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TAILORING SOLID ROCKET PROPELLANT BALLISTIC RESPONSES THROUGH CHEMICAL ADDITIVES

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ABSTRACT

This paper presents the static test evaluation of two solid propellant rocket motors using a Baseline Formulation (BF) and a Modified Baseline Formulation (ModBF). The objective was to assess the effect of propellant modification on motor performance parameters. Both motors were tested with 1.0 kg of propellant under identical conditions. Results show that ModBF out performed BF across key metrics. ModBF achieved a maximum thrust of 573 N and an average thrust of 359.2 N, representing increases of 19.1% and 18.9% over BF, respectively. Total impulse and specific impulse for ModBF were 897.8 Ns and 91.52 s, compared to 815.7 Ns and 83.15 s for BF, indicating a 10.1% improvement in both. Burn time was slightly reduced from 2.7 s to 2.5 s, with burn rate increasing from 0.014074 m/s to 0.01520 m/s. Maximum chamber pressure also rose from 1.02 MPa to 1.21 MPa. The improved performance of ModBF is attributed to enhanced combustion efficiency and higher burn rate. These findings provide a validated basis for further optimization of indigenous solid propellant formulations for improved propulsion performance.

Keywords: Solid propellant; Baseline formulation; Modified formulation; Static test; Thrust; Specific impulse; Burn rate; Rocket motor performance.

1 INTRODUCTION

Solid rocket propellants have remained indispensable in modern aerospace applications because of their structural simplicity, operational reliability, high energy density, and long-term storage capability. Their extensive use in space launch vehicles, tactical missiles, sounding rockets, and defence systems is largely attributed to their ability to deliver consistent thrust with minimal mechanical complexity. Despite these advantages, the performance of solid rocket propellants continues to be constrained by several challenges, including limited combustion efficiency, inadequate thermal stability, mechanical degradation during storage and operation, and variations in thrust characteristics. These limitations can adversely affect system reliability, mission accuracy, and operational lifespan, particularly in applications requiring high precision and extended service life.

To address these challenges, considerable research has focused on the incorporation of chemical additives into solid rocket propellant formulations. Although present in relatively small quantities, chemical additives play a significant role in modifying the thermal behaviour, physicochemical properties, microstructure, and long-term stability of composite materials. They are also incorporated to improve material processing, enhance thermal resistance, increase moisture tolerance, strengthen mechanical integrity, and promote compatibility among formulation constituents. The performance of composite propellants depends not only on the primary constituents, such as polymeric binders and oxidizing phases, but also on the interactions between reinforcing materials and chemical additives [1]. Nevertheless, the selection and incorporation of additives remain largely empirical because the mechanisms through which individual or combined additives influence material behaviour under different operating conditions are not yet fully understood. Consequently, formulation development often relies on extensive experimental evaluation, increasing both development time and cost.

Among the numerous additives investigated, aluminium has received considerable attention because of its high energy content, favorable availability, and compatibility with composite propellant systems. Micron-sized aluminium particles increase the overall energy released during combustion, although their use may also result in incomplete oxidation and condensed combustion residues [2]. To overcome these limitations, subsequent studies explored nanoscale aluminium particles, which possess significantly larger specific surface areas and enhanced reactivity. It is observed that nano-aluminium exhibits faster ignition characteristics and promotes more efficient combustion; however, challenges associated with nanoparticle production, handling, storage stability, and cost continue to limit their widespread application [3].

Chemical additives have also been extensively investigated for their influence on combustion behaviour and thermal decomposition processes. Iron oxide (Fe_2O_3) is among the earliest and most widely studied inorganic additives because of its catalytic influence on the thermal decomposition of oxidizing components. Iron oxide modifies decomposition pathways, resulting in significant changes in combustion behaviour [4]. Later investigations expanded the range of catalytic additives to include ferrocene derivatives, copper chromite, and nanoscale metal oxides [5]. It is reported that ferrocene-based additives improve ignition behaviour and combustion characteristics. Nanosized ferrites have been reported to modify the thermal decomposition behaviour of energetic materials, owing to their catalytic activity and high surface area [6]. Similarly, it demonstrated that iron oxide functions as an effective catalyst during oxidizer decomposition, contributing to improved combustion stability. It further showed that nanosized metal oxides exhibit enhanced catalytic activity compared with their micron-sized counterparts, primarily because of their larger surface area and increased interfacial activity.

Recent advances in nanotechnology have accelerated research into nanostructured additives because of their unique physicochemical characteristics. Recent reviews on developments in composite propellant formulations and highlighted the growing application of nanomaterials for improving thermal characteristics, microstructural uniformity, and material stability. Their review emphasized that the increased surface area of nanomaterials enhances interactions among formulation constituents, thereby influencing heat transfer, reaction kinetics, and combustion processes [7]. Despite these advantages, challenges associated with nanoparticle dispersion, agglomeration, reproducibility, and manufacturing scalability remain important considerations requiring further investigation.

Current research has also shifted towards understanding the combined effects of multiple additives within composite formulations. This demonstrated that combining nano-aluminium with iron oxide produced more pronounced changes in combustion characteristics than either additive alone, suggesting the existence of synergistic interactions between metallic fuels and catalytic additives [8]. Also, it employed statistical optimization techniques, including Response Surface Methodology, to evaluate the influence of multiple formulation variables on composite propellant characteristics, highlighting the importance of systematic formulation design over conventional trial-and-error approaches [7,9].

Environmental sustainability has become another major focus in energetic materials research. Investigation in environmentally benign additive systems designed to reduce hazardous combustion products and improve the environmental acceptability of composite propellant formulations [10]. Their findings demonstrated that environmentally friendly additives can reduce toxic emissions while improving material handling and occupational safety [11]. More recently, review on catalytic energetic ionic salts and highlighted their potential to influence thermal decomposition behaviour and material stability [12]. Similarly, it was examined that environmentally friendly composite formulations incorporating alternative oxidizing materials together with metallic additives, emphasizing the importance of balancing material performance with environmental responsibility [13].

Although substantial progress has been achieved in understanding the role of individual additives, significant knowledge gaps remain regarding the interactions among multiple additives and their combined influence on the thermal, physicochemical, and combustion characteristics of composite propellant systems. Most published studies investigate individual additives under varying experimental conditions, making direct comparisons difficult and limiting the development of generalized formulation strategies. Consequently, further systematic investigations are required to improve understanding of additive interactions and establish more reliable relationships between formulation composition and material behaviour.

Accordingly, this study investigates the influence of selected chemical additives on the combustion behaviour and overall characteristics of composite solid rocket propellants. The study evaluates the effects of the selected additives on key formulation characteristics, including density, combustion temperature, characteristic velocity, molecular weight, specific impulse, and specific heat ratio. The findings are expected to contribute to a better understanding of additive–material interactions and provide experimental evidence that supports the development of more reliable, thermally stable, and environmentally responsible composite propellant materials for aerospace applications.

2 MATERIALS AND METHODOLOGY

2.1 Propellant Formulation Optimization

This method involves the selection of the propellant constituents, the mathematical model development, propellant preparation, performance parameters measurements and experimental testing for the model validation [14]. Propellant ingredients such as ferric oxide and aluminium were varied to see how their interactions improved the performance and their effects on the propellant formulation were studied. Aluminium is widely used as an energy additive in composite solid propellants, but its combustion can lead to particle agglomeration and reduced combustion efficiency [15]. Ferric oxide (Fe_2O_3) acts as a burn-rate catalyst, although its effectiveness depends on the propellant composition and particle characteristics.

Table 1: Propellant Formulation Performance Prediction @ 1000psi

Mixture ratio	% KN	% SB	% Al	% Fe_2O_3	Isp (s)	Tc (K)	Density (kg/m^3)	Heat ratio	C* (m/s)	Mw (g/mol)
0	65	25	0	10	106.9	1865	1948.1	1.1064	856.7	44.16
0.1	65	25	1	9	109.23	1919	2009.5	1.1091	872.49	43.71
0.2	65	25	2	8	111.69	1966	2002.5	1.1126	894.15	43.19
0.3	65	25	3	7	114.31	2006	1995.6	1.1167	916.21	42.64
0.4	65	25	4	6	116.71	2041	1988.6	1.1215	934.55	42.04
0.5	65	25	5	5	118.94	2071	1981.8	1.1269	944.99	41.41
0.6	65	25	6	4	121.47	2097	1975	1.1329	970.83	40.76
0.7	65	25	7	3	123.86	2120	1968.2	1.1395	989.67	40.11
0.8 (ModBF)	65	25	8	2	126.18	2140	1961.5	1.1467	1008.28	39.44
0.9	65	25	9	1	128.92	2158	1954.8	1.1544	950.39	38.76
1	65	25	10	0	131.48	2173	1958.1	1.163	1001.49	38.07
Base Formulation	65	35	0	0	114.88	1603	1837.3	1.1362	924.46	35.40

At the nanoscale, iron oxide can enhance burning behaviour, while aluminium may influence its catalytic effect during combustion [16, 17, 18]. The propellant ingredients used are oxidizer (Potassium Nitrate) (KN), fuel/binder (Sorbitol)(SB), fuel (Aluminium)(Al) and burn rate catalyst (Ferric Oxide) (Fe_2O_3) (Table 1). The propellant characteristics performance parameters of interest in this work are the specific impulse, density, combustion temperature, characteristic velocity, molecular weight and heat ratio of the propellant [19]. The grain geometry analysis is presented in (Table 2) (Figure 1).

Table 2: Propellant Grain Geometry Design

Propellant Parameter	Symbol	Unit	Value
Outer diameter	Do	m	0.091
Core diameter	dc	m	0.015
Grain length	lo	m	0.1
Propellant mass	mp	kg	1.0
Web thickness	w	m	0.038
Number of bates	N	-	1
Acceleration due to gravity	g	m/s	9.81
Nozzle throat diameter	dt	m	0.022

The test procedure involves three stages: sample preparation, setting up the testing equipment and the ballistic validation test. In this investigation, the propellant sample (KN (65 %), SB (35 %) is referred to as the base formulation (BF) and sample 8 is referred to as the modified base formulation (ModBF), based on its highest characteristic velocity. Both the BF propellant and ModBF propellants were designed to have same propellant grain geometry and mass of propellant.

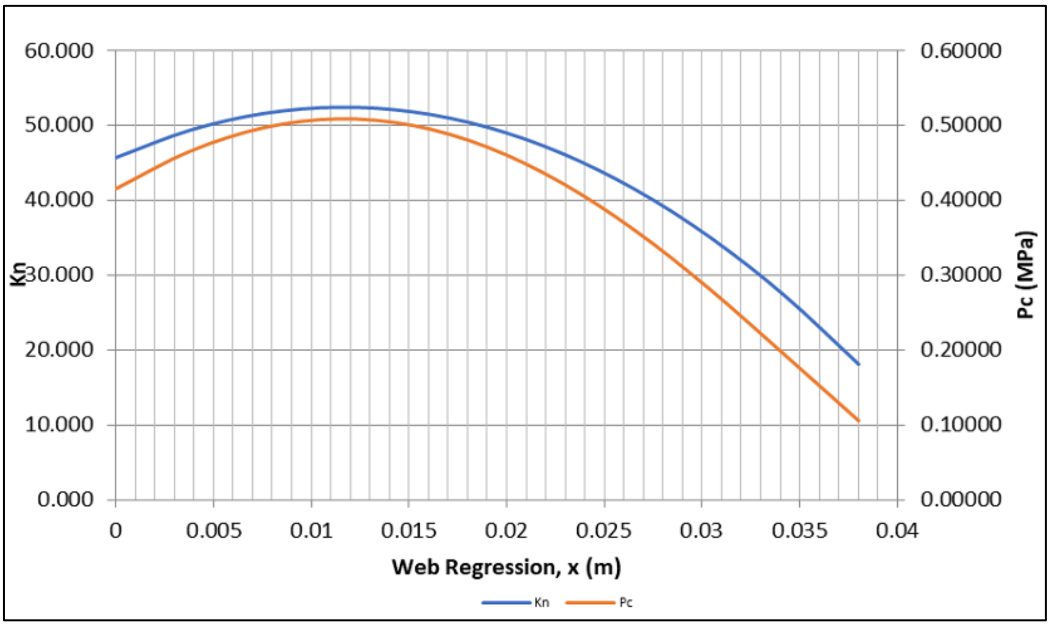

Figure 1: Propellant grain geometry analysis for 0.022 nozzle diameter

2.2 The ballistic test set-up description

Experimental validation of the Modified base formulation (ModBF) propellant performance parameters was carried out using the ballistic evaluation at the premises of the Bola Ahmed Tinubu Centre for Space Transport and Propulsion, Epe, Lagos State, Nigeria. This method involved the design of the thrust chamber and the required pressure and the thermal energy for ignition of the propellant grain was produced by the igniters. Static tests were performed on solid propellant grains using 6 nozzle diameters to vary chamber pressure. The goal was to determine the Saint Robert's Law burn rate coefficient (a) and pressure exponent (n); $r = aP_c^n$ [18]

During the combustion process, the thrust generated was sensed as an electrical signal by the load cell and recorded by the data acquisition module which serves as an intermediary between the load cell and the laptop where signals are collected as data. Thrust, burn time and the propellant exit temperature were measured using a data acquisition facility (This system is capable of repeatedly recording the thrust-time characteristics of rocket motors generating up to 20 kN of maximum thrust with dispersion errors of ±.005%. The system essentially consists of single-point 2,000 kg linearly defined load cell (Figure 2) interfaced to a 12 Bit DATAQ DI-1100 Data Acquisition Unit. A precision mass measurement and accelerometer were also interfaced with the DATAQ system [19].

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Figure 2: Data Acquisition Modules (DAQ)

3 RESULTS AND DISCUSSIONS

The measured thrust-time curves obtained from the static motor tests loaded with the both propellant formulations consecutively are presented in Figure 3, and the major delivered ballistic parameters of interest are summarized in Table 3. Both motors exhibited a progressive-regressive thrust profile with a near-plateau burn segment. ModBF produced consistently higher thrust throughout the burn duration. The maximum thrust for BF was 481 N, while ModBF achieved 573 N, representing a 19.1% increase. Average thrust increased from 302.1 N for BF to 359.2 N for ModBF. Total impulse and specific impulse also showed improvement. ModBF recorded a total impulse of 897.8 N·s and a specific impulse of 91.52 s, compared to 815.7 N·s and 83.15 s for BF, corresponding to a 10.1% increase in both parameters.

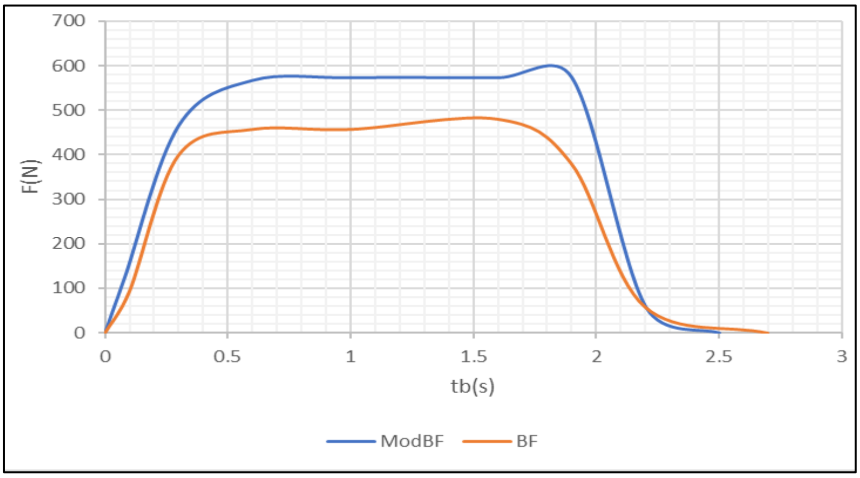

Figure 3: Delivered thrust-time curve of BF and ModBF

Burn time decreased from 2.7 s to 2.5 s, with burn rate increasing from 0.0141 m/s to 0.0152 m/s. Propellant mass for both tests was 1.0 kg. Maximum chamber pressure increased from 1.02 MPa for BF to 1.21 MPa for ModBF. The performance gains in ModBF are attributed to the higher burn rate, which resulted in increased mass flow rate, chamber pressure, and thrust. The improved specific impulse indicates enhanced combustion efficiency (Figure 4 and 5). Stable thrust-time curves for both motors indicate good grain integrity and stable combustion with no significant pressure oscillations.

Table 3: Delivered Ballistic Performance Parameters of BF and ModBF Solid Rocket Ppropellants

S/N	Parameters	Unit	BF	ModBF
1	Max Thrust	N	481	573
2	Average thrust	N	302.10	359.2
3	Total impulse	Ns	815.70	897.8
4	Specific impulse	s	83.15	91.52
5	Burn time	s	2.70	2.5
6	Burn rate	m/s	0.014	0.0152
7	Propellant mass	kg	1.00	1.00
8	Max chamber pressure	MPa	1.02	1.21

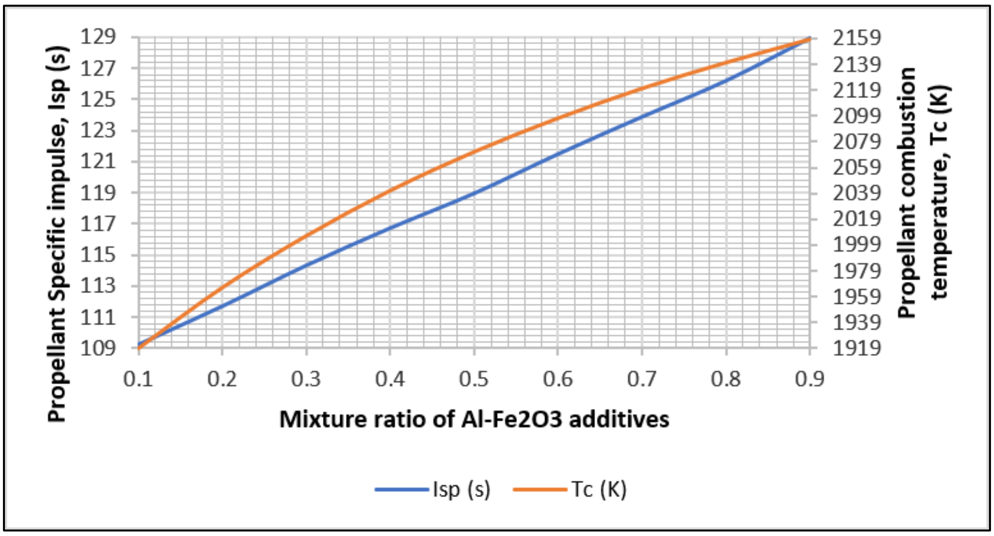

Figure 4: Spans of specific impulse (s) and combustion temperature (K) Over Al and Fe_2O_3 mixture ratio

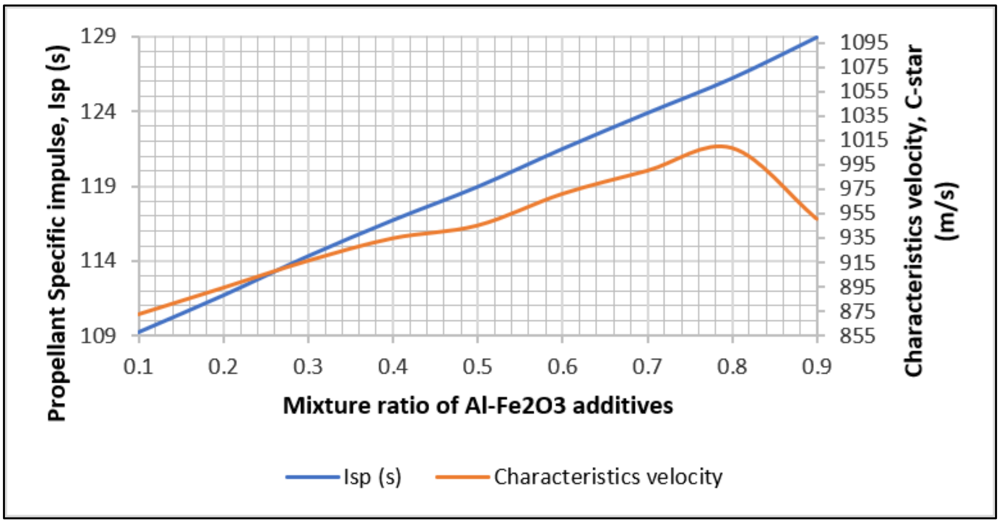

Figure 5: Spans of specific impulse (s) and characteristic velocity against Al and Fe_2O_3 mixture ratio

Table 4 confirmed the fundamental pressure-dependent behaviour of solid propellant combustion. As nozzle diameter decreases, the mass flow rate out of the nozzle decreases for a given chamber condition. To maintain mass balance, chamber pressure must rise. The higher chamber pressure increases the heat feedback from the flame zone to the propellant surface, thereby increasing the pyrolysis rate and consequently the burn rate. The burn rate coefficient of

0.0014697 m/s·MPa^{-n}, and burn rate exponential of 0.255 were 0btained from the correlation (Figure 6). The increase in pressure reduces mass flow, raising heat feedback to the surface and thus burn rate. The low burn rate exponential indicates low pressure sensitivity, stable combustion, and predictable thrust. The good power-law fit confirms Saint Robert's Law is valid for 0.73–3.07 MPa with no change in combustion mechanism. However, errors may arise from pressure measurement, burn rate calculation, and heat losses. Data assumes steady-state burning and should not be extrapolated beyond 3.07 MPa. For a chamber pressure of between 0.73MPa to 3.07MPa, the values of burn rate coefficient (a) and pressure exponent (n) is found to be 1.47mm/s and 0.26 respectively

Table 4: Propellant Burn Rate Analysis

Nozzle diameter (m)	Chamber pressure (MPa)	Burn rate (m/s)
0.026	0.73	0.013871
0.024	0.93	0.01473
0.022	1.21	0.0152
0.02	1.6	0.01652
0.018	2.17	0.018095
0.016	3.07	0.01999

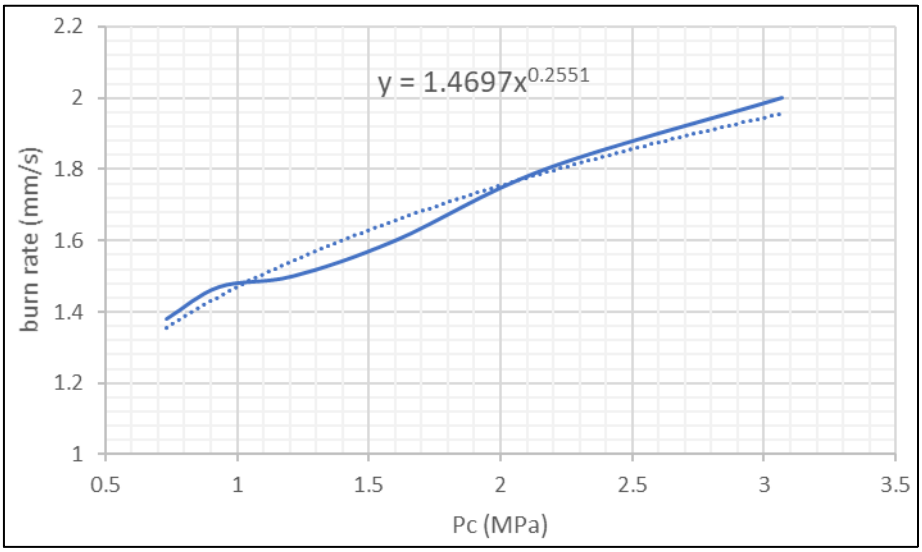

Figure 6: Burn rate coefficient and pressure exponent graphical determination

4 CONCLUSION

The static test results show that the modification to the baseline propellant formulation significantly improved motor performance. ModBF achieved higher maximum thrust, average thrust, total impulse, specific impulse, burn rate, and chamber pressure compared to BF, with a marginally shorter burn time. The results confirm that the modified formulation enhances combustion efficiency and energy release while maintaining stable operation. This study provides validated experimental data as a baseline for further development of indigenous solid propellant formulations.

Recommendations

The Post-Fire Characterization is suggested. Perform material analysis of combustion products and chamber deposits to assess combustion completeness and nozzle erosion. Also, expanded Test Matrix is required. Test ModBF with different grain geometries and nozzle expansion ratios to evaluate performance under varied operating conditions. Finally utilize the validated ModBF data to advance the development of indigenous high-performance solid rocket motors.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

There are no conflicts of interest.

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