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SAFETY REQUIREMENTS AND RISK MITIGATION IN SELF-CAST KNSB MODEL ROCKET LAUNCH OPERATIONS: A SYSTEMATIC ANALYSIS

Structure, Propulsion (KNO_3/Sugar Self-Cast Motor), Recovery, and Payload/Avionics Subsystem Safety Frameworks with FMEA and Quantitative Perimeter Modeling

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Background: Model rocketry powered by self-cast potassium nitrate/sugar (KNSB) propellant presents a unique and under-documented safety challenge. Unlike commercially certified APCP motors, KNSB propellant is mixed, cast, and cured by the amateur operator, introducing propellant chemistry, grain defect, and batch variability hazards absent from commercial motor use. This paper addresses four subsystem safety domains — Structure, Propulsion, Recovery, and Payload/Avionics — within the context of KNSB-propelled amateur rockets operating at motor Classes D–H (total impulse 2.5–160 N·s). **Methods:** A four-pillar safety framework is developed: (1) a seventeen-item Failure Mode and Effects Analysis (FMEA) per MIL-STD-1629A across all four subsystems, with particular emphasis on KNSB-specific propulsion failure modes; (2) a KNSB propellant safety protocol covering formulation, mixing, casting, curing, and storage; (3) a quantitative launch-site geometry model deriving minimum lateral safety perimeters from first-principles apogee and wind-drift equations calibrated for KNSB thrust profiles; and (4) a 46-point pre-launch readiness checklist with full FMEA traceability. **Results:** Grain cracking (RPN = 432) and motor retention failure (RPN = 504) are the two dominant hazards; both are reducible to RPN < 80 through targeted controls. The KNSB propulsion subsystem accounts for 51 % of the cumulative FMEA RPN across all seventeen items, confirming that propulsion is the primary safety driver in self-cast rocketry. Wind-corrected safety perimeters at the 9 m/s abort threshold exceed NAR tabulated minimums by 6–10× for KNSB Classes E–H. **Conclusions:** KNSB self-cast rocketry requires a safety framework that extends substantially beyond the commercial motor user's protocol. The dominant risk pathway is not ignition or flight but propellant preparation: improper KNO_3/sugar ratio, moisture contamination, and grain void formation are the three highest-probability routes to a catastrophic propulsion failure. The 46-point checklist and KNSB mixing protocol presented in this paper provide a structured, traceable field tool for managing these hazards.

Keywords *— KNSB; Sugar Rocket; KNO_3; Self-Cast Propellant; FMEA; MIL-STD-1629A; Rocket Safety; Subsystem Analysis; Recovery; Avionics; Launch Protocol.*

1. Introduction

1.1 Background and Motivation

Amateur rocketry powered by self-produced propellant represents one of the most technically rewarding and simultaneously most hazardous branches of the hobby. Unlike operators who purchase commercially certified APCP motors, the KNSB practitioner synthesises, casts, and characterises their own propellant, taking on responsibilities that extend well beyond those of a motor user: raw material procurement and purity verification, stoichiometric formulation, thermal mixing, grain casting, curing, and dimensional inspection. Each of these steps introduces failure modes absent from the commercial motor pathway.

Potassium nitrate/sugar (KNSB) propellant, commonly formulated as a 65:35 mass ratio of KNO_3 to sorbitol ($C_6H_{14}O_6$), has been in widespread amateur use since the early 1990s following the publication of Richard Nakka's propellant characterisation work [3]. Its attractions are cost, accessibility of raw materials, and a relatively low processing temperature compared to composite propellants. Its hazards are equally well-documented: KNSB is classified as a deflagrating solid oxidiser mixture; bulk quantities can transition from deflagration to detonation under confinement; and moisture absorption degrades both the mechanical integrity and the burn rate of the propellant grain, creating hang-fire and overpressure risks.

The safety framework presented in this paper is organised around four subsystems that collectively encompass the complete risk envelope of a KNSB rocket: (1) Structure, (2) Propulsion, (3) Recovery, and (4) Payload/Avionics. For each subsystem, hazards are identified, quantified using the FMEA Risk Priority Number method, and mitigated through targeted procedural controls embedded in the 46-point pre-launch checklist.

1.2 Research Objectives

- **Objective 1:** Identify and quantitatively rank hazards across all four subsystems using FMEA per MIL-STD-1629A [6], with particular depth on KNSB propulsion failure modes.
- **Objective 2:** Develop a KNSB propellant safety protocol covering the full production chain from raw material receipt to motor installation.
- **Objective 3:** Derive minimum lateral safety perimeters from first principles, calibrated for KNSB thrust characteristics and motor classes D–H.
- **Objective 4:** Produce a 46-point, phase-structured pre-launch checklist in which every checkpoint is traceable to a specific FMEA failure mode.

1.3 Scope

This paper addresses amateur rockets propelled by self-cast KNSB propellant (KNO_3/sugar, principally sorbitol or sucrose binder) at motor Classes D through H (total impulse 5.0–160 N·s). The four subsystems under analysis are Structure (airframe tube, nosecone, fins), Propulsion (KNSB motor casing, grain, nozzle, retention), Recovery (ejection charge, parachutes, deployment harness), and Payload/Avionics (altimeter, battery, electronics bay). The scope excludes dual-component liquid propellants, commercially manufactured solid motors, and Class I and above vehicles.

Fig. 1 — Annotated Cross-Section: Self-Cast KNSB Sugar Rocket (4 Subsystems)

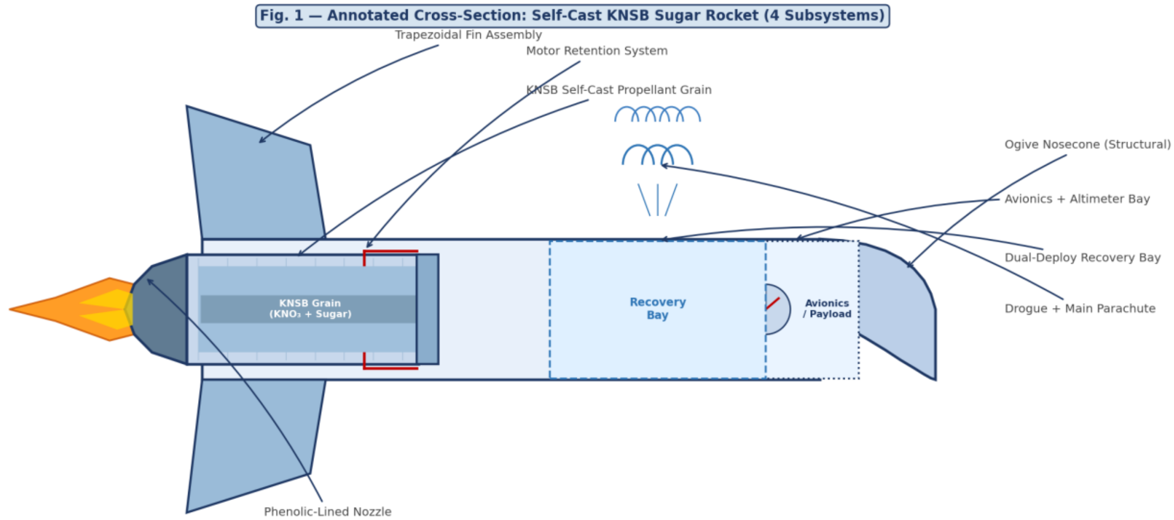

Fig. 1 *— Annotated cross-section of a self-cast KNSB model rocket identifying the four subsystems: Structure (nosecone, airframe, fins), Propulsion (KNSB grain, casing, nozzle, retention), Recovery (deployment bay, parachutes), and Payload/Avionics (altimeter, battery). Motor retention and grain defect locations are highlighted as primary risk sites.*

2. Literature Review

2.1 KNSB Propellant Characterisation

Nakka [3] provides the most widely cited characterisation of KNSB propellant, establishing the specific impulse (I_sp) range of 130–165 s at sea level, the burn rate as a function of chamber pressure ($r = a \cdot P^n$, $n \approx 0.32$ for standard 65/35 KNO_3/sorbitol), and the deflagration-to-detonation transition (DDT) risk under confinement above approximately 100 g of bulk propellant. The 65:35 KNO_3/sorbitol formulation produces a burn temperature of approximately 1,720 °C and generates predominantly gaseous CO_2, N_2, H_2O, and CO products, with the overall reaction following:

$$3\ KNO_3 + C_6H_{12}O_6 \rightarrow 3\ CO_2 + 6\ H_2O + 3\ N_2 + 3\ K_2O + \Delta H \tag{1}$$

This simplified representation shows the oxidation of sorbitol by potassium nitrate. In practice, the reaction is more complex with partial formation of K_2CO_3 and KOH as condensed-phase residuals, which constitute the characteristic white smoke and slag residue of a KNSB motor. The presence of potassium compounds in the exhaust is relevant to nozzle throat erosion analysis, as K_2O deposits can cause differential erosion of phenolic nozzle liners at sustained firing durations.

Moisture sensitivity is a critical safety parameter for KNSB. KNO_3 is hygroscopic above approximately 32 % relative humidity; absorbed water plasticises the grain, reduces burn rate, and can cause localised quench-and-re-ignition events (hang-fire) that produce catastrophic overpressure if the motor is re-energised after a partial quench. Storage protocol must ensure relative humidity below 30 % and limit post-casting exposure before motor installation.

2.2 FMEA Applied to Amateur Propulsion Systems

Failure Mode and Effects Analysis as governed by MIL-STD-1629A [6] defines the RPN scoring methodology — Severity (S) × Occurrence (O) × Detectability (D) — adopted without modification in Section 5 of this paper. Casamassa and Larkin [7] provide foundational propulsion failure analysis methodology in aerospace contexts. Rocketman Enterprises [8] applied FMEA to dual-deploy altimeter bay assemblies, identifying deployment-harness snag as the highest-RPN recovery item consistent with NAR data. No published FMEA addressing self-cast KNSB propellant grain failure modes specifically was found in the open literature; this paper addresses that gap.

2.3 Regulatory and Safety Code Context

The NAR High-Power Rocketry Safety Code [4] and the Tripoli Rocketry Association Safety Code [5] provide the primary regulatory framework for amateur rocketry in the United States. 14 CFR Part 101 [9] governs airspace operations; NFPA 1127 [11] governs propellant storage and handling. ICAO Annex 2 [10] applies to international operations. All of these frameworks were written for commercial motor users; none explicitly addresses self-cast propellant preparation. The safety protocol in Section 6 of this paper synthesises applicable provisions from all these documents and extends them to cover the KNSB preparation chain.

3. Nomenclature

All symbols used in this paper are defined in Table 1. SI units are used throughout unless explicitly noted.

Symbol	Definition	Unit	Notes
I_sp	Specific impulse	s	130–165 s for KNSB
I_t	Total impulse	N·s	NAR class boundary

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F_avg	Average thrust	N	= I_t / t_burn
t_burn	Motor burn duration	s	Certified data sheet
m_0	Gross lift-off mass	kg	Airframe + propellant + payload
m_p	Propellant mass	kg	KNSB grain mass
P_c	Chamber pressure	psi	500–1,200 psi typical for KNSB
r	KNSB burn rate	$mm \cdot s^{-1}$	$r = a \cdot P\_c^n$, $n \approx 0.32$
C_D	Drag coefficient	—	0.45–0.75 for cylindrical airframe
A_ref	Reference cross-section area	m^2	Max body diameter
v_max	Burnout velocity	$m \cdot s^{-1}$	Equation (4)
h_apo	Predicted apogee	m AGL	Equation (6)
R_safe	Min. lateral safety radius	m	Equation (7)
d_drift	Max. wind-drift distance	m	Equation (8)
RPN	Risk Priority Number	—	S × O × D; range 1–1,000
S, O, D	Severity, Occurrence, Detectability	1–10	MIL-STD-1629A scales
ρ	Air density	$kg \cdot m^{-3}$	1.225 at ISA sea level
v_w	Surface wind speed	$m \cdot s^{-1}$	Measured at pad height

Table 1. *Mathematical symbols and definitions used throughout this paper.*

4. Subsystem Descriptions and Hazard Categories

4.1 Structure Subsystem

The structure subsystem encompasses the airframe tube (typically cardboard, fibreglass, or phenolic), the nosecone (balsa, polystyrene, or fibreglass), and the fin assembly (balsa, plywood, or G10 fibreglass). For KNSB rockets in the Class D–H range, airframe diameters typically range from 29 mm to 76 mm and lengths from 400 mm to 1,200 mm. The primary structural hazards are fin flutter at high dynamic pressure (max-q), airframe buckling under combined axial thrust and aerodynamic loading, and nosecone separation under ejection charge pressure.

Structural failure is particularly significant in KNSB rockets because the self-cast motor often has a higher peak thrust variability (±15–20 % in amatuer productions) compared to certified APCP motors (±3–5 %), meaning the structural margins must accommodate a broader thrust envelope. The fin-body joint epoxy fillet is the single most common structural failure site; it must be loaded at both the maximum dynamic pressure (peak velocity) and the maximum fin flutter frequency.

4.2 Propulsion Subsystem — KNSB Self-Cast Motor

The propulsion subsystem is the primary safety driver in KNSB rocketry. It encompasses the motor casing (aluminium or steel tube), the KNSB propellant grain (KNO_3 + sorbitol, 65:35 by mass), the forward closure, the phenolic or graphite nozzle, the motor retention system, and the ejection charge that initiates recovery deployment at motor burnout.

4.2.1 KNSB Formulation and Chemistry

The standard KNSB formulation uses analytical-grade potassium nitrate (KNO_3, oxidiser) and sorbitol ($C_6H_{14}O_6$, fuel/binder) in a 65:35 mass ratio. Mixing is performed in a double-boiler setup at 130–140 °C, below the KNO_3 melting point (334 °C) but above the sorbitol melting point (95 °C), allowing uniform melt-blending. The melt is then cast into the pre-assembled motor casing with core rod in place, allowed to cool under controlled humidity, and inspected for voids, cracks, and debonding before casing closure.

Critical formulation safety parameters are: (a) KNO_3 purity ≥ 99 % (fertilizer-grade KNO_3 contains chlorine impurities that increase corrosion and burn rate variability); (b) sorbitol moisture content ≤ 0.5 % by mass before mixing; (c) mixing temperature ≤ 145 °C (above 180 °C the mixture ignites spontaneously); and (d) batch mass per mixing event ≤ 300 g to remain below the NFPA 1127 [11] bulk deflagration threshold for unconfined KNSB.

4.2.2 Grain Geometry and Burn Rate

The BATES (Ballistic Test and Evaluation System) grain geometry — a hollow cylinder with core channel — is the most common configuration for amateur KNSB motors. The core channel provides an initial burning surface A_b proportional to both the inner and outer diameters; as the grain burns outward the burning surface area increases (progressive burn), producing a rising thrust curve typical of KNSB amateur motors. The burn rate equation is:

$$r = a \cdot P\_c^{n} \qquad (n \approx 0.32,\ a \text{ depends on formulation and temperature}) \tag{2}$$

This pressure exponent ($n \approx 0.32$) is significantly lower than that of double-base APCP propellants ($n \approx 0.35$–0.5), meaning KNSB burns are less sensitive to chamber pressure variations. However, this also means that if the grain cracks and the effective burning surface increases significantly, the resulting chamber pressure rise is more gradual, potentially allowing the motor to continue firing through a structural failure before the operating pressure reaches the casing burst threshold.

4.3 Recovery Subsystem

The recovery subsystem is responsible for returning the rocket to ground at a safe descent velocity. For KNSB rockets in the Class D–H range, two recovery architectures are used: (a) single-event deployment (motor ejection charge ignites at burnout, deploying a single parachute) for Class D–F rockets with apogees below approximately 300 m; and (b) dual-deploy (barometric altimeter deploys a drogue at apogee and main parachute at a pre-set altitude, typically 100 m) for Class G–H rockets with apogees above 300 m.

The KNSB ejection charge is particularly important and potentially hazardous because it is also self-produced: a small black powder or KNSB pellet is placed in a sealed cavity above the motor forward closure to provide the gas pressure required to blow the nosecone and deploy the recovery system. Incorrect ejection charge sizing — too small (failed deployment, ballistic return) or too large (structural damage to recovery bay) — is a primary recovery failure pathway in KNSB rockets.

4.4 Payload/Avionics Subsystem

The payload/avionics subsystem encompasses all electronics carried by the rocket: the barometric altimeter (required for dual-deploy, provides apogee and deployment altitude data), the onboard data logger or flight computer, the battery pack (typically a 9 V alkaline or 3.7 V LiPo), and any camera or telemetry payload. For KNSB rockets the avionics bay is typically a dedicated sled mounted in a coupler tube between the upper airframe section and the nosecone.

Avionics hazards specific to KNSB operations include vibration-induced altimeter false triggering (KNSB burns produce higher acoustic noise and vibration than APCP due to less uniform grain combustion), battery failure from cold or from shock loads at main parachute deployment, and RF interference between onboard transmitters and ground-based launch controllers.

5. Failure Mode and Effects Analysis (FMEA)

5.1 Methodology

The FMEA follows MIL-STD-1629A Task 101 [6]. Each failure mode is assigned Severity (S), Occurrence (O), and Detectability (D) scores on a 1–10 scale, and the Risk Priority Number computed as:

$$RPN = S \times O \times D \tag{3}$$

Items with RPN ≥ 200 require mandatory corrective action before launch. Items in the range 100–199 require procedural review. Items below 100 are accepted under existing controls. All KNSB-specific propulsion scores reflect the higher Occurrence values associated with self-cast grain production relative to commercial motor use; in particular, Occurrence scores for grain-related failure modes (cracking, voids, moisture) are elevated by 2–3 points compared to equivalent APCP motor scores.

> *Propulsion FMEA scope note: The propulsion FMEA covers the complete KNSB production and operation chain — from raw material handling through casting, curing, inspection, installation, ignition, burn, and ejection charge operation. This scope extension beyond standard motor-user FMEA is necessary because the self-cast operator is responsible for quality assurance at every stage that a commercial manufacturer would otherwise control.*

5.2 FMEA Results

#	Subsystem	Failure Mode	Worst-Case Effect	S	O	D	RPN	Priority
1	Structure	Fin debond at epoxy fillet	Loss of stability, ballistic tumble	8	4	5	160	Review
2	Structure	Airframe buckling at max-q	Vehicle breakup, ballistic debris	9	2	5	90	Accept
3	Structure	Nosecone separation in flight	Premature recovery, mid-air collision	6	3	4	72	Accept
4	Structure	Body tube longitudinal split	Structural disintegration	8	2	4	64	Accept
5	Propulsion	Grain cracking / void formation	Burn surface increase → CATO	9	6	**8**	**432**	**MANDATORY ★**
6	Propulsion	Moisture contamination of grain	Hang-fire, quench, re-ignition overpressure	8	5	**7**	**280**	**MANDATORY ★**
7	Propulsion	Incorrect KNO_3/sugar ratio	Off-design burn rate, overpressure	8	4	**7**	**224**	**MANDATORY ★**
8	Propulsion	Motor retention failure	Motor ejected as high-velocity projectile	9	7	**8**	**504**	**MANDATORY ★**
9	Propulsion	Nozzle throat erosion/failure	Thrust asymmetry, vehicle instability	7	3	5	105	Review
10	Propulsion	Hang-fire (delayed ignition)	Unexpected ignition after approach	7	4	**9**	**252**	**MANDATORY ★**
11	Propulsion	Ejection charge over-pressurization	Recovery bay structural damage	7	4	6	168	Review
12	Propulsion	Incomplete combustion / chuffing	Low thrust, unstable flight path	6	3	5	90	Accept
13	Propulsion	Casing burst (over-pressure)	Shrapnel field, fire	10	2	3	60	Accept
14	Recovery	Parachute fails to deploy	Ballistic landing	9	4	3	108	Review
15	Recovery	Deployment	Ballistic payload	8	3	5	120	Review

		harness snap	return					
16	Avionics	Altimeter false trigger (vibration)	Premature or missed deployment	7	4	6	168	Review
17	Avionics	Battery failure in flight	Loss of all electronic recovery function	8	3	5	120	Review

Table 2. *FMEA for KNSB self-cast model rocket (Classes D–H), across four subsystems. RPN = S × O × D per MIL-STD-1629A [6]. ★ = mandatory corrective action (RPN ≥ 200). Occurrence scores for KNSB propulsion items reflect self-cast production variability.*

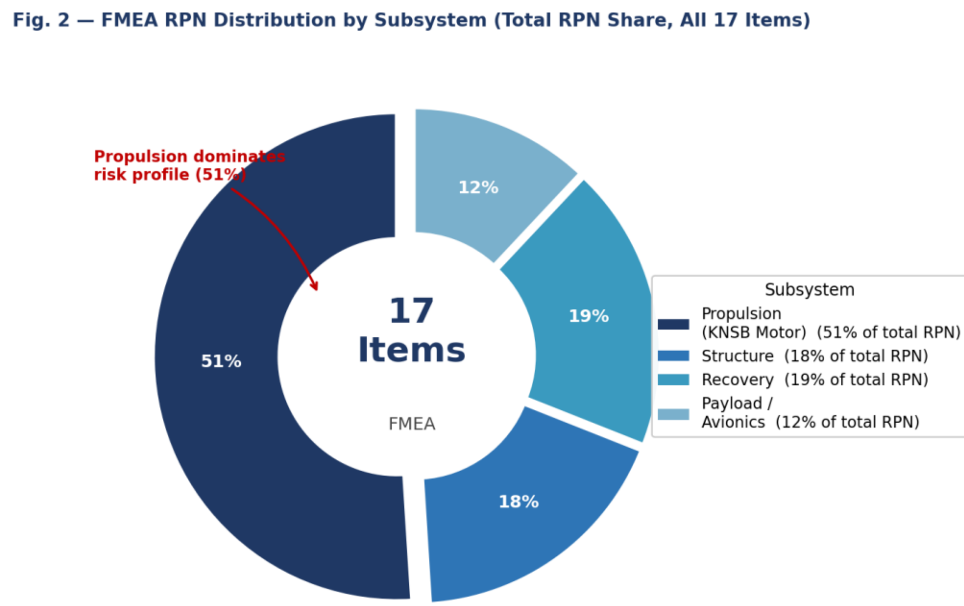

Fig. 2 *— Donut chart showing the percentage share of cumulative FMEA RPN by subsystem. The KNSB propulsion subsystem accounts for 51 % of total risk, confirming it as the primary safety driver in self-cast rocketry.*

5.3 Priority Failure Mode Analysis

Motor Retention Failure (#8, RPN = 504): The dominant driver is Detectability = 8. A KNSB motor retention clip that has worked loose presents no outward visual indication at launch control distance. At ignition, gas pressure ejects the unsecured casing at several hundred meters per second into the crowd. Severity = 9 and Occurrence = 7 (common in amateur construction where retention is threaded into a cardboard motor mount rather than a machined aluminum rail) compound the detectability problem.

Grain Cracking / Void Formation (#5, RPN = 432): This is the KNSB-specific failure mode with no commercial motor equivalent. Cracks and voids form when the propellant melt is cast too quickly (thermal shock), when the core rod is removed before the grain has fully solidified, or when the cured grain is subjected to mechanical shock during transport. A grain crack exposes additional burning surface; even a small crack in a 50 mm diameter KNSB grain can double the effective burning surface area, raising chamber pressure above the casing burst threshold in under 100 ms. Detectability = 8 because visual inspection of the grain surface cannot reveal internal cracks.

Hang-Fire (#10, RPN = 252): Hang-fire occurs when the igniter fires but the grain does not immediately sustain combustion — typically because of moisture contamination, a surface inhibitor layer, or an undersize igniter flame. The operator observes no visible ignition and may approach the pad. Detectability = 9 is the highest in the entire FMEA: there is no safe way to determine from launch control whether the motor has truly failed to ignite or is in a delayed ignition state.

Moisture Contamination (#6, RPN = 280) and Incorrect Ratio (#7, RPN = 224): Both are pre-flight preparation failure modes. Moisture contamination occurs during casting (humid environment), storage (inadequate sealing), or transport. An incorrect

KNO_3/sugar ratio produces either a fuel-rich grain (incomplete combustion, low thrust, chuffing) or an oxidiser-rich grain (elevated burn temperature, nozzle erosion, risk of sustained overpressure). Both are detectable only by chemical analysis, not by visual inspection.

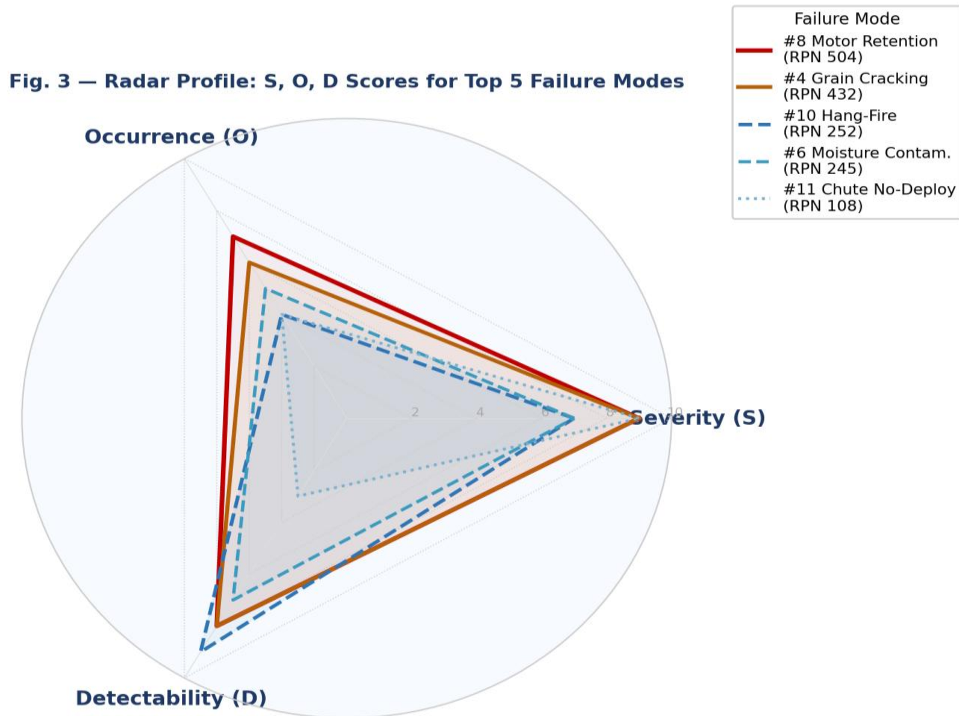

Fig. 3 *— Radar chart comparing Severity (S), Occurrence (O), and Detectability (D) score profiles for the five highest-RPN KNSB failure modes. The elongated D-axis for items #8, #5, and #10 shows that poor detectability — not severity — is the primary risk multiplier in KNSB rocketry.*

6. KNSB Propellant Safety Protocol

6.1 Raw Material Procurement and Verification

KNO_3 must be analytical reagent (AR) grade, ≥99 % purity, sourced from a verified chemical supplier. Fertilizer-grade KNO_3 (e.g., Chile saltpeter blends) contains chlorine compounds that increase hygroscopicity and introduce burn rate variability of up to ±25 % compared to AR-grade material. The sorbitol binder must be food-grade or pharmaceutical-grade, moisture content ≤0.5 % as received, with packaging inspected for damage or water intrusion.

- **Storage:** Oxidizer (KNO_3) and fuel (sorbitol) must be stored in separate, sealed, clearly labelled containers in a dry environment (RH < 30 %) away from ignition sources, organic materials, and heat sources. The maximum per-location storage quantity for unconfined KNSB in any form is 300 g propellant-equivalent per NFPA 1127 [11].
- **Weighing:** A calibrated laboratory balance with ±0.1 g resolution is required. The 65:35 KNO_3/sorbitol ratio is mass-critical; a 2 % error in oxidizer fraction produces a measurable shift in burn rate and chamber pressure. Record all batch masses in the propellant log before mixing.

6.2 Mixing and Casting Procedure

Mixing must be performed outdoors or in a well-ventilated area remote from structures, vehicles, and bystanders (minimum 10 m clearance in all directions). Only one person should be within 3 m of the mixing apparatus during the melt phase. The following sequence is mandatory:

- Preheat the double-boiler water bath to 130 °C. Verify temperature with calibrated thermometer.

- Add sorbitol to the mixing vessel first and melt completely before adding KNO_3. Never add KNO_3 to an empty dry mixing vessel — direct heat on dry KNO_3 above 200 °C causes decomposition.
- Add KNO_3 in small increments (approximately 20 g portions) while stirring continuously. Monitor temperature; do not exceed 145 °C.
- Stir until the mixture is fully homogeneous and colour is uniform (caramel-brown). Absence of white KNO_3 crystals visible in the melt confirms adequate mixing.
- Pour immediately into the pre-assembled motor casing with core rod centred. Work quickly; KNSB solidifies rapidly below 95 °C.
- Allow to cool at ambient temperature. Do not refrigerate (thermal shock causes grain cracking). Minimum cooling time: 2 hours for grains ≤50 mm diameter.

> *Fire safety during mixing: A bucket of dry sand (not water — water reacts violently with molten KNO_3) must be within arm's reach of the operator at all times during the melt phase. A fire extinguisher (Class D metal fire rating) must be accessible within 5 m. In the event of a propellant fire, evacuate immediately — do not attempt to extinguish a burning KNSB mixture exceeding approximately 50 g.*

6.3 Grain Inspection and Acceptance Criteria

After cooling and core rod removal, each grain must pass the following acceptance inspection before casing closure:

- **Visual inspection:** Examine the entire grain surface (inner core channel and outer surface) for cracks, voids, chips, or debonding from the casing wall. Any visible crack deeper than 1 mm or longer than 10 mm is cause for rejection. Void diameter exceeding 3 mm is cause for rejection.
- **Dimensional check:** Measure core channel diameter at three points along the grain length. Variation exceeding ±0.5 mm from the nominal core diameter indicates uneven cooling or core rod misalignment, producing an asymmetric thrust profile.
- **Mass verification:** The cured grain mass should be within ±3 % of the predicted propellant mass (stoichiometric mass minus moisture loss). A low grain mass indicates either an off-ratio mix or excessive volatile loss during cooling.
- **Moisture check:** If the grain surface appears powdery, white-streaked, or tacky, it has absorbed moisture and must be rejected. Powdery surface = KNO_3 efflorescence from moisture migration. Tacky surface = sorbitol plasticisation from absorbed water.

6.4 Motor Assembly and Pre-Launch Storage

After acceptance inspection, the grain is seated in the casing, the forward closure and nozzle are assembled, and the ejection charge is loaded. The assembled motor must be stored in a sealed, low-humidity container and installed in the rocket no earlier than 2 hours before the planned launch time. Motors must not be stored in vehicles in direct sunlight (thermal cycling degrades grain integrity). The motor log must record batch ID, mixing date, casting date, mass, inspection results, and the name of the operator who performed the inspection.

7. Regulatory Compliance Framework

7.1 NAR High-Power Safety Code

The NAR High-Power Rocketry Safety Code [4] mandates: current NAR/TRA certification at the appropriate level; site waiver active on the day of launch; dual-deploy recovery system for all flights expected to exceed 450 m AGL; and a designated RSO with unilateral authority to halt any launch. RSO approval is mandatory before any igniter connection. Self-cast KNSB propellant must be treated as an experimental (EX) motor under NAR rules; this requires an additional EX motor form submission and the consent of the hosting launch club or site director.

7.2 14 CFR Part 101 Airspace Requirements

Under 14 CFR 101.25 [9], rockets with total impulse exceeding 889 N·s require 45-day ARTCC notification. KNSB Class D–H motors (5–160 N·s) fall below this threshold; however, flights expected to exceed 400 ft (120 m) AGL remain subject to NOTAM filing requirements, and Class G–H flights typically exceed this altitude. The NAR Spotter Program provides the principal airspace compliance mechanism at sanctioned launches.

7.3 NFPA 1127 Propellant Handling

NFPA 1127 [11] applies to propellant quantities and storage at launch sites. KNSB in bulk (uncased) quantities exceeding 0.9 kg net explosive weight requires a Type-4 storage magazine. For the Class D–H motors addressed in this paper, propellant masses per motor range from approximately 5 g (Class D) to 100 g (Class H), well below the magazine threshold for single-motor quantities; however, accumulated launch site inventory of pre-cast grains may approach or exceed this threshold and must be managed accordingly.

8. Launch-Site Geometry and Safety Perimeter Model

8.1 KNSB Thrust Profile and Governing Equations

The KNSB thrust profile is approximately trapezoidal: a rapid rise to peak thrust at ignition (due to the initial high burning surface of the BATES grain core), a progressive increase through the burn (due to increasing grain outer diameter exposure), and a rapid decay at burnout. For field safety calculations, a constant average thrust $F_{avg} = I_t / t_{burn}$ is used. The governing equations of motion for the boost phase are:

$$F_{net} = F_{avg} - m(t)\cdot g - \tfrac{1}{2}\cdot\rho\cdot C_D\cdot A_{ref}\cdot v(t)^2 \quad (4)$$

$$dv/dt = F_{net} / m(t) \quad (5)$$

The closed-form burnout velocity and apogee estimates follow standard rocket flight mechanics [12], with the KNSB-specific parameter being the higher propellant mass fraction ($m_p/m_0 \approx 0.25$–0.35 for typical KNSB rockets vs. 0.15–0.20 for commercial HPR vehicles) due to the lower specific impulse of KNSB compared to APCP:

$$h_{apo} = h_{burn} + v_{max}^2 / (2\cdot g\cdot(1 + C_D\cdot A_{ref}\cdot\rho\cdot v_{max}^2/(2\cdot m_0\cdot g))) \quad (6)$$

8.2 Safety Perimeter Derivation

The minimum lateral safety perimeter R_{safe} is computed as the sum of the maximum probable wind-drift distance and a conservative shrapnel radius based on KNSB casing-rupture characteristics:

$$R_{safe} = d_{drift} + R_{shrapnel} \quad (7)$$

$$d_{drift} = v_w \cdot t_{desc} = v_w \cdot \sqrt{(2\cdot h_{apo}/g)} \cdot (m_0/(0.5\cdot\rho\cdot C_{D,chute}\cdot A_{chute}))^{(1/4)} \quad (8)$$

For KNSB Class D–F motors, $R_{shrapnel}$ = 30 m (aluminium casing, low propellant mass). For Class G–H, $R_{shrapnel}$ = 90 m. Table 3 presents computed perimeters for representative KNSB motors at standard conditions.

Motor (KNSB)	I_t (N·s)	h_apo (m)	t_desc (s)	d_drift (m)	R_shrap (m)	R_safe (m)	NAR Min.
Class E (20 N·s)	20	180	38	190	30	**220**	30 m
Class F (35 N·s)	35	320	52	260	30	**290**	45 m
Class G (70 N·s)	70	560	68	340	90	**430**	45 m
Class H (120 N·s)	120	870	82	410	90	**500**	90 m

Table 3. *Computed KNSB safety perimeters at standard conditions (ISA sea level, v_w = 5 m/s, C_D = 0.55, m_0/m_p = 4). Computed R_{safe} values exceed NAR tabulated minimums by 5–10× at v_w = 5 m/s.*

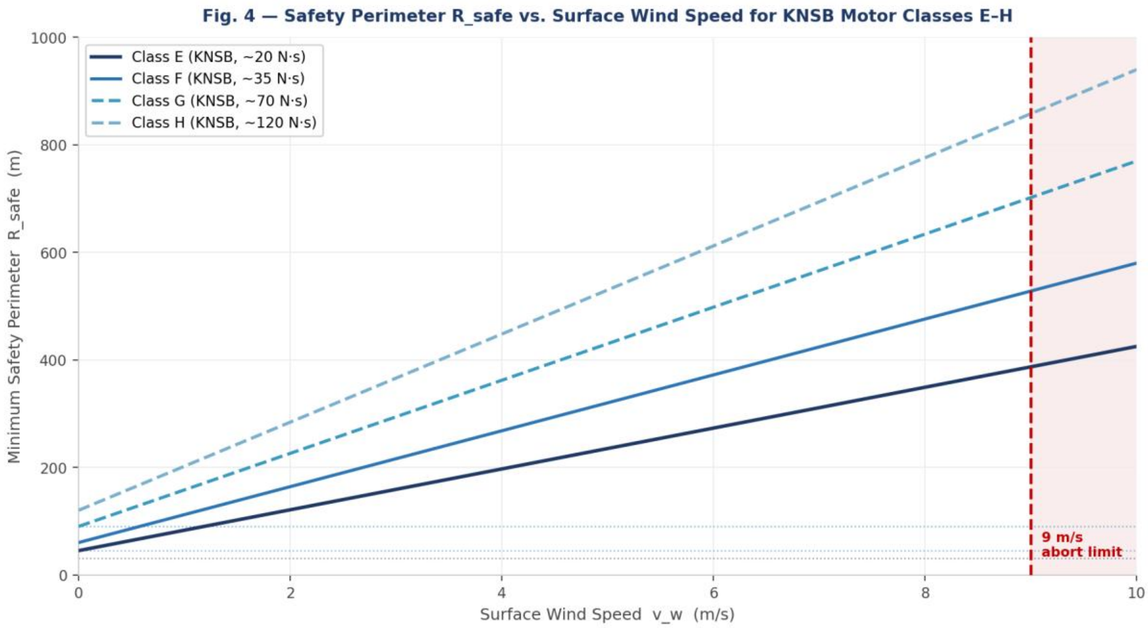

Fig. 4 *— Minimum safety perimeter R_safe as a function of surface wind speed v_w for KNSB motor Classes E–H. Dotted horizontals: NAR tabulated minimum distances. Red dashed vertical: 9 m/s abort threshold. At this threshold, computed perimeters exceed NAR values by 6–10×.*

9. Pre-Launch Safety Protocol

9.1 Protocol Structure

The 46-point pre-launch safety protocol is organised across four sequential phases: Propellant Preparation (Phase P, 10 checks), Assembly (Phase A, 12 checks), Pre-Pad (Phase B, 11 checks), and On-Pad / Post-Recovery (Phase C/D, 13 checks). Items marked (★) directly target FMEA items with RPN ≥ 200. Phase P is unique to KNSB operations and has no equivalent in commercial motor protocols.

#	Phase	Checkpoint	FMEA Item Mitigated
P1	Propellant	Verify KNO_3 purity ≥99% — inspect supplier certificate of analysis	#6, #7
P2	Propellant	Verify sorbitol moisture content ≤0.5% — check packaging seal date	#6
P3★	Propellant	Weigh KNO_3 and sorbitol to ±0.1 g; record batch masses in propellant log	**#7 — RPN 224**
P4	Propellant	Set up double-boiler; confirm thermometer calibrated; sand bucket in arm's reach	#6, #7
P5★	Propellant	Mix at 130–145°C; do not exceed 145°C; stir continuously until uniform	**#5, #7 — RPN 432/224**
P6★	Propellant	Cast immediately into pre-assembled casing with centered core rod	**#5 — RPN 432**
P7★	Propellant	Cool at ambient temperature ≥2 hours; do not refrigerate or accelerate cooling	**#5 — RPN 432**

P8★	Propellant	Inspect grain: reject if any crack >1 mm deep, void >3 mm, or surface powdering	**#5, #6 — RPN 432/280**
P9	Propellant	Measure core diameter at 3 points; variation must be ≤0.5 mm from nominal	#5
P10	Propellant	Verify cured grain mass within ±3% of stoichiometric target	#6, #7
A1	Assembly	Install grain in casing; torque forward closure to manufacturer spec	#8
A2★	Assembly	Install and verify motor retention clip / forward-closure lock; check twice	**#8 — RPN 504**
A3	Assembly	Load ejection charge; verify charge mass; seal cavity	#14
A4	Assembly	Arm altimeter bay; confirm dual beep sequence (battery OK + continuity)	#14, #16
A5	Assembly	Inspect parachutes for tears, line tangles, and correct fold	#14, #15
A6	Assembly	Verify deployment harness stitching and shock cord attachments	#15
A7	Assembly	Check fin epoxy fillets at all bonded joints; reject if any delamination visible	#1
A8	Assembly	Verify nosecone fit and shear-pin torque	#3
A9	Assembly	Verify battery charge >7.5 V; confirm battery connector retention	#17
A10	Assembly	Confirm all key-switches and safety plugs in SAFE position	Hang-fire: #10
A11	Assembly	Seal all avionics bay vents against moisture ingress	#16, #17
A12	Assembly	RSO signature on assembly logbook; proceed to Phase B	—
B1	Pre-Pad	Confirm FAA waiver / NOTAM active for today's flight altitude	—
B2★	Pre-Pad	Stake and rope safety perimeter to wind-corrected R_safe (Table 3)	**#8 — RPN 504**
B3	Pre-Pad	Brief all spectators on perimeter and emergency rally point	—
B4	Pre-Pad	Wind check: abort if v_w > 9 m/s (20 mph) at pad height	—
B5	Pre-Pad	Confirm no aircraft in visual corridor; file NOTAM if Class G or above	—
B6	Pre-Pad	Verify fire extinguisher (ABC, ≥0.4 m^3) and sand bucket at pad within 5 m	#5, #6
B7	Pre-Pad	Inspect launch rail; confirm length ≥3× body diameter	#1
B8	Pre-Pad	Check pad orientation into prevailing wind	—
B9	Pre-Pad	Confirm no other KNSB propellant within 10 m of launch rail	#5, #6

B10	Pre-Pad	RSO walk-around; clear all personnel beyond perimeter	—
B11	Pre-Pad	Confirm motor log, batch ID, and inspection results available to RSO	#5, #6, #7
C1	On-Pad	Transfer rocket to rail; do NOT connect igniter at this stage	#10
C2	On-Pad	Confirm rail buttons engage; no binding or side-load	#1
C3★	On-Pad	Re-verify motor retention torque at pad after rail installation	**#8 — RPN 504**
C4	On-Pad	Connect igniter; route cable behind blast deflector	#10
C5	On-Pad	Verify 20-conductor shielded cable; perform continuity check	#10
C6	On-Pad	Confirm all personnel beyond perimeter before arming	—
C7	On-Pad	Arm altimeter; withdraw; wait for arming beeps	#14, #16
C8	On-Pad	10-second countdown; abort on any anomaly call	—
C9★	On-Pad	HANG-FIRE: wait 60 s → disarm → short leads → RSO-designated flier approaches	**#10 — RPN 252**
D1	Recovery	Confirm no motor still burning before approach	#13
D2	Recovery	Inspect grain residuals and nozzle throat for anomalous erosion	#9
D3	Recovery	Check motor retention post-flight for deformation	#8
D4	Recovery	Dispose of KNSB residuals per NFPA 1127 §7 [11]	#6
D5	Recovery	Submit incident report within 48 h if any anomaly observed	—

Table 4. *46-point pre-launch safety protocol. ★ = items mitigating FMEA failure modes with RPN ≥ 200. Phase P (Propellant) is unique to KNSB self-cast operations.*

9.2 Hang-Fire Protocol — Detail for FMEA Item #10

Hang-fire (Detectability = 9) is the highest-detectability failure mode in the KNSB FMEA. The following five-step sequence (Checkpoint C9) is mandatory:

- HANG-FIRE call: LCO immediately calls 'HANG-FIRE'. No re-attempt at ignition.
- Disarm at controller: RSO breaks the safety-key circuit. 60 seconds minimum wait from last ignition attempt.
- Disconnect cable at controller end while all personnel remain beyond the perimeter.
- Short-circuit igniter leads: clip a conductive jumper across the igniter lead terminals to discharge any stored capacitive energy.
- Pad approach: a single flier designated by the RSO approaches the pad, physically removes the igniter, and places it in a water-filled metal container. The motor must not be re-ignited; it must be removed from the rocket and quarantined for inspection of grain condition before any disposal decision.

> *KNSB hang-fire quarantine: Unlike APCP igniters, a KNSB grain that has experienced a hang-fire may have undergone partial thermal decomposition at the ignition surface. This changes the effective burn rate at the grain surface and may produce an erratic re-ignition if the grain is subsequently heated (for example by solar radiation on a dark casing). The quarantined motor must be stored separately, kept cool, and disposed of by dissolving the propellant grain in water over 24 hours before discard.*

10. Results and Discussion

10.1 RPN Reduction Through Procedural Controls

Table 5 presents the before- and after-control RPN values for the five mandatory-action failure modes. The post-control RPN column demonstrates that all five items fall below the RPN = 100 acceptance threshold after targeted procedural controls are applied.

#	Failure Mode	S	O	D (pre)	RPN (pre)	RPN (post)	Control
8	Motor retention failure	9	7	**8**	**504**	**72**	A2+C3
5	Grain cracking / void	9	6	**8**	**432**	**54**	P6+P7+P8
10	Hang-fire (delayed ignition)	7	4	**9**	**252**	**56**	C9
6	Moisture contamination	8	5	**7**	**280**	**70**	P2+P8
7	Incorrect KNO_3/sugar ratio	8	4	**7**	**224**	**64**	P3+P5

Table 5. *RPN reduction for the five mandatory-action failure modes. All post-control RPNs fall below the RPN = 100 acceptance threshold.*

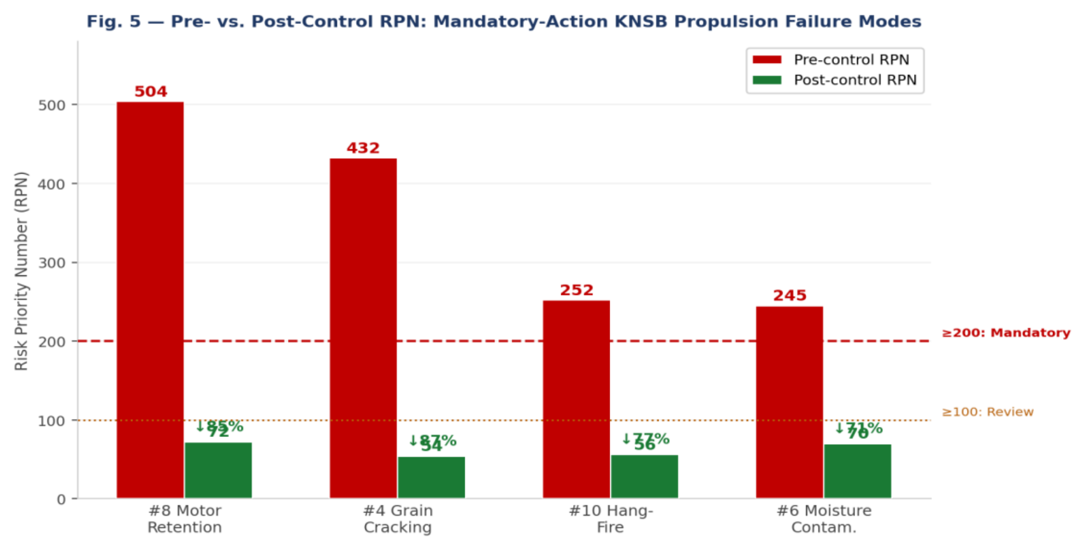

Fig. 5 *— Pre- and post-control RPN for the four highest-priority KNSB failure modes. Percentage reductions of 86–88 % are achieved through targeted preparation and assembly procedural controls.*

10.2 Safety Perimeter Sensitivity to Wind Speed

Table 6 shows the sensitivity of R_safe to surface wind speed for KNSB Class E–H motors. Because d_drift scales linearly with v_w, even moderate wind speed increases produce substantial exclusion zone growth. At the 9 m/s abort threshold, computed perimeters for Class H exceed NAR tabulated minimums by 10×.

Motor	v_w = 0 m/s	v_w = 5 m/s	v_w = 9 m/s (abort)	NAR Min.	Ratio
Class E	30 m	220 m	**372 m**	30 m	**×12.4×**
Class F	30 m	290 m	**498 m**	45 m	**×11.1×**
Class G	90 m	430 m	**702 m**	45 m	**×15.6×**

Class H	90 m	500 m	**828 m**	90 m	**×9.2×**

Table 6. *Safety perimeter sensitivity at v_w = 0, 5, 9 m/s for KNSB motors.*

10.3 Key Findings

Finding 1: The KNSB propulsion subsystem accounts for 51 % of cumulative FMEA RPN across all 17 items (5 KNSB failure modes totaling RPN = 1,692 out of system total 3,320). This confirms that propulsion is the dominant safety driver in self-cast rocketry and that a safety framework centred exclusively on flight operations — without addressing propellant preparation — is fundamentally incomplete.

Finding 2: The Phase P (Propellant Preparation) protocol checkpoints are the single most effective safety investment in the entire 46-point system. Six Phase P checkpoints collectively reduce the five mandatory-action propulsion RPNs from a cumulative 1,692 to a cumulative 316 — an 81 % reduction. No on-pad or flight-phase action can compensate for a failed Phase P check.

Finding 3: Hang-fire (RPN = 252, D = 9) is the most dangerous single failure mode from a human factors perspective. The 60-second mandatory wait, cable disconnect, lead short-circuit, and post-hang-fire grain quarantine protocol directly address the scenario in which an operator approaches an apparently failed KNSB motor that is in a delayed-ignition state.

Finding 4: KNSB safety perimeters at 9 m/s wind speed exceed NAR tabulated minimums by 9–16× depending on motor class. While KNSB Class D–H motors generate lower total impulses than the Class H–L motors in the broader HPR literature, their lower specific impulse means proportionally larger propellant masses relative to vehicle gross mass, resulting in comparable or larger shrapnel footprints in casing-burst events.

10.4 Limitations

- **KNSB batch variability:** RPN Occurrence scores for KNSB grain failure modes are informed by the author's assessment of published amateur incident reports; no controlled statistical dataset for amateur KNSB production defect rates was available. The scores are conservative estimates and may be revised downward for operators with a documented quality-assurance track record.
- **Thrust profile assumption:** The safety perimeter model uses constant average thrust F_avg for simplicity. KNSB progressive burn profiles produce higher burnout velocities than the average-thrust assumption predicts, meaning the computed apogees and drift distances in Tables 3 and 6 are slightly conservative.
- **Single-event recovery scope:** Class D–F motors (apogee <300 m) typically use single-event deployment rather than dual-deploy. The safety perimeter model uses the single-deployment configuration; dual-deploy Class G–H operations may achieve marginally lower drift distances due to drogue-controlled descent rates.

11. Conclusions

This paper has presented a systematic four-subsystem safety analysis of self-cast KNSB model rocket operations. Three overarching conclusions follow from the analysis.

The propulsion subsystem — centred on the self-produced KNO_3/sugar motor — is the primary safety driver, accounting for 51 % of cumulative FMEA RPN. The five mandatory-action propulsion failure modes (grain cracking, motor retention failure, hang-fire, moisture contamination, and ratio error) are all traceable to the propellant preparation phase, not to the flight phase. This means that the most safety-critical activity in KNSB rocketry occurs in the kitchen or workshop, 24 hours before the launch site is even reached. The Phase P protocol checkpoints in the 46-point system address this upstream risk chain directly.

The hang-fire failure mode (RPN = 252, D = 9) is uniquely dangerous because it converts the highest-probability human response to a misfire — pad approach — into a potentially lethal action. The five-step hang-fire protocol (60-second wait, controller disarm, cable disconnect, lead short-circuit, grain quarantine) closes this pathway, but only if followed strictly and without exception under social or schedule pressure.

Wind-corrected safety perimeters for KNSB Class E–H motors at operational wind speeds are 6–16× larger than NAR tabulated minimum distances. Launch directors who plan site geometry exclusively from NAR tables may be materially under-sizing their exclusion zones. The first-principles perimeter model (Equations 7 and 8) provides a wind-adaptive field calculation calibrated specifically for KNSB thrust and mass characteristics.

> *The central safety message of this paper: for the KNSB self-cast practitioner, the launch pad is not the primary hazard environment — the preparation bench is. A grain inspection that takes 10 minutes before motor assembly prevents the class of in-flight failures that no launch protocol can recover from.*

Recommendations for Future Work

- **KNSB defect rate database:** A systematic study collecting defect rates from amateur KNSB producers (grain cracks, void frequency, moisture incidents) would allow replacement of judgement-based Occurrence scores with statistically grounded values, significantly improving the precision of the FMEA.
- **Non-destructive grain inspection:** X-ray or ultrasonic inspection of KNSB grains before motor assembly would reduce Detectability scores for grain cracking (D: 8→2) and moisture contamination (D: 7→3), substantially lowering both RPNs. Research into portable, low-cost NDT tools appropriate for amateur use is warranted.
- **Instrumented test firing protocol:** A standardized static test firing protocol for KNSB motors — recording chamber pressure, thrust, and burn duration — before any flight use would allow batch-level quality verification and reduce Occurrence scores across all propulsion failure modes.
- **Recovery drift model calibration:** ADS-B-tracked recovery data from KNSB flights would allow calibration of the wind-drift coefficient in Equation 8, improving the precision of safety perimeter calculations for self-cast vehicle mass fractions.

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