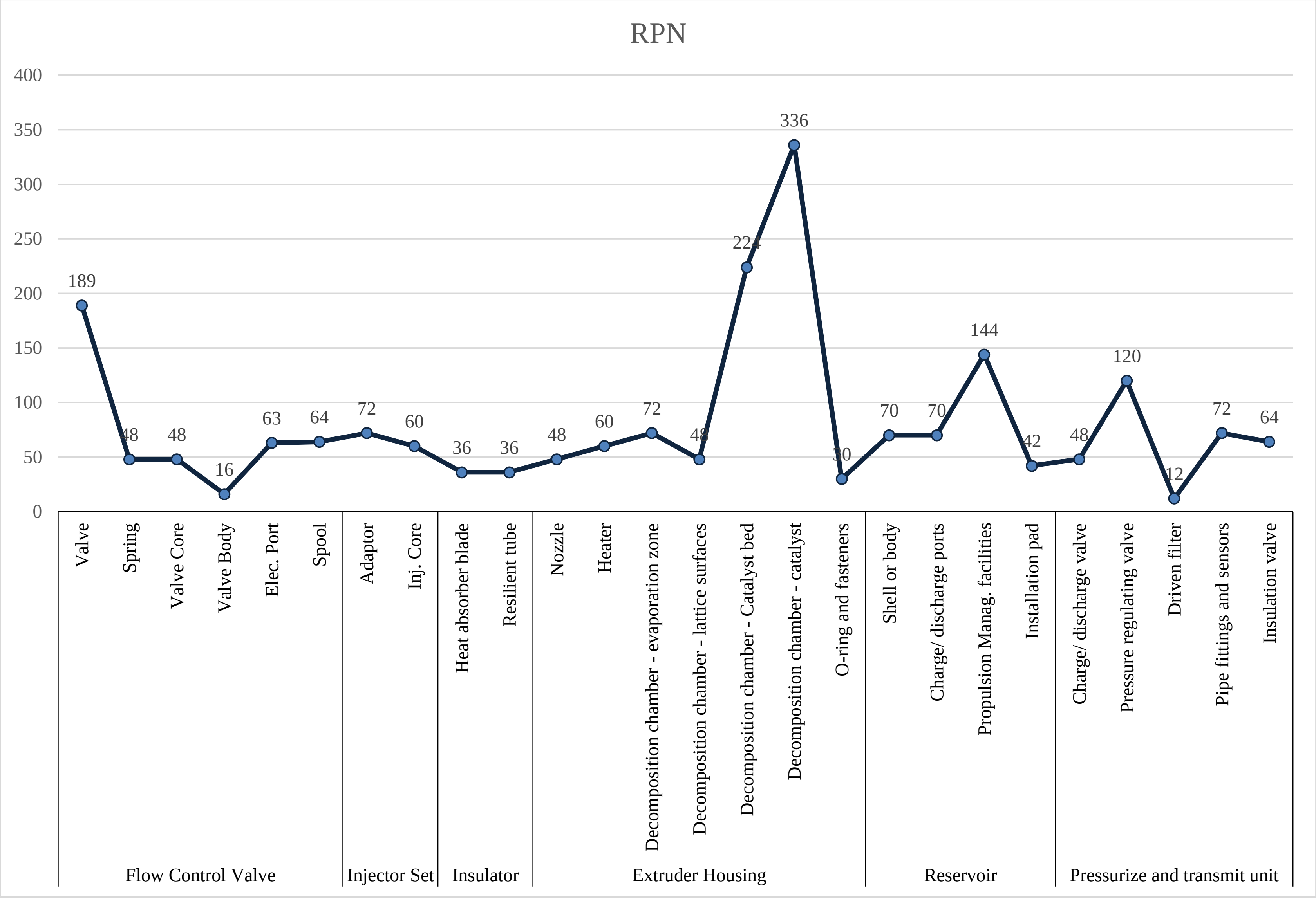


Fig. 6. Evaluated Risk values of the MPHP's Items based on FMEC

The RPN is from 1 to 1000 to classify the corrective actions needed to reduce or eliminate the potential failure pattern. Failure patterns that have the highest RPN score should be considered first. It is very important to pay attention to the severity index. If the severity of the categories is 9 or 10, regardless of the RPN, the cause should be investigated immediately. After the necessary corrective actions are taken, a new RPN is performed by re-evaluating the severity, probability of occurrence, and detectability, the resulting RPN or new RPN. Optimization and correction measures continue until (iteration process as shown in **Fig. 5**) the resulting RPN reaches an acceptable level for all potential failure patterns. Therefore, in addition to choosing the highest RPN, it should also look for high severity and occurrence numbers.

The three areas in the demarcated area diagram are:

1) High priority area
2) Medium priority area
3) Low priority area

These areas are introduced based on the FMEA safety policy. The following is a common principle found in many FMEA implementation methods.

1) Reduce the severity of the failure
2) Reduce the occurrence possibility of an event
3) Improve the probability of discovery and detectability

It is suggested that the 1st and 2nd factors are more important and must be considered. Although improving the probability of discovery because of its post-event nature should always be considered the latter.

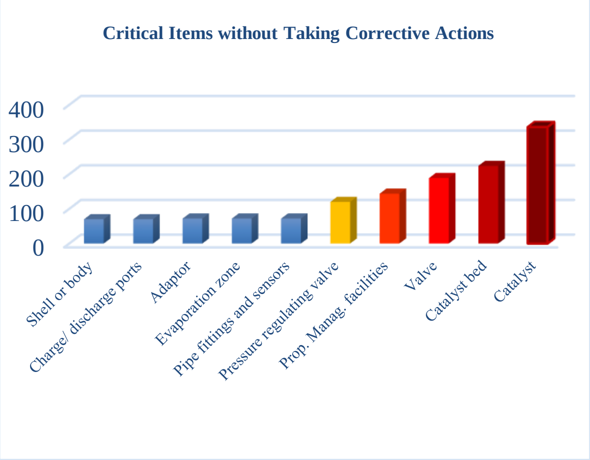


Fig. 7. High-Risk value (Critical Elements) of the MPHP based on FMECA

In the case of the mentioned case study, according to the FMECA table, the obtained RPNs, and observing the average of the numbers, we prioritize corrective measures for improvement from RPN above 100. In each case, we examine the effect of corrective measures on reducing the severity. The effect or the probability of its occurrence are discussed to reduce the RPN in total and ensure that the product will reach the set goals. The corrective actions for high RPN values are recommended as follows: 1) Catalyst decomposition chamber with RPN=336 by selecting the appropriate catalyst from approved manufacturers; 2) Catalyst Bed with RPN=224 by selecting the appropriate catalyst-bed from approved manufacturers; 3) Inlet flow control valve to the extruder motor with RPN=189 by selecting parts with appropriate quality, putting valve before heat-retaining, and performing environmental tests; 4) Propellant management facilities with RPN=144 by performing control simulations. After implementing the corrective actions and applying the suggestions, the final RPN values for the above-mentioned critical items are reduced to the following values (shown in **Fig. 8**).

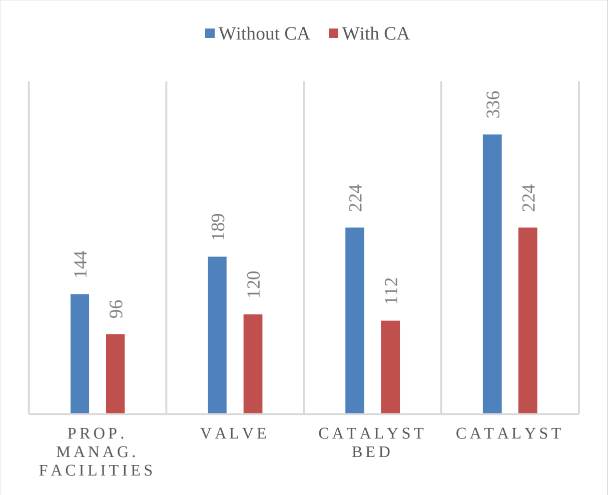


Fig. 8. RPN values of Critical Items After Applying Corrective Actions (CA)

After applying corrective actions, the final RPN values for critical items are significantly reduced, as shown in **Fig. 8**. However, given that most of the threats and risks still involve these items, it should be noted that the considerations that could disrupt performance and operations for each of these items should be noted.

Conclusions

Risk management aims to create a systematic and continuous framework for identifying, evaluating, eliminating, or reducing risk. In the risk management process, decisions are made based on comparing the results of risk determination with the risk acceptance criteria. Risk management is a structured and systematic method for identifying and assessing risks for ranking and making decisions to reduce risk to an acceptable level. In other words, risk management helps project management identify its safety priority correctly and be careful in allocating resources to have the greatest impact on the safety management system. To achieve these goals, in this paper, implementation, and completion of the relevant FMECA forms, the technical knowledge of designers with experience in this field was used. In the first step of execution, the critical items were identified. In the next step, according to identifying these critical components/items of the propulsion system, appropriate corrective actions and measures were developed. After corrective actions were taken, the critical areas were reduced to acceptable risk areas. Considering the risk reduction and rationality of the numbers in the critical areas of the RPNs and according to the technical knowledge of the experts involved in the project, the correctness of risk reduction methods and corrective actions is clear. It is shown that lack of access to technology in supplying parts and purchasing from approved suppliers in a few parts makes it impossible to reduce the risk. Only by taking preventive measures can it be prevented or the severity of events be reduced. Multi-criteria risk analysis to improve safety-related issues will be investigated in the future. This paper aims to assess the critical item’s risks by creating FMECA tables according to designers' technical knowledge and expert opinions. In order to extract RPN, the proposed FMECA flowchart to assess the risk of the system based on the failure modes, effects, and critical analysis with aiming to reduce the potential risks in the design phase is presented. In the next step, decisions and corrective actions are formulated regarding the inherent failures of the system. Finally, the necessary measures to reduce the risks will be taken according to the system's failure modes, and the reduction of the identified risks to an acceptable level will be presented. After applying corrective actions, the final RPN values for critical items are significantly reduced. However, given that most of the threats and risks still involve these items, it should be noted that the considerations that could disrupt performance and operations for each of these items should be noted. By implementing FMECA on the desired system, it was determined that four elements have the highest risk index values (RPN), which are: Catalyst decomposition chamber (RPN=336), Catalyst Bed (RPN=224), Inlet flow control valve (RPN=189), and Propellant management facilities (RPN=144), respectively. In order to reduce this index in the aforementioned elements, corrective actions were proposed in order as follows: selecting the appropriate catalyst from approved supplier to decrease catalyst decomposition chamber’s RPN (corrective RPN=224); selecting the appropriate substrate and approved suppliers to decrease catalyst bed’s RPN (corrective RPN=112); selecting parts with appropriate quality, putting valve before heat retaining, and performing environmental tests to decrease inlet flow control valve’s RPN (corrective RPN=120); and performing control simulation to decrease Propellant management facilities’s RPN (corrective RPN=96).

Conflict of Interests

No conflict of interest has been expressed by the authors.

References

[1] T. Herrmann and D. Akin, "A critical parameter optimization of launch vehicle costs," in *Space 2005*, ed. 2005, p. 6680, https://doi.org/10.2514/6.2005-6680 .

[2] D. E. Koelle, "Launch vehicle evolution-from multistage expendables to single-stage reusables," *Acta Astronautica*, vol. 14, pp. 159-166, 1986, https://doi.org/10.1016/0094-5765(86)90118-9 .

[3] J. R. Wertz, "Economic model of reusable vs. expendable launch vehicles," in *IAF, International Astronautical Congress, 51 st, Rio de Janeiro, Brazil*, 2000.

[4] John M. Logsdon, editor with Linda J. Lear. .. [et al.], *Exploring the unknown: Selected documents in the history of the US civil space program*, vol. 1: NASA, 1995.

[5] E. Stampfl and L. Meyer, "Assessment of existing and future launch vehicle liquid engine development," *Acta Astronautica*, vol. 17, no.1, pp. 11-22, 1988, https://doi.org/10.1016/0094-5765(88)90123-3

[6] U. Hueter, "Access-to-space: Potential future united states launch vehicle transportation systems," *Acta Astronautica*, vol. 35, pp. 753-761, 1995, https://doi.org/10.1016/0094-5765(95)00024-T .

[7] A. Charania, A. M. Crocker, J. E. Bradford, and J. R. Olds, "A Method For Strategic Technology Investment Prioritization For Advanced Space Transportation Systems," in *IAF-01-U. 2.06, 52nd International Astronautical Congress*, 2001.

[8] C. Chaplain, *NASA: Assessments of Selected Large-Scale Projects*: DIANE Publishing, 2009.

[9] M. Negri, "Replacement of hydrazine: overview and first results of the H2020 project Rheform," 2015.

[10] O. Morgan and D. Meinhardt, "Monopropellant selection criteria-hydrazine and other options," in *35th Joint Propulsion Conference and Exhibit*, 1995, pp. 2595, https://doi.org/10.2514/6.1999-2595 .

[11] R. L. Sackheim and R. K. Masse, "Green propulsion advancement: challenging the maturity of monopropellant hydrazine," *Journal of Propulsion and Power*, vol. 30, No. 2, pp. 265-276, 2014, https://doi.org/10.2514/1.B35086 .

[12] R. A. Spores, "GPIM AF-M315E propulsion system," in *51st AIAA/SAE/ASEE Joint Propulsion Conference*, 2015, pp. 3753, https://doi.org/10.2514/6.2015-3753 .

[13] A. Nosseir, A. Pasini, and A. Cervone, "Modular impulsive green-monopropellant propulsion system for micro/nano satellites high-thrust orbital maneuvers (MIMPS-G)," in *Proceedings of the International Astronautical Congress, CyberSpace Edition*, 2020, pp. 12-14, https://doi.org/10.3390/aerospace8060169 .

[14] J. L. Rovey, C. T. Lyne, A. J. Mundahl, N. Rasmont, M. S. Glascock, M. J. Wainwright, *et al.*, "Review of multimode space propulsion," *Progress in Aerospace Sciences*, vol. 118, pp. 100627, 2020, https://doi.org/10.1016/j.paerosci.2020.100627 .

[15] A. Adami, M. Mortazavi, M. Nosratollahi, M. Taheri, and J. Sajadi, "Multidisciplinary design optimization and analysis of hydrazine monopropellant propulsion system," *International Journal of Aerospace Engineering*, vol. 2015, 2015, https://doi.org/10.1155/2015/295636 .

[16] M. Nadjafi, M. A. Farsi, and H. Jabbari Khamnei, "Dynamic fault tree analysis using fuzzy LU bounds failure distributions," *Journal of Intelligent & Fuzzy Systems*, vol. 33, no. 6, pp. 3275-3286, 2017, doi:10.3233/JIFS-161781.

[17] S. Oveisi, M. Nadjafi, M. Farsi, and A. Moeini, "Design Software Failure Mode and Effect Analysis using Fuzzy TOPSIS Based on Fuzzy Entropy," *parameters*, vol. 10, p. 14, 2020.

[18] C. J. Price, "Effortless incremental design FMEA," in *Proceedings of 1996 Annual Reliability and Maintainability Symposium*, 1996, pp. 43-47. doi: 10.1109/RAMS.1996.500640

[19] M. Nadjafi and P. Gholami, "Bayesian inference of reliability growth-oriented weibull distribution for multiple mechanical stages systems," *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 3, no. 1, pp. 77-84, 2020, doi: 10.30699/IJRRS.3.1.9 .

[20] M. Nadjafi, M. Farsi, E. Zio, and A. K. Mousavi, "Fault trees analysis using expert opinion based on fuzzy-bathtub failure rates," *Quality and Reliability Engineering International*, vol. 34, no. 6, pp. 1142-1157, 2018, https://doi.org/10.1002/qre.2313 .

[21] M. Nadjafi and M. A. Farsi, "Reliability analysis of system with timing functional dependency using fuzzy-bathtub failure rates," *International Journal of System Assurance Engineering and Management,* vol. 12, no. 5, pp. 919-930, 2021, https://doi.org/10.1007/s13198-021-01156-1

[22] M. Nadjafi, M. A. Farsi, and H. Jabbari, "Reliability analysis of multi-state emergency detection system using simulation approach based on fuzzy failure rate," *International Journal of System Assurance Engineering and Management,* vol. 8, pp. 532-541, 2017, https://doi.org/10.1007/s13198-016-0563-7 .

[23] M. Nadjafi, M. A. Farsi, and H. Jabbari Khamnei, "Quantitative based fault tree analysis: An integrated fuzzy Monte Carlo and its application on launch escape emergency detection system," *Journal of Intelligent & Fuzzy Systems*, vol. 35, no. 1, pp. 845-859, 2018, https://doi.org/10.3233/JIFS-171491

[24] H. Karimaei, M. R. Salimi, H. Naseh, and E. Jokari, "Design of Physical Configuration of a 10N Monopropellant Hydrazine Thruster," *Journal of Space Science and Technology*, vol. 12, no. 1, pp. 13-22, 2019, (in Persian), https://doi.org/10.30699/jsst.2019.1115 .

[25] H. Karimaei, "Design and Simulation of Fuel Injector of a 10N Monopropellant Hydrazine Thruster," *Journal of Space Science and Technology*, vol. 11, no. 3, pp. 9-19, 2018, (in Persian)

[26] M. Abdelgawad and A. R. Fayek, "Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP," *Journal of Construction Engineering and Management*, vol. 136, no. 9, pp. 1028-1036, 2010, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000210

[27] N. Chanamool and T. Naenna, "Fuzzy FMEA application to improve decision-making process in an emergency department," *Applied Soft Computing*, vol. 43, pp. 441-453, 2016, https://doi.org/10.1016/j.asoc.2016.01.007 .

[28] H.-C. Liu, J.-X. You, Q.-L. Lin, and H. Li, "Risk assessment in system FMEA combining fuzzy weighted average with fuzzy decision-making trial and evaluation laboratory," *International Journal of Computer Integrated Manufacturing*, vol. 28, no.7, pp. 701-714, 2015, https://doi.org/10.1080/0951192X.2014.900865

[29] D. H. Stamatis, *Failure mode and effect analysis: FMEA from theory to execution*: Quality Press, 2003.