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Risk Assessment of Solid Propellant Rocket Motor using a Combination of HAZOP and FMEA Methods

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ABSTRACT

The development of rockets in Indonesia has long been carried out by the National Aeronautics and Space Agency (LAPAN), which has now been integrated into the National Research and Innovation Agency (BRIN). The Research Centre for Rocket Technology, which is one of the centres within BRIN, has been developing solid propellant-based rockets with a various sizes and types. Solid-propellant rocket technology is commonly used because of their reliability, cost-effectiveness, and simple design. However, this technology is one of the high-risk technologies, whose failure can harm humans, damage the environment and cause huge losses to assets. As a high-risk technology, risk assessment activities must be carried out, starting from the design, manufacturing, testing and up to the launching stage. In this paper, we studied a risk assessment for general Solid-propellant Rocket Motor (SRM). SRM is basically a device that processes chemical energy in solid propellant into thrust (kinetic energy) in a container that functions as a pressure vessel. The risk assessment methods commonly used in this technology are the HAZOP or FMEA methods. The HAZOP is excellent in identifying failure modes systematically through identifying the deviation of physical process parameters but has difficulties in prioritizing the risk. The FMEA has effectiveness in understanding failure mechanisms and establishing necessary countermeasures, but for a product with a lot of components, the worksheet is also complex. By combining these two methods, integrating the superiority of each method, this research can identify modes, causes and effects of failure that may occur in SRM effective and accurately. In addition, this research also proposes corrective or preventive actions for each failure mode. As the objective of the risk assessment, results of the research can be used as input for the designers to improve their design and as inspection and surveillance objects for QC officers.

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1. Introduction

The development of rockets in Indonesia has long been carried out by the National Aeronautics and Space Agency (LAPAN), which has now been integrated into the National Research and Innovation Agency (BRIN) to become the Research Centre for Aeronautics and Space (ORPA). Research and development of rocket technology is one of the 9 focuses of Indonesia's National Research Priority for 2020 – 2024. The Research Centre for Rocket Technology, which is one of the centres within ORPA, has been developing solid propellant-based rockets with a various sizes and types. One of them is a rocket with a range of more than 100 km named RHAN 450 rocket.

Solid propellant rocket technology is commonly used because of their reliability, cost-effectiveness, and simple design. The main advantage of solid propellant rocket is their readiness for immediate combat action and the possibility of long-term storage. However, this technology is one of the high-risk and safety-critical technologies, whose failure can harm humans, damage the environment and cause huge losses to assets. As a high-risk technology, risk assessment activities must be carried out in rocket technology development, starting from the design, manufacturing, testing and up to the launching stage.

Risk assessment for solid-propellant rocket motor has conducted by several researcher. Srivastava *et al.,* [1] studied composite rocket motor casing using Failure Mode Effect Analysis (FMEA) and Failure Mode Effect and Criticality Analysis (FMECA) methods. They performed qualitative analysis in line with MIL-STD-1629A and quantitative analysis using FMECA Risk Priority Number (RPN). Jenab and Pineau [2] analyzed safety critical components on the Solid Rocket Boosters (SRBs) and illustrated the use of FMECA with modified RPN approach to reliable space travel. Razionale *et al.,* [3] performed safety assessment on solid propellants for satellites engines. Based on specific past experience, they presented some of the critical elements which can be encountered in the risk analysis of the production process of aerospace propellants.

In this paper, we studied risk assessment for general solid-propellant rocket motor (SRM). SRM is basically an equipment that processes chemical energy in solid propellant into a thrust (kinetic energy) in a container that functions as a pressure vessel. There are no moving parts or other active components in an SRM system that need a continuous supply of energy to function, so that this system can be categorized as a passive system. Potential failure modes in passive systems are directly tied to elemental physics. As a passive system, the safety of SRM must be evaluated from two angles: the dependability of the system's passive components, and the dependability associated with physical events that occur when the system is in use. The FMEA technique is just one of many that can be used to assess the dependability of parts. The FMEA has effectiveness in understanding failure mechanisms and establishing necessary countermeasures, but for a product with a lot of components, the worksheet is also complex. Meanwhile, the HAZOP technique is commonly used for qualitative examination of the system's most crucial physical properties. The HAZOP is excellent in identifying failure modes systematically through identifying the deviation of physical process parameters but has difficulties in prioritizing the risk. By combining these two methods, integrating the superiority of each method, this study can identify number of modes, causes and effects of failure that may occur in SRM parts, i.e. the igniter, solid propellant, casing and nozzle. In addition, this research also proposes corrective or preventive actions for each failure mode. As the objective of the risk assessment, results of the research can be used as input for the designers to improve their design and as inspection and surveillance objects for QC officers.

2. Solid-propellant Rocket Motor (SRM)

Rocket motor is basically an energy conversion device that converts chemical energy into kinetic energy. Chemical energy from chemical fuel is converted into heat energy from the combustion process in the combustion chamber. Kinetic energy is generated by expanding a high pressure and high temperature combustion product gases through a converging-diverging nozzle [4]. Solid chemical propellant is widely used as fuel for rocket motors because of its relatively simple design, high reliability, ease of manufacture, ease to store and handle, high density as well as ready to use on demand. These features plus low cost and durability for long periods of time, make solid propellant rockets ideal for military and space applications [5,6].

However, solid propellants have a lower specific impulse than liquid fuels. The manufacturing and installation processes require a high degree of care to prevent cracks and voids in the propellant. Solid propellant is intolerant of cracks and voids, so it requires a rigorous inspection and checking process after being manufactured and inserted into the rocket casing. The combustion process in a rocket depends on the surface area of the propellant. The presence of cracks and voids in the propellant will cause excessive combustion at the crack and void locations, resulting in local over temperature at these locations and can cause catastrophic failure of the casing or nozzle [6,7].

SRM consists of casing, thermal insulation, nozzle, grain (propellant charge) and igniter [5]. Grain can be bound (case-bonded grain) or not bound (cartridge-loaded grain) to the casing, however between the grain and casing there is a barrier material in the form of thermal insulation. The exact dimensions for grain, nozzle and casing geometry are calculated as follows. The design of the rocket motor begins with determining the required impulse. The impulse value determines the mass amount of fuel and oxidizer. The characteristics of the rocket motor are determined by the grain geometry and chemical content. The grain burn rate is calculated based on the combustion surface area and chamber pressure. Chamber pressure is determined by the nozzle throat diameter and grain burn rate. Allowable chamber pressure is set based on the casing design. And, the length of the grain burning time is determined by the grain web thickness [8]. Simple diagram of SRM is shown in Figure 1.

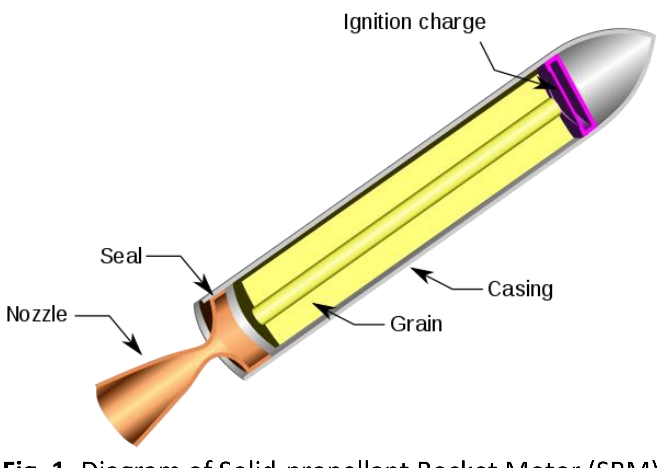

Fig. 1. Diagram of Solid-propellant Rocket Motor (SRM)

2.1 Casing

The motor casing is a part of the SRM to contain the propellant grain. It also provides a structural interface for other motor components, such as nozzle and ignition system. As a place for burning a propellant (combustion chamber), the casing also works as a pressure vessel, since it has to withstand an internal pressure of about 3 – 30 MPa from the combustion product gases. Motor casings are usually made either of metal (high-strength steel or high-strength aluminum alloy) or of composite materials (Glass, Kevlar and Carbon) [5].

2.2 Propellant

There are various types of solid propellants, as described below.

Black powder (gunpowder) propellant is composed by charcoal (fuel), potassium nitrate (oxidizer), and sulfur (fuel and catalyst). This is the oldest type of solid propellant, used for low-power rocket types, but it is cheap and easy to manufacture [8].

"Candy" propellant is composed by potassium nitrate as oxidizer and sugar (typically dextrose, sorbitol, or sucrose) as a fuel. Candy propellant generates low-medium impulse, used mainly by amateur and experimental rocketeers [8].

Double-base (DB) propellant is composed by two monopropellant fuel components where one typically acts as a high-energy (unstable) monopropellant and the other acts as a lower-energy stabilizing monopropellant. The propellant comprises nitrocellulose (NC) and nitroglycerine (NG) mixed together at the molecular level to form a homogeneous substance. NC constitutes the fuel and NG as oxidizer. DB propellant generate medium-high impulse and addition of metal fuels (such as aluminum) can increase the performance [7-9].

Composite propellant is composed by ammonium nitrate-based (ANCP) or ammonium perchlorate-based (APCP). Ammonium nitrate composite propellant uses magnesium and aluminum as fuel and delivers medium impulse. Ammonium perchlorate composite propellant uses aluminum fuel and delivers high impulse. Composite propellants are cast and retain their shape after the rubber binder, such as Hydroxyl-terminated polybutadiene (HTPB), solidify with the aid of a curative additive. Because of its high impulse, moderate ease of manufacturing, and moderate cost, APCP finds widespread use in space rockets, military rockets, hobby and amateur rockets, whereas cheaper and less efficient ANCP finds use in amateur rocketry [7-9].

Composite modified double base propellant is composed with a nitrocellulose/nitroglycerin as a binder and solids (typically ammonium perchlorate (AP) and powdered aluminum) normally used as addition. The ammonium perchlorate makes up the oxygen deficit introduced by using nitrocellulose, improving the overall specific impulse. The aluminum improves specific impulse as well as combustion stability [7-9].

2.3 Thermal Insulation

Combustion of propellant in SRM produces high temperature gas, ranging from approximately 2000 to 3500 K [5]. Therefore, the motor casing must be protected from exposure to high temperatures by providing insulation between the casing and the propellant. During the life of the rocket motor, structural integrity of case, insulation and propellant must be maintained. For this purpose, insulator materials used generally have low thermal conductivity and high heat capacity properties and are able to provide ablative cooling, such as Ethylene Propylene Diene Monomer (EPDM) with addition of reinforcing materials.

2.4 Igniter

Igniter is a device to provide the necessary energy to the surface of the propellant to initiate burning. The heat energy is generated by the combustion of an easily burnable mixture such as potassium nitrate with charcoal powder and Sulphur. Adding metal oxide to the igniting mixture enhances the temperature of the products of combustion generated by the igniter. The combustion of pyrotechnic materials is triggered by an electric current and the combustion products provide sufficient heat to the surface of the propellant to reach the combustion point [5,9].

2.5 Nozzle

Nozzle is a part that serves to create thrust on the rocket motor. The combustion chamber contains high temperature and high-pressure combustion gases from the combustion of the propellant. The gases are exhausted and accelerated through the converging-diverging nozzle, thus generating thrust to propel the rocket. The geometry of the nozzle determines how much of the total energy is converted to kinetic energy [5].

3. Methodology

SRM is basically a process system in which the energy transformation process occurs. In this energy transformation process, the possibility of danger or undesirable events can occur, which results in the release of excessive amounts of energy (mechanical energy, thermal energy and chemical energy) or matters or both to their surroundings. Therefore, this rocket motor can be classified as a safety critical system. A safety critical system is a system whose failure can cause injury or death to humans, damage to property and damage to the environment [10].

For safety critical systems, risk assessment activities are required; which includes identification, analysis, elimination, prevention and or mitigation of hazards; to ensure the safety of design and operation. There are various methods commonly used for risk assessment activities, including the FMEA method and the HAZOP method [10,11].

3.1 Failure Mode and Effects Analysis (FMEA)

FMEA is an inductive technique for analyzing hazards in the system. The analysis begins by identifying the failure mode for each component in the analyzed system and assessing the effect of these failures on the entire system. The results of the analysis are recorded in the FMEA table.

The FMEA table is organized into several entries, each entry recording information related to the effects of potential failures on the system. Generally, the information that is always available includes a description of the failure mode and the corresponding effect on the system (consisting of local effects and system effects). Subsequent information records include severity classification of each identified failure mode, operational mode (phase) in which the failure can occur, list of possible causes of failure, failure detection mean and corrective actions that need to be taken to prevent or limit failures [10]. An example of an FMEA table is given in Table 1.

Table 1
Typical format of FMEA table

Process Step or System Component	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Process Controls	Detection	RPN	Recommended Action(s)

3.2 Hazard and Operability Studies (HAZOP)

HAZOP is another method to analyze hazard inductively. The purpose of HAZOP is to investigate the basic set of operation of the system being assessed, considering deviations that may occur in normal operation and identifying their potential hazardous effects. For each identified hazard, it is possible to propose corrective actions in the system that can help prevent them or reduce their impact.

The HAZOP study begins with the identification of parts of the process called nodes. Each node is associated with process parameters and design intentions which state operational conditions under which the process must take place for correct operation. For each parameter and corresponding design intention identified, the study continued by identifying all possible deviations from the design intention and their impact on the system as a whole. For each node and parameter, the study is repeated for each possible deviation that has been identified. Possible deviation from normal operation is classified in the form of guide words [10].

Examples of guide words include NO (negation of the intention), MORE or LESS (an increase or decrease in the amount of a physical entity), and REVERSE (the opposite of the design intention). The combination of guide words with parameters is a deviation from the design intention. The results of the HAZOP study are recorded in the HAZOP Table. The HAZOP table generally contains specifications of the analyzed parameters and deviations, descriptions of relevant causes, consequences on the system and possibly corrective actions recommended to reduce risk to an acceptable level. An example of a HAZOP table is given in Table 2.

Table 2
Typical format of HAZOP table

Guide Word	Deviation	Possible Cause	Consequences	Existing Safeguards	Action Required	Action by	Action taken
No	No Flow						
More	More Flow						
	More Pressure						
	More Temperature						
Less	Less Flow						
	Less Pressure						
	Less Temperature						
Reverse	Reverse Flow						

3.3 Combination FMEA and HAZOP Method

SRM is a passive system, where this system does not have any active components that require a continuous supply of energy for its operation (such as motors, pumps, valves, etc.). In passive systems, failure modes that may occur are basically related to basic physical parameters (such as pressure, temperature, flow, etc.) [12]. As a passive system, the safety of SRM must be analyzed through two aspects; i.e. the reliability of the passive components in the system and the reliability associated with physical phenomena that occur during the system's operation. Many methods are used to analyze the reliability of components, one of which is the FMEA method. Meanwhile, qualitative analysis related to critical physical parameters in the system generally uses the HAZOP method.

The main difference between the HAZOP and FMEA methods is that HAZOP is a system-centered approach whereas FMEA is a component-centered approach [13]. The investigation in the FMEA method is one direction, from cause to consequence. The HAZOP method looks at the deviation that may occur from the design intent and then proceeds in two directions, the first to investigate the cause of the deviation and the second to identify the consequences of the deviation effect.

Several researchers have proposed the combined use of HAZOP and FMEA methods [12-15]. Guimaraes and Lapa [12] uses classical HAZOP analysis steps, but adds the Risk Priority Number (RPN) from the FMEA method to the HAZOP. HAZOP-RPN is calculated by multiplying the Severity (S) of the consequences by ease level of failure detection (D) and Estimated Occurrence Probability (EOP), where EOP is a new created parameter to represent the estimated occurrence probability.

Trammell *et al.,* [14] combines the FMEA and HAZOP methods for risk management activities at Motorola, a semiconductor manufacturing company. Merging the two methods is done by taking the advantages of each method. HAZOP has advantages in identifying system failure modes. By dividing the system into smaller parts (called nodes), identification of failure modes can be done systematically through process parameter deviations. On the other hand, FMEA has the advantage of understanding the failure mechanism (in order to identify the cause of failure), determining detection methods and corrective actions, and ranking each event. Simply; Trammell places the HAZOP node in the process function/requirements column in the classic FMEA table, HAZOP deviation represents failure mode, HAZOP consequences represents potential effects and HAZOP cause represents potential cause; as shown in Table 3.

Table 3
Motorola's HazOp/FMEA Methodology Worksheet [14]

Process Function/ Requirements (HAZOP Node/Item)	Potential Failure Mode (HAZOP Deviation)	Potential Effect(s) of Failure (HAZOP Consequences)	Severity	Potential Cause(s)/ Mechanisms (HAZOP Causes)	Occurrence	Current Design/ Process Controls	Detection	RPN	Recommended Action(s)

Laloix *et al.,* [15] proposed the approach based on combination FMECA and HAZOP to identify the causal relationship between root cause, degradation, failure and flow deviation. Combination FMECA/HAZOP analysis worksheet is given in Table 4. In Table 4, the combination is done by expanding the classical FMECA analysis with HAZOP analysis characteristics, namely properties (parameters) and deviation. The causal horizontal relationship is identified through property deviation, failure mode, cause and local effects. While the causal vertical relationship is highlighted with sub-system effects.

Table 4
Combination FMECA/HAZOP Analysis worksheet from Laloix *et al.,* [15]

Element	Function	Properties	Failure Mode/ Deviation	Causes	Local Effect	Sub-system Effect	D	F	G	RPN	Monitoring Parameters

In this paper, we propose a combination of HAZOP and FMEA methods for risk analysis, as shown in the worksheet as given in Table 5.

Table 5
Combined HAZOP-FMEA Risk Assessment Worksheet

Description of Process, Function and Item		Description of Failure		Effect of Failure			Cause of Failure			Prevention / Detection Control		RPN	Recommended Action(s)
Process / Function/ Parameter at NODE	Item / Component at NODE	Guide Word	Failure Mode; Process / Operational	Local Effect of Failure	End Effect of Failure	Severity	Item / Component Causing of Failure	Non-Item / Component Causing of Failure	Occurrence	Prevention / Detection Methods	Detection		

In the combination of the two methods we propose, we divide the classic FMEA table worksheet into 6 columns: i.e., Description of Process, Function and Item; Description of Failure; Effect of Failure; Cause of Failure; Prevention/Detection Control; and Recommendation columns. First of all, the system being analyzed is divided into several manageable nodes, describes the functions or processes at the nodes and identifies the basic physical parameters of the design intent at the nodes (especially safety-related parameters). These data are recorded to the sub-column of Process/Function/ Parameter at Node. Then, it is identified what components are located and perform the functions at the node, they are listed in the sub-column of Item/Component at Node. For the column of Description of Failure, we use the guide word in the HAZOP process to investigate Failure Modes; i.e. failures that represent deviation conditions relating to basic physical parameters that are set up for the normal operation or process of the system. For the Effect of Failure, we consider two effects, local effects and end effects. The local effect describes the impact of failures at the node whereas the end effect describes the impact of failures on the whole system. In the three stages (columns) described above, we perform the analysis using the same procedure as the HAZOP method, except in determining the severity of the effect of failure using the FMEA procedure.

Regarding the Cause of Failure, there are two types of causes. The first cause comes from direct component or hardware failure, such as component damage, corrosion, cracking, etc. The second cause comes from failures that are not directly related to components, such as design errors, maintenance errors, procedural errors, etc. Prevention control is carried out so that the predicted failure does not occur. Prevention activities include the implementation of tight quality control, design verification and validation, testing, checking, etc. Detection control is implemented so that failures can be detected as early as possible and avoid hidden failures. The detection methods are generally in the form of installing alarms, detecting physical parameters related to safety, installing condition monitoring devices, etc. The RPN which is the multiplication of the severity (S), occurrence (O) and detection (D) parameters is used to place a priority scale for each failure mode. The RPN value is also used to set the necessary recommendations regarding the failure modes. The recommendations given can complement, add to or improve the existing prevention/detection controls as well as establish mitigation actions when failures occur. The three steps (columns) described in this paragraph are carried out using the procedures performed when conducting an FMEA, including in calculating the RPN value. Figure 2 describe the flowchart for conducting combined HAZOP-FMEA analysis.

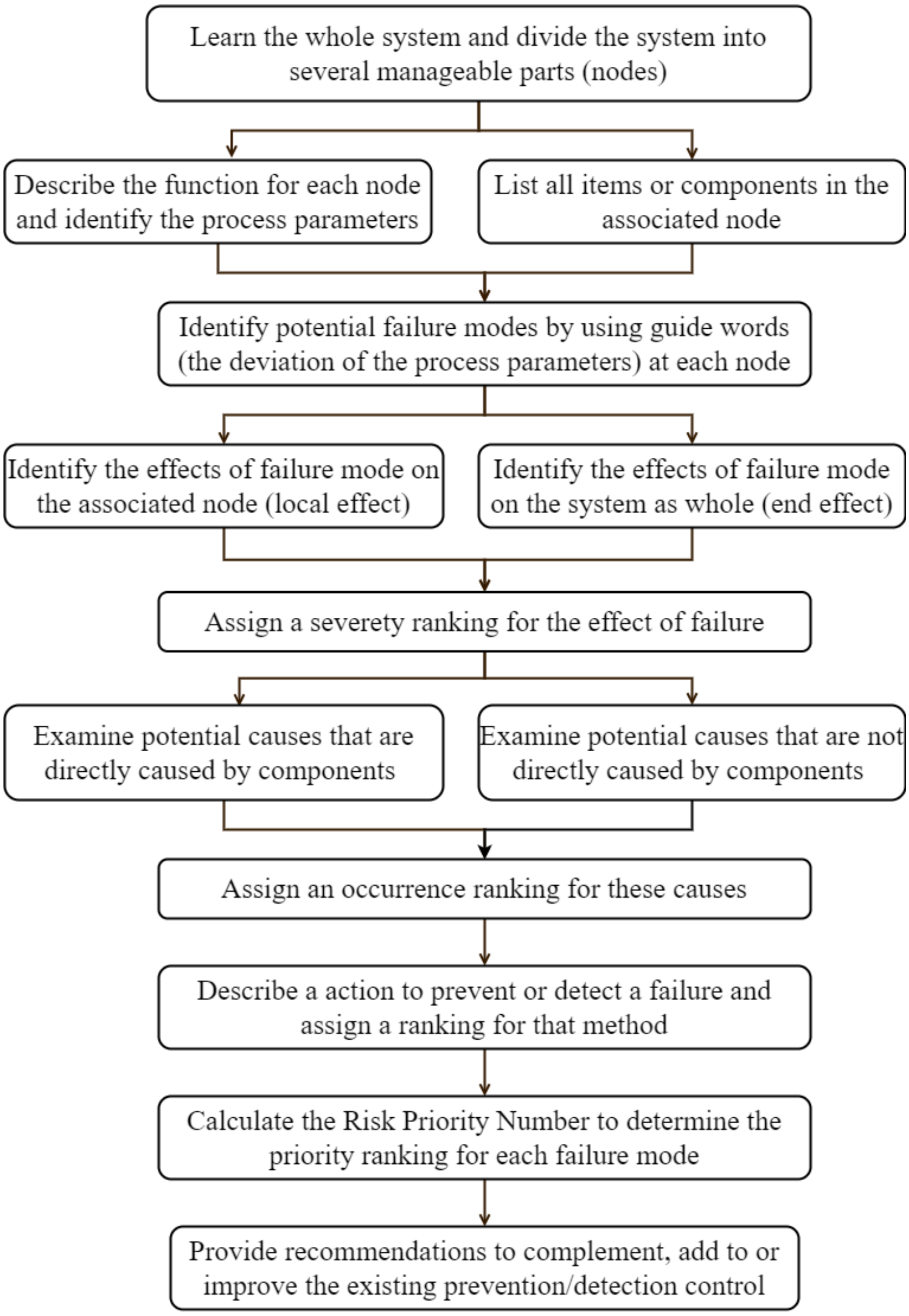

Fig. 2. Flowchart for conducting combined HAZOP-FMEA Analysis

4. Results and Discussion
4.1 Results

For risk assessment of SRM, we use combined HAZOP-FMEA method such as described in Table 5 and Figure 2. First, we compose functional block diagram of SRM, as shown in Figure 3, to describe workflows, related parameters, components and their functions in systems, sub-systems or nodes. We specify several nodes in the system, based on specific functions in the SRM system. In this study, we skip the column of recommended action. We provide the prevention/detection methods; that mean these methods should be implemented to prevent or detect the failures in the system. The results of the study are given in the Table 6.

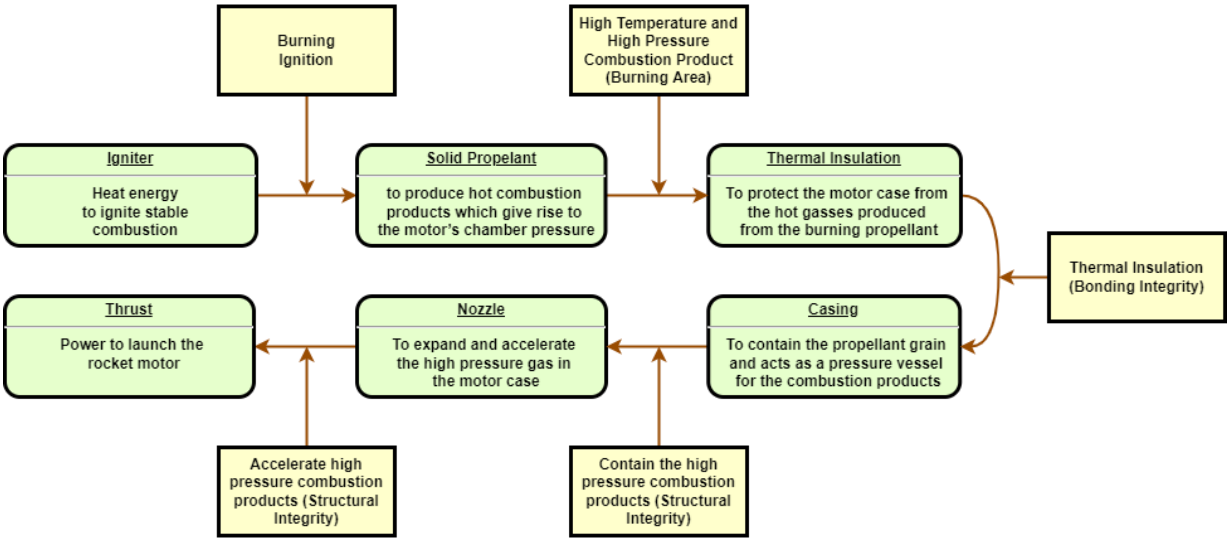

Fig. 3. Functional Block Diagram of SRM

4.2 Discussion

The results of the risk assessment for solid rocket motors are given in Table 6. At the rocket ignition stage, there are two significant failures to consider, ignition failure and spurious / accidental ignition. The ignition failure came from the igniter failing to provide sufficient heat energy so that the rocket could not be activated and caused the launch mission to fail. This failure is mostly due to the material quality of the igniter charge, which is also related to errors in the igniter design, manufacturing or installation process [16]. Therefore, a good Quality Control (QC) process needs to be implemented, including functional testing and physical checking. The most dangerous failure to safety is incorrect ignition of the igniter [16]. Misfire or inadvertent ignition failure can be caused by a system malfunction or human error. To prevent this, it is important to implement strict enforcement of safety and security procedures, in addition to the implementation of functional testing, physical checking and good operation procedures.

Regarding the containment of high-pressure gas as a result of propellant combustion, the rocket motor casing plays a major role in this regard. The integrity of the casing is the parameter that most determines the success of this containment function. Casing loss of integrity (casing rupture) can be caused directly from the performance of the casing itself and can also result from failure of other parts in the rocket motor. The direct cause of casing failure can come from design errors (errors in material selection, calculation, casing size, etc.) or errors in manufacture, assembly or installation [7,17,18]. The direct failure of this casing can be prevented by the use of proven codes and standards in design, manufacturing and installation; implementation of good verification and validation procedures; as well as the involvement of competent engineer and technician. Indirect causes of casing failure can come from local over heating due to thermal insulation failure and over pressure in the combustion chamber due to propellant failure [7,17].

Regarding the combustion process in the combustion chamber, the combustion process can fail because the propellant experiences excessive deformation (ageing due to long storage). For this reason, the environmental conditions of the storage area need to be maintained properly. In this combustion process, catastrophic conditions can occur with excessive burning area on the surface of the propellant. Excessive increase in burning area will cause over pressure in the combustion chamber, which in turn will cause the casing to rupture and trigger an explosion. The increase in burning area is directly caused by the failure of the solid propellant structure; such as cracking, voiding or unbounding [7,17-19].

Table 6
Combined HAZOP-FMEA Risk Assessment Worksheet for SRM

Node	Description of Process, Function and Item		Description of Failure		Effect of Failure		Severity	Cause of Failure		Occurrence	Prevention / Detection Methods	Detection	RPN
	Process / Function / Parameter	Item / Component	Guide Word	Failure Mode; Process Deviation	Local Effect(s) of Failure	End Effect(s) of Failure		Item / Component Causing of Failure	Non-Item / Non-Component Causing of Failure				
1	To deliver energy to the propellant surface and pressurize the motor casing in order to initiate stable combustion of the propellant (Parameter: Burning Ignition)	Igniter	NO	No Ignition	Ignition failure	Mission failure; rocket motor fails to activate	3	Igniter malfunction (open circuit, lead wire failure, pyrotechnic material degradation, etc)	Design, manufacturing or installation error on Igniter	2	Functional testing and physical checking	1	6
			Un-expected	Spurious Ignition	Unexpected ignition of the rocket during storage or on the near of rocket launching.	Mission failure; premature ignition	5		Human error or operation / handling procedures error	2	Access control enforcement (security procedures), handled by competent personnel	1	10
								System malfunction (short circuit, improper environment, etc)		1	Functional Test, Physical Checking, Operation Procedures	1	5
2	To contain the propellant grain and acts as a pressure vessel for the combustion products (Parameter: Integrity)	Casing	Loss	Loss Integrity	Casing rupture	Physical explosion / detonation	5	Local overheating due to propellant-insulation-motor casing bond failure		2	QC and Surveillance Procedures, Storage Environment and Transportation Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard.	1	10
								Over pressure in combustion chamber due to propellant failure (crack, void, porosity, etc)		2	QC and Surveillance Procedures, Storage Environment and Transportation Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard	1	10
									Design Error (Material Selection, Calculation, Size, etc)	2	Competent Designer, Design based on Codes and Standards, Verification and Validation Procedures used in Design	1	10

									Improper manufactured, welding, joining/ connection, heat treatment, assembling and Installations	2	Competent Technician and Engineer, Manufacturing based on Codes and Standards, adequate Testing during and after manufacturing	1	10
3	To produce hot combustion products which give rise to the motor's chamber pressure and thrust (Parameter: Burning Area)	Grain (Solid Propellant)	Loss / Less	Loss / Less of active burning area	Propellant fails to burn	Mission Failure (Rocket Motor fails to ignite)	3	excessive deformation due to long storage (ageing)		2	Storage Environment and Transportation Procedures	1	6
			More	Increasing active burning area	Over pressure in combustion chamber	Potential to cause Casing rupture and explosion	5	Structural Failure (Cracking, Void or Unbounding)	Improper manufacturing, handling, transportation or storage environment condition	2	QC and Surveillance Procedures, Storage Environment and Transportation Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard	1	10
			Other Than	Instabilities in burning area	Combustion instabilities	Potential to cause Casing failure due to pressure oscillations inside the combustion chamber	4		Improperly prepared propellant (wrong oxidizer vs. fuel ratio, incomplete mixing, etc.)	2	QC and Propellant Preparation Procedures, Static Testing	1	8
4	To protect the motor case from the hot gasses produced from the burning propellant (Parameter: Insulation Integrity)	Thermal Insulation	Loss	Loss of insulation	Local burning-through (overheating) at the rocket casing	Rocket Casing rupture	5	material failure (due to degradation or improper material)	installation error	2	QC and Surveillance Procedures, Storage Environment and Transportation Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard	1	10
5	To expand and accelerate the high-pressure gas in the motor case in order to produce	Nozzle	Loss	Loss of integrity	Mechanical Failure (Nozzle Crack or Break)	Decreasing or loss of thrust force in the rocket motor and potentially cause explosion	5	Excessive Erosion in Nozzle, causing the Nozzle Insulator break up	Design Error (Material Selection, Calculation, Size, etc)	2	QC and Surveillance Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard	1	10

thrust (Parameter: Integrity)	Joint Failure between Nozzle and Casing	Decreasing or loss of thrust force in the rocket motor and potentially cause explosion	5	Improper manufactured, welding, joining/ connection, heat treatment, assembling and installation	2	QC and Surveillance Procedures, NDT Testing (X-Ray/Radiography Testing, UT Testing, etc), Manufacture, Assembling and Installation Based on Standard	1	10

The occurrence of structural failure of propellant can come from improper manufacturing, handling, transportation or storage environment conditions and can also be from improperly propellant preparation (wrong formulation, incomplete mixing, etc.) [7,17,18]. To prevent this incident, it is necessary to strictly implement QC and surveillance procedures; storage and transportation procedures; manufacturing, assembling and installation based on standards; and also, the implementation of NDT testing/inspection at every stage of the process. Another problem that can occur in the combustion process is combustion instability [17]. Combustion instability causes shock waves inside the chamber, due to a grain geometry problem that causes unstable burning.

To protect motor casing from the hot gases produced in the propellant burning, there is thermal insulation between the casing and the grain. Material of thermal insulation can experience degradation or delamination at any location in the rocket motor so that the casing overheats at that location. To prevent this incident, the installation of thermal insulation must be done carefully and using the appropriate material. The installation of thermal insulation should also be checked using the NDT method [20,21].

The process to expand and accelerate the high-pressure gases in the combustion chamber takes place at the nozzle. The nozzle can experience a loss of integrity (mechanical failure) in this process such as cracking or breaking, which in turn can cause the rocket to lose thrust and potentially trigger an explosion. This incident was triggered by excessive erosion in the nozzle so that it damaged the heat-retaining layer on the nozzle surface [21]. Another incident that has the same effect as the problem described above on the nozzle is the joint failure between the nozzle and casing. This incident comes from improperly manufactured, welding, joining/connection, heat treatment, assembly and installation. Therefore; QC and surveillance procedures, NDT testing, manufacture, assembly and installation based on standards must be strictly applied to the nozzle design and manufacturing process.

NDT testing methods are mostly used to inspect structural failure or flaw in casing, insulation, solid propellant and nozzle. X-ray NDT method is a relatively fast and easy method to check irregularities in the object material. Cracks, voids and porosity in the propellant; as well as debonding and delamination between propellant and insulation are visible as dark spots in the X-ray film [19,22]. Ultrasonic Test (UT) NDT method also can detect cracks, voids, debonding and delamination. UT method is mostly used to detect the delamination between casing, insulation and propellant in the solid rocket motor [19,20]. In practical implementation, these two NDT methods (X-ray and UT) are used simultaneously to check the structure of the casing, thermal insulation and propellant. Other NDT methods, such as Eddy Current, Dye Penetrant and Infra-Red Thermography, are sometimes also used to complement the inspection results of the two methods above. The use of various NDT methods for structural inspection of parts on solid propellant rocket motors is highly recommended because each method has different characteristics and sensitivity.

5. Conclusions

SRM is a high risk and safety critical device, where failure of this device can injure or even cause fatalities to the public and cause severe damage to property and the environment. Based on this, risk assessment activities must be carried out so that the hazards contained therein can be controlled so that accidents can be prevented. There are various methods that can be used for risk assessment, such as the HAZOP and FMEA methods which are commonly used. HAZOP is a system/process-centered analysis, while FMEA is a component-centered analysis. SRM can be classified as a passive system, i.e. systems that do not require a continuous supply of external power to operate. Once the SRM is activated, the rocket will continue to operate following the physical and chemical processes it contains. Risk assessment for such device is suitable to be analyzed based on the physical-chemical process it undergoes (HAZOP) along with analysis of the performance of the passive components in the device (FMEA). In this paper, we propose a format or analytical framework that combines classical HAZOP and FMEA analytical procedures. We implement this format on general SMRs. From the analysis, several failure modes can be identified that represent the deviation of parameters related to safety on SRMs operation process, such as ignition, structural integrity and burning area, which in the end leads to the main safety parameters (pressure and temperature). Prevention and detection means were also described in the analysis; especially regarding the use of recognized / proven code and standards, implementation of strict standard operating procedures (SOP) and Quality Control (QC) for every stage of manufacturing, storage and transportation, as well as the involvement of competent engineers and technicians. NDT inspection is an obligation in every stage/process, if possible using a complete NDT method or at least using X-ray and UT methods. The results of this risk assessment can be guidance and consideration for the designers and technicians in developing, manufacturing, assembling, installing and testing of the SRM.

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