

Perspective

The Technical Hypothesis of a Missile Engine Conversion and Upgrade for More Sustainable Orbital Deployments

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Abstract

The conversion of legacy missile engines into space propulsion systems represents a strategic opportunity to accelerate Europe's access to orbit while advancing sustainability and circular-economy goals. Rather than discarding decommissioned hardware, repurposing missile propulsion can reduce development timelines, retain valuable materials, and leverage proven architectures for new applications. This perspective outlines the potential of the Soviet-era Isayev S2.720 engine as a representative case, drawing on historical precedents of missile-to-launcher conversions worldwide. A three-pillar methodology is proposed to frame such efforts: (i) the adoption of cleaner propellants such as LOX–LCH₄ in place of toxic hypergolics; (ii) remanufacturing and upgrading of key subsystems through additive manufacturing, AI-assisted inspection, and digital twin modelling; and (iii) validation supported by dedicated testing, life-cycle assessment (LCA), and life-cycle costing (LCC). Beyond the technical aspects, the paper discusses retrofit applicability, cost considerations, and the role of standardization in enabling future certification. By positioning the S2.720 as a model, this study highlights the broader strategic value of adapting decommissioned propulsion systems for modern orbital use, providing insight into how Europe might integrate legacy assets into a more sustainable and resilient space transportation framework.

Keywords: conversion; reuse; propulsion system; liquid rocket engine



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1. Introduction

The availability of powerful, efficient, low-cost, and reliable transportation solutions for access to Space is a key enabler for Europe's competitiveness in the realm of commercial space flight. Europe is committed to making space flight eco-sustainable. ESA (European Space Agency) Director General's Agenda 2025 [1], published in March 2021 and recently introduced ESA Strategy 2040 [2], reiterate that making ESA a greener organization is a priority, fully supporting the implementation of the Paris Agreement [3] and the European Green Deal [4]. Current rocket propulsion technology could benefit from and is in the need of new solutions that exploit and re-use existing, proven technologies and enhance them

with new, eco-friendly, more sustainable, and commercially competitive approaches. The need for European launch autonomy stems from the desire to achieve strategic independence, ensuring control of access to orbit for national security, defense, weather monitoring, and critical infrastructure such as Galileo [5] and Copernicus [6]. Autonomous launch capability is equally vital for economic competitiveness, supporting industrial innovation, job creation, and technological leadership in the fast-growing space economy. It also provides operational flexibility, enabling timely, mission-critical deployments (e.g., Earth observation during disasters) without dependence on foreign scheduling or export control restrictions. Finally, sovereignty and resilience are at stake: recent launcher retirements (Ariane 5 [7]), delays with Ariane 6 [8], and the Ukraine conflict (which ended cooperation with Russia's Soyuz [9]) have highlighted Europe's vulnerability, underscoring the importance of a self-sufficient launch sector to withstand global disruptions.

In this perspective, two cases of successful conversion of missile systems specifically designed for military use, converted to fit space launch highly demanding criteria, will be briefly described. The authors' view on the possibility of adapting solely the propulsion systems of ground-to-air missiles in order to fit the demand of a small satellite launcher will be discussed. The aim of the article is to provide a feasible hypothesis while describing the possible challenges. The idea of repurposing existing missile propulsion engines from decommissioned or underused military systems for cryogenic space use offers a shortcut to capability, with technical, economic, and geopolitical upsides. The case of the Isayev S2.720 [10] engine is analyzed, and work perspectives are formulated.

2. Historical Precedents

2.1. Russia and the Former Soviet Union

Countries across the globe have historically leveraged decommissioned or dual-use missile technologies to accelerate the development of cost-effective and reliable space launch systems. A prime example of this is the Soyuz rocket, which traces its origins to the R-7 Semyorka [11], the world's first intercontinental ballistic missile (ICBM). Originally developed for military purposes, the R-7 was repurposed to launch Sputnik 1 [12] in 1957, inaugurating the space age. The Soyuz, derived from the R-7, has since become a staple for both crewed missions to the International Space Station (ISS) and commercial satellite launches. While its design has remained largely unchanged, modern versions have been upgraded with improved engines, avionics, and increased payload capacity. The Soyuz employs LOX (liquid oxygen) as the oxidizer and RP-1 (kerosene) as the fuel, ensuring a reliable propulsion system for both military and civilian missions [13].

Moving into the Cold War era, the R-36MUTTH (SS-18 "Satan") [14], one of the most powerful ICBMs ever built, was repurposed to create the Dnepr [15] space launch vehicle. This conversion began in 1999 and stands as a significant example of military-to-civilian rocket technology transfer. ISC Kosmotras retrofitted decommissioned SS-18s with a commercial upper stage and payload fairing, enabling orbital insertion. The Dnepr successfully launched 22 missions, delivering payloads ranging from small satellites to a record-setting 34-satellite deployment in June 2014, with a maximum payload capacity of about 4500 kg to low Earth orbit (LEO) [16]. The Dnepr used the modified R-36M first stage, powered by UDMH + N₂O₄ (unsymmetrical dimethylhydrazine + dinitrogen tetroxide) hypergolic propellants, which ensured higher reliability and easier ignition [17]. The third stage utilized the Block DM upper stage, typically powered by RP-1/LOX, for optimized orbital insertion [18].

Similarly, the UR-100N (Rokot) [19], derived from the UR-100N (SS-19 Stiletto) ICBM [20], was adapted for space launches from 1990 to 2019. The Rokot's success lies in its ability to deliver nearly two metric tons to LEO, with launch costs as low as \$15 million in the late 1990s [20,21]. It utilized the first two stages of the original UR-100N missile, powered by UDMH + N₂O₄, while a new third stage, the Breeze-KM, equipped with advanced guidance, control systems, and restart capabilities, enabled precise orbital deployment [22]. This design allowed for efficient satellite deployment while maintaining the high reliability inherent in the original missile's propulsion system.

Similarly, the Zenit rocket [23] was developed from the RS-27 missile, a modified version of the Soviet R-27 (SS-N-6) submarine-launched ballistic missile [24]. The R-27 was designed for strategic deterrence, but its components—particularly its engines and guidance systems—were adapted to create the Zenit, a medium-to-heavy payload space launch vehicle capable of reaching LEO.

The Proton rocket, based on the UR-500 heavy-lift missile [25], was initially designed as an ICBM capable of carrying nuclear payloads over vast distances. Repurposed for space, the Proton has been integral in launching satellites into geostationary orbit (GEO). The first stage uses LOX + RP-1, while the upper stages utilize UDMH + N₂O₄ for reliable ignition and thrust control, making it ideal for heavy payload launches [26].

2.2. USA

The United States, like other nations, has effectively repurposed decommissioned missile systems for space exploration, creating versatile launch vehicles. A prominent example is the Minotaur family, derived from the decommissioned Minuteman [27] and Peacekeeper [28] ICBMs. These rockets, including the Minotaur IV and Minotaur V, have proven capable of both suborbital and orbital missions [29,30], demonstrating the flexibility of missile technology for peaceful purposes.

Another key example is the Aerojet AJ10 engine family, which traces its origins to missile and sounding-rocket technology. The AJ10-37 variant, which powered the upper stage of Project Vanguard [31], placed Vanguard 1 into orbit on 17 March 1958, using a combination of nitric acid and UDMH [32]. The AJ10 lineage continued to evolve with later variants such as the AJ10-101 and AJ10-118, which powered the second stages of the Atlas-Able and Thor-Able rockets during the late 1950s and early 1960s. These engines utilized hypergolic propellants and became foundational for many subsequent space missions. The AJ10-137 variant served as the Service Propulsion System (SPS) for the Apollo Command and Service Module, delivering ~91 kN of thrust with Aerozine 50/N₂O₄ for lunar orbit insertion and trans-Earth injection [33]. Later, the AJ10-190 powered the Orbital Maneuvering System (OMS) pods on the Space Shuttle, enabling orbit insertion, on-orbit maneuvers, and deorbit burns with MMH/N₂O₄. The adaptability of the AJ10 engine family is a testament to its longevity across both missile-derived and orbital platforms [34].

Civilian space programs in the U.S. also quickly adopted missile technology. A notable case is the Thor intermediate-range ballistic missile, which served as the foundation for NASA's Delta upper stage. In 1959, NASA began developing the Delta stage from the second stage of the Thor-Able launcher—an early milestone in the development of the Delta launch vehicle series. To support this evolution, Douglas Aircraft improved the inertial guidance system for greater accuracy during ballistic coasting prior to third-stage separation.

Atlas [35] and Titan [36] rockets are a classical example of how ICBMs were successfully adapted into space launch vehicles (SLV). This strategy helped the U.S. rapidly enter the space age during the Cold War [37]. The original role of the Atlas rocket was to deliver nuclear warheads, in its initial form (SM-65 Atlas ICBM), as developed in the 1950s by the

USAF [38]. NASA and the military repurposed the Atlas as a launch vehicle [39]. It was used to launch the Friendship Mission 7 in 1962, carrying John Glenn, the first American to orbit Earth [40]. Variants of the Atlas rocket went on to launch satellites, interplanetary probes, and weather spacecraft [41,42]. The Atlas used LOX and RP-1 as propellants and the innovative stage-and-a-half design with side boosters jettisoned mid-flight while the center engine continued [43]. The propulsion system has been adapted for space flight. Although the original setup already used LOX and RP-1 as propellants, the ICBM was designed for short, suborbital flights (10–15 min [44]) to deliver warheads. To assume the space role, longer, more controlled burns to reach orbital velocity (8 km/s) were needed [45]. The space version of the Atlas required improved propellant management, achieved through updates such as better insulation and pressurization systems to prevent boil-off, as well as enhanced flow control to enable longer and more precise burns during staging. The stage-and-a-half system, already present in the military configuration with two booster engines and one sustainer, was refined for space launch by improving the timing and structural reliability of booster jettison and upgrading turbopump operation and shutdown logic for greater orbital precision [45]. Later space variants of Atlas incorporated cryogenic upper stages (such as Agena [46] and Centaur [45]), which made possible geosynchronous satellite insertions and deep-space missions, including Pioneer [47] and Mariner [48]. This addition required major upgrades to control systems, which now had to support multi-stage ignition and guidance. Significant modifications also enhanced engine reliability and redundancy: while ICBM applications tolerated some risk in a military context, space missions—especially crewed flights like Mercury [49]—demanded much higher reliability. These changes included redundant igniters and sensors, improved engine gimballing (whereas the military version relied on guidance for ballistic targeting, the space launcher required precise orbital insertion and staging), as well as improved thermal shielding and structural support. The Atlas-Agena A enabled key early payloads, including the MIDAS and SAMOS reconnaissance satellites in the 1960s [50]. Later, the Atlas-E/F variants orbited the first NAVSTAR GPS satellites between 1978 and 1980, demonstrating the long-term utility of missile-derived launch vehicles [34].

Meanwhile, the Titan II, originally an ICBM, became the main launch vehicle for NASA's Project Gemini. While the Titan III series is often considered purpose-built for space, its design was rooted in the Titan II ICBM core, continuing the trend of missile-to-launch vehicle adaptation. The Titan IIIC variant introduced solid rocket boosters, a design philosophy later adopted by the Titan IV and the Space Shuttle [51]. The Gemini Agena Target Vehicle (GATV), developed for Project Gemini, was based on a modified Agena D upper stage, equipped with enhancements such as secondary propulsion, radar, and communication systems to support rendezvous and docking operations. Separately, in 1963, the Delta B launch vehicle successfully launched Syncom 2, the first satellite to achieve geosynchronous orbit [52]. This vehicle featured an upgraded AJ10-118D upper-stage engine and improved guidance systems, demonstrating early advances in upper-stage restart capability and orbital precision [53].

Finally, the Centaur upper stage, initially developed as an Air Force initiative, was transferred to NASA in 1959 [54]. Despite early technical setbacks, the Centaur eventually succeeded in delivering Surveyor 1 to the Moon in 1966 [55]. With its dual RL10 cryogenic engines, Centaur became a key component of numerous space missions, proving its capability in both civilian and military space applications [43].

2.3. Asia

Like their American and Soviet counterparts, China accelerated its space program by converting ballistic missiles into space launch vehicles—a pragmatic and cost-effective strategy that leveraged the high degree of interchangeability between the two, including nearly identical manufacturing techniques and propulsion systems [56]. One of the earliest examples of this conversion was the adaptation of the DF-3 missile into the Chang Zheng 1 (CZ-1), China's first SLV. The DF-3 was modified to serve as the first and second stages of the CZ-1, with a third stage added in the form of a solid-fuel rocket [57]. This configuration successfully launched China's first satellite in 1970 [57].

Following this milestone, China began development of the CZ-2 series based on the DF-5 intercontinental ballistic missile [58]. The first CZ-2 flight took place on November 5, 1974, though it was destroyed shortly after liftoff due to a wiring failure between the gyroscope and flight control system [59]. The CZ-2C variant, operational between 1982 and 1988, became one of China's most reliable and frequently used launchers, capable of placing payloads of up to 2500 kg into low Earth orbit [60]. Further refinements led to the CZ-2F, which was used for launching Shenzhou crewed spacecraft, while the CZ-2C and CZ-4B were employed for placing satellites into low Earth and sun-synchronous orbits [61]. The CZ-3B/3BE versions now serve to launch heavier payloads into geostationary orbit, while the most powerful CZ rockets can lift over 8000 kg into low Earth orbit and 5000 kg into geostationary orbit. By 2020, the Long March family had completed a total of 323 launches [62].

China has made significant strides in both cryogenic propulsion and reusability for its space program. Cryogenic propellants, primarily LOX and liquid hydrogen (LH₂), are utilized in the upper stages of many of China's most advanced rockets, such as the Long March 5 and Long March 7 [63], to achieve higher efficiency and payload capacity. The LM-5 rocket is the first iteration of the brand-new design and is China's first-ever purely space launch vehicle design [64].

At the same time, China is developing reusable rocket technologies, aiming to reduce the cost of access to space. While the Long March 8 is being designed with a partially reusable first stage [65], China's efforts also include reusable spacecraft like the Tianlong spaceplane [66], which could function similarly to SpaceX's Falcon 9 [67] by landing after launch for refurbishment. These developments are part of China's long-term strategy to enhance its space capabilities by integrating cutting-edge propulsion technologies with cost-effective reusability, positioning itself as a major player in the global space race.

Likewise, India has strategically leveraged missile-derived technology to strengthen its space-launch capabilities, particularly through the Polar Satellite Launch Vehicle (PSLV). The first-stage solid motor and flex-nozzle thrust vector control from the Agni-II ballistic missile were directly adapted to enhance PSLV's guidance precision and performance [33]. Additionally, the PSLV's second stage employs the Vikas engine, which is a licensed and modified variant of France's Viking engine—originally developed for missile use—demonstrating another clear crossover from military to civilian space systems [68]. The PSLV's core S139 stage and its strap-on boosters also trace their lineage to DRDO-developed missile motors, underscoring the dual-use heritage of its propulsion architecture. India's Agni-V missile, developed by DRDO, includes a Ring Laser Gyroscope-based Inertial Navigation System, enabling highly accurate guidance and control. Meanwhile, ISRO's PSLV-C20/SARAL mission successfully placed seven satellites into their precise orbits, demonstrating the reliability and precision of India's space-launch capability [69]. Collectively, these examples reflect India's deliberate strategy of cross-pollinating missile technology into its launch vehicle program—creating a synergistic feedback loop that accelerates technological development and reinforces sovereign propulsion capabilities.

North Korea has repurposed its ballistic missile technologies, primarily the Taepodong family, to develop SLVs like the Unha series [70]. The Unha-1, derived from the Taepodong-1, failed in its 1998 launch attempt but marked the country's first step toward space exploration. Later, the Unha-2 and Unha-3 rockets, derived from the more advanced Taepodong-2, were used for subsequent satellite launches, with the Unha-3 successfully placing the Kwangmyŏngsŏng-3 satellite into orbit in 2012. These rockets utilized a combination of liquid propellants, with the first stage powered by UDMH and N_2O_4 , and later stages using RP-1 and LOX. Additionally, North Korea's newer Hwasong missile family, particularly the Hwasong-14, has the potential to be adapted for future space missions, and is likely powered by similar liquid propellants such as UDMH/ N_2O_4 for its first stages, and RP-1/LOX for its upper stages, demonstrating the ongoing evolution of their missile-to-space launcher technology [71].

2.4. Europe

Europe, unlike the United States, Russia, China, and India, has not directly converted ballistic missiles into SLVs in the same explicit manner. However, it has pursued parallel industrial strategies that echo the rationale behind missile-to-SLV conversions seen globally. European programs like Prometheus, CALLISTO, and ETID focus on developing reusable, green-propellant, and cost-efficient engines by repurposing existing manufacturing infrastructure and expertise, embodying the same principles of industrial synergy and technological reusability that underpin missile-derived launchers elsewhere [72].

European hypergolic upper-stage engines such as the Aestus (used on Ariane 5) and Viking (used on Ariane 1 through 4) share a technological heritage with missile propulsion systems. These engines are designed to allow upgrades and refits with greener propellants, leveraging missile engine design experience, representing an indirect but significant crossover between missile and space launcher technology [73]. The Prometheus engine program, led by ESA and ArianeGroup, is a prominent example of Europe's strategic approach. Though not a missile conversion per se, Prometheus repurposes industrial capabilities to develop a low-cost, reusable liquid oxygen–methane (LOX-CH_4) engine, first tested in 2023. It aims to reduce production costs to about one-tenth that of the current Vulcain engine and is built using advanced manufacturing techniques like 3D printing, targeting multiple reuses over several flights [74].

Similarly, the CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations) project, a vertical take-off/vertical landing (VTVL) demonstrator co-developed by CNES, DLR, and JAXA, plans its first flight around 2026 [75]. CALLISTO's LOX-LH_2 engine and reusability development align with principles established in missile interceptor technology, reinforcing Europe's focus on leveraging dual-use vertical propulsion systems [76]. Additional European initiatives under the RocketRoll and Enlighten [77] projects study nuclear-electric propulsion, additive manufacturing, AI-enabled diagnostics, and integration of green propellants, all while emphasizing cost-effectiveness and the reuse of industrial capacity [78].

A notable example of international propulsion collaboration is the Avio–Isayev (KBKhA) partnership, which led to the development of the LM10-MIRA engine [79]. This collaboration exemplified a strategic division of labor. Russian institutions contributed deep technical expertise and development capabilities, while Italian partners provided targeted engineering inputs and financial support. The result was a cutting-edge upper-stage engine that met ESA specifications by building upon established Russian R&D infrastructure, a rare and effective synergy [80].

Although the MIRA program was ultimately discontinued, it was widely regarded as a technical success [81–83]. It delivered a full-scale demonstrator of advanced propulsion technologies and fostered valuable international knowledge exchange. Its termination, driven by geopolitical realignment, marked a shift toward a fully European effort now embodied in the Vega E launcher. The MIRA engine remains a compelling case study of how transnational engineering cooperation can yield state-of-the-art results, even when later curtailed by political forces. The legacy of MIRA continues in the Vega E upper stage [84], carrying forward the original vision of a more capable and environmentally sustainable European launch system, a vision co-developed through the combined efforts of Italian and Russian aerospace innovation. The program also paved the way for the AVIO MR-10 engine, which applied Additive Manufacturing (AM) technologies; the first firing tests were successfully conducted in 2020 at NASA’s Marshall Space Flight Center in Huntsville, with additional campaigns ongoing at the new Space Propulsion Test Facility (SPTF) in Perdasdefogu, Sardinia [85]. On the research side, CIRA has been actively contributing to R&D efforts in LOX/LCH₄ propulsion, in collaboration with ASI. Since 2010, CIRA has managed the HYPROB (HYdrocarbon PROpulsion Bench) program, which also encompasses hybrid rocket engine design and testing [86]. Final demonstrators, based on LOX/LCH₄ couple (30 kN-thrust-class, regeneratively cooled and realized by means of electrodeposition) [87] and LOX/paraffin (10-kN-thrust-class) [88] have been manufactured and tested. Furthermore, a research test facility (H-IMP) has been realized and will be fully available in 2026. The program is funded by the Italian Ministry of University and Research (MUR), which is also supporting successor projects: TEME, focused on methane-based technologies, and HREP, focused on hybrid rocket engines.

Table 1 provides a comparative overview of the technical characteristics of missile-derived launchers across different countries, emphasizing their potential for reusability and transition to green propulsion technologies.

Table 1. Global comparison of missile-derived and related launch vehicle programs.

Program	Technical Characteristics	Shortcomings in Reusable Technology	Green Propulsion Solutions	Cost Engine Development	Historical Significance
Russia and the Former Soviet Union					
Soyuz (R-7)	LOX + RP-1, highly reliable, stage-and-a-half derived from R-7 ICBM.	Fully expendable; no recovery systems.	LOX/RP-1 cleaner than hypergols, but kerosene produces soot.	RD-107/108 engines mass-produced, keeping costs low.	Longest-serving orbital launcher; launched Sputnik 1 and all ISS crew missions until Crew Dragon.
Dnepr (R-36M/SS-18)	Converted ICBM; 4.5 t to LEO; first stage UDMH/N ₂ O ₄ , upper stage RP-1/LOX.	No reusability; toxic hypergols.	Requires full replacement with LOX/methane or LOX/LH ₂ .	Conversion reduced costs but no new tech.	Symbol of missile-to-commercial repurposing; multi-satellite launches.
Rokot (UR-100N/SS-19)	2 t to LEO; UDMH/N ₂ O ₄ first two stages; Breeze-KM upper stage with restart.	Expendable; toxic hypergols.	Would need methane-based redesign.	Low cost (~\$15 M) from stockpile conversion.	Affordable smallsat launcher during 1990s–2000s.

Table 1. Cont.

Program	Technical Characteristics	Shortcomings in Reusable Technology	Green Propulsion Solutions	Cost Engine Development	Historical Significance
Zenit (R-27 heritage)	Medium-heavy lift, LOX + RP-1, modular RD-170 engine family.	Expendable only.	Cleaner than hypergols but kerosene still polluting.	Modular, cost-efficient RD-170 engines.	Basis for Energia boosters, Sea Launch.
Proton (UR-500)	Heavy-lift to GEO, LOX + RP-1 first stage, hypergolic upper stages.	Toxic hypergols; no reuse.	Needs full LOX/methane or LOX/LH ₂ transition.	Robust but costly hypergolic engines.	Soviet heavy-lift backbone; GEO sats, ISS modules, interplanetary probes.
USA					
Minotaur (Minute-man/Peacekeeper)	Retired ICBM stages + commercial upper stages; 0.6–1.7 t LEO.	Expendable; solid propellants not reusable.	Solid propellants environmentally harmful; hybrids or LOX/methane better.	Very low cost from missile stockpiles.	Enabled low-cost smallsat launches for U.S. gov.
AJ10 Engine Family	From nitric acid/UDMH to MMH/N ₂ O ₄ . Variants powered Vanguard, Apollo SPS, Shuttle OMS. Restartable, reliable.	Hypergols toxic; reusable only on Shuttle OMS with high maintenance.	Replacement by LOX/methane or LH ₂ needed.	Long lifecycle lowered costs via reuse of design.	One of longest-serving rocket engines; powered Apollo lunar return.
Thor (Delta)	Thor IRBM adapted; LOX + RP-1, incremental upgrades.	Fully expendable.	Kerosene moderately polluting; methane future option.	Incremental upgrades kept cost low.	Foundation of Delta family; NASA's early satellites.
Atlas (SM-65)	Stage-and-a-half LOX + RP-1; later Agena/Centaur upper stages.	No reusability; needed redesign for longer burns.	LOX/RP-1 clean vs. hypergols; methane upgrade possible.	Incremental upgrades reduced costs.	First American orbital astronaut (John Glenn, 1962); GPS and planetary probes.
Titan II/III/IV	Titan II: hypergols; Titan III/IV added solid boosters.	Hypergols toxic; no reuse.	Future cryogenics or methane needed.	Reused ICBM cores kept costs lower.	Carried Gemini astronauts, defense payloads, planetary probes.
Centaur	First cryogenic upper stage; LOX + LH ₂ RL10 engines.	Expendable; complex cryogenics.	Already green (water exhaust).	High cost due to precision RL10 engines.	Pioneered cryogenics; enabled Surveyor, planetary missions.
Asia					
CZ-1 (DF-3 based)	First SLV (1970). Two DF-3 stages + solid third stage.	Fully expendable.	Early use of polluting propellants.	Conversion kept costs down.	Launched China's first satellite.

Table 1. Cont.

Program	Technical Characteristics	Shortcomings in Reusable Technology	Green Propulsion Solutions	Cost Engine Development	Historical Significance
CZ-2/3/4 (DF-5 based)	2.5 t LEO; crewed and satellite launches; later CZ-3B to GEO.	No reusability; early failures.	Still uses UDMH/N ₂ O ₄ in many stages.	Incremental upgrades = low R&D cost.	Established China's orbital presence; Shenzhou, satellites.
Long March 5/7/8	New LOX/LH ₂ and LOX/methane designs; LM-8 reusable 1st stage in dev.	Reusability in progress.	Green cryogenics (LOX/LH ₂ , LOX/CH ₄).	YF-100, YF-77 advanced engines, costly to develop.	China's heavy-lift, reusable future.
PSLV (Agni-II tech + Viking engine heritage)	Derived from Agni-II solid motors + Vikas (Viking). Precise, reliable 4-stage.	Expendable.	Uses solids + hypergols; methane alternatives under study.	Low cost (~\$15–20 M) from missile/foreign engine synergy.	Workhorse of ISRO; Chandrayaan, Mangalyaan.
Unha (Taepodong)	Taepodong-derived; UDMH/N ₂ O ₄ first stage, RP-1/LOX upper.	No reusability.	Hypergols toxic; only partial shift to kerosene/LOX.	Adapted from missile stockpiles.	Symbolic orbital access; strategic display.
Europe					
Aestus (Ariane 5 upper stage)	Ariane 5 hypergolic upper stage (MMH/N ₂ O ₄).	Expendable; toxic hypergols.	Future replacement with methane/LOX.	Simple design reduced cost.	Supported reliable Ariane 5 orbits.
Viking (Ariane 1–4 main stage)	Ariane 1–4 hypergolic stages.	Toxic, expendable.	Basis for future methane engines.	Scaled production reduced costs.	Established Europe's launcher autonomy.
Prometheus (ESA/ArianeGroup)	LOX–methane reusable engine (1000 kN). 3D-printed.	Still in development.	Clean methane–oxygen.	Designed to be 10× cheaper than Vulcain.	Europe's move toward reusability and sustainability.
CALLISTO (CNES–DLR–JAXA)	VTVL demo with LOX–LH ₂ . Reusable first-stage recovery.	First flight planned 2026.	Cryogenic = green.	Aims at reusability to lower costs.	European Falcon 9–style demo.
MIRA (Avio–Isayev)	LOX–CH ₄ upper-stage demo; additive manufacturing.	Cancelled, no ops reuse.	Methane = green.	Additive manufacturing lowered cost.	Tech success; legacy in Vega E, MR-10.
HYPROB (CIRA, Italy)	Italian LOX–CH ₄ and hybrid propulsion program; demo engines 10–30 kN.	Still experimental	Green propulsion explicit focus	Uses AM for cost efficiency	Builds Europe's hydrocarbon propulsion expertise.

Figure 1 shows a timeline for the same regions, illustrating how missile technologies were either adapted into space launch vehicles (SLVs) or developed in parallel programs, with entries color-coded by region.

Both space and ballistic missile programs are integral to a state's ability to showcase its technological capabilities, which, in turn, bolsters its global prestige. This is particularly true for nations developing liquid-fueled ballistic missiles, as SLVs also rely on similar propulsion technologies. SLVs and ICBMs share common roots in their use of liquid propellants, including cryogenic substances like liquid hydrogen, liquid oxygen, and liquid methane for their upper stages. Both systems, whether carrying satellites or warheads, serve as carriers, one for peaceful purposes and the other for strategic military goals, demonstrating a state's technological sophistication and its ability to assert power in both space and terrestrial domains.

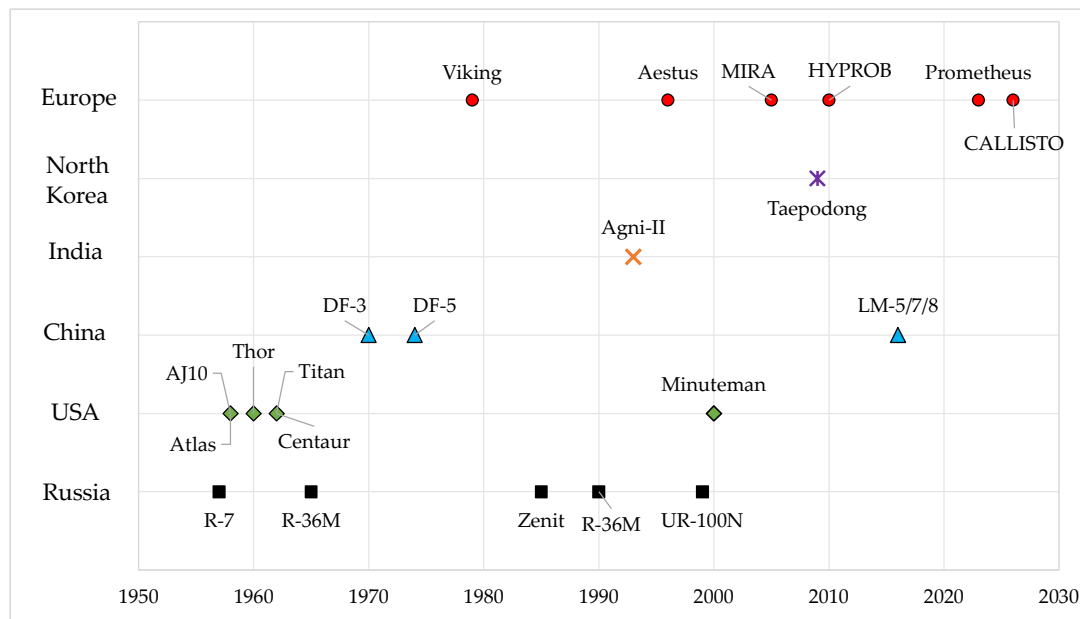


Figure 1. Global timeline of missile-to-launch vehicle programs.

3. Technical Feasibility of the Conversion of the Isayev S2.720

3.1. Proposed Approach for the Conversion Methodology

Converting a missile engine into a space-capable propulsion unit would likely follow a structured sequence of engineering adaptations, reflecting the historical pathway of ICBMs repurposed as orbital launch vehicles. As seen in the case of the Atlas, Titan, and Dnepr systems, the process would begin with a reassessment of the propulsion system to accommodate longer-duration burns, orbital insertion profiles, and vacuum operation, conditions far exceeding the short suborbital flight requirements of missile missions. Hypothetically, structural reinforcements might be introduced to withstand altered aerodynamic and vibrational loads during ascent, while propellant feed systems could be redesigned for stability and thermal control in microgravity. Subsystems such as ignition, guidance, and telemetry would require upgrades or replacement to ensure compatibility with space mission architectures. Building on Cold War precedents, such a methodology would aim to retain core propulsion hardware while meeting the reliability, precision, and safety standards demanded by orbital deployment scenarios.

In the context of adapting missile engines for space applications, the conversion methodology could be structured around three key pillars.

First, the propulsion system would be reengineered to operate on cryogenic or alternative green propellants, enabling cleaner combustion and alignment with emerging environmental standards in space transportation. Second, critical components, such as combustion chambers, nozzles, or injector heads, would be remanufactured using advanced

production methods, including additive manufacturing and hybrid subtractive-additive processes, to enhance precision, reduce material waste, and accelerate fabrication. Third, the converted engine would undergo a dedicated testing campaign to validate performance across a range of mission-representative conditions. Throughout this process, environmental and economic impacts would be continuously assessed using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. This integrated approach aims not only to maximize sustainability and cost-efficiency but also to significantly reduce traditional engine development timelines, bridging the gap between legacy hardware and next-generation space propulsion demands.

The Isayev S2.720 engine is a strong candidate for reconversion into a space-grade propulsion system thanks to its robust architecture and the design lineage of similar Isayev engines that have been used for space missions. The Isayev (KBKhA) Bureau, behind the S2.720, also collaborated with Avio on the MIRA engine demonstrator, which contributed to the development of the Vega-E upper stage, underscoring the continuity between legacy missile propulsion and modern European launcher programs. Building on this heritage, the present article aims to describe the perspective according to which such legacy hardware can be remanufactured and qualified for sustainable space applications.

3.2. The Hypothetical Test Case: Isayev S2.720

The Isayev S2.720 is a Soviet-era liquid rocket engine developed for the S-75 (SA-2 “Dvina”) [89] surface-to-air missile system. It is a single-chamber, pressure-fed engine that operates on hypergolic storable propellants, specifically AK-27I, a nitric acid-based oxidizer stabilized with nitrogen tetroxide and an iodine additive, and TG-02, a fuel blend composed of xylidine and triethylamine. TG-02 belongs to the same class of fuels as the German-developed “Tonka” series and was selected for its spontaneous ignition with AK-27I and storability. The engine delivers a maximum thrust of approximately 34.3 kN (3500 kgf). Designed for operational reliability and rapid deployment, the S2.720 featured an integrated thrust control system and a compact architecture, enabling long-term readiness for Cold War air defense missions.

Despite its substantial thrust, the Isayev S2.720 remains remarkably lightweight—with an unfueled mass of just 48 kg. This yields an exceptional thrust-to-mass ratio of approximately 714 N/kg, a highly efficient figure for its era. In its original role aboard the S-75 Dvina (SA-2 Guideline) surface-to-air missile, the high thrust-to-weight ratio provided rapid acceleration and minimized structural mass—critical for effective air defense intercepts. If considered for space applications, such efficiency becomes even more valuable: lower engine mass allows for greater payload capacity, higher delta-v performance, and reduced launch infrastructure demands. Combined with its use of storable hypergolic propellants and compact design, the S2.720 presents a compelling case for adaptation via remanufacturing into modern orbital propulsion systems.

The components of the Isayev are presented in Figure 2, while the working diagram is presented in Figure 3. Both images are structured according to the SA-2 Dvina user manual [90].

A short summary of the engine workings is presented next.

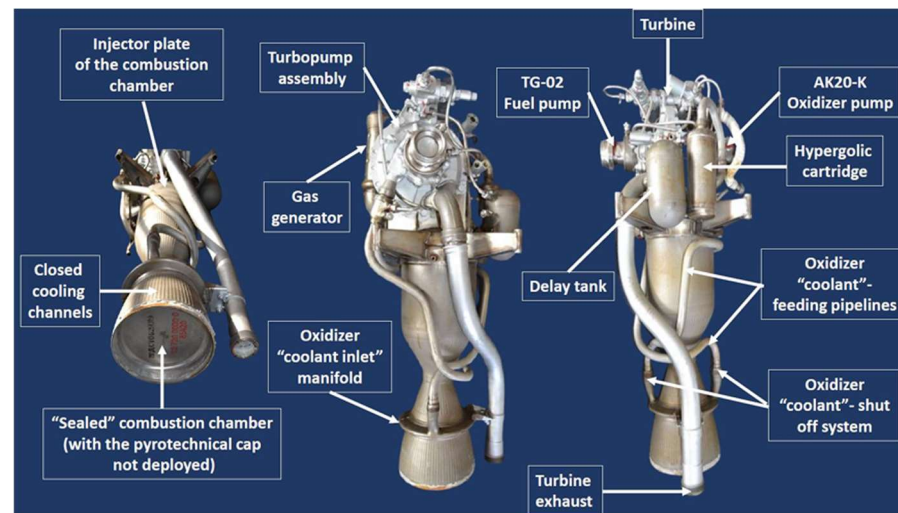


Figure 2. Current configuration of the Isayev S2.720 LRE.

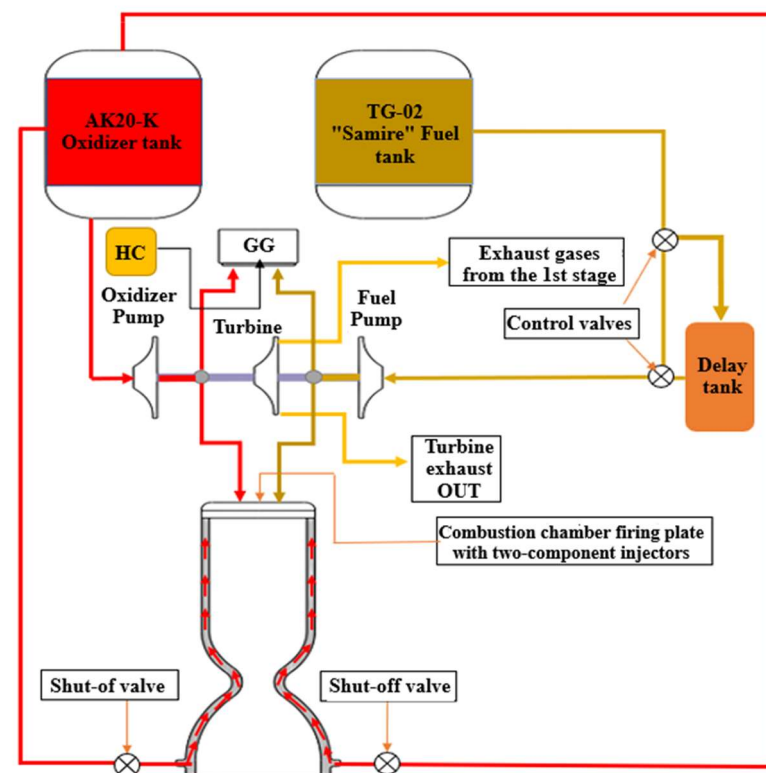


Figure 3. Operating diagram of the Isayev S2.720 LRE (hypergolic propellants).

The engine is a single-chamber, liquid bipropellant propulsion system equipped with a turbopump-fed supply and automatic thrust control. It is capable of operating in two thrust regimes, selected based on the missile's launch inclination. For shallow launch angles ($<24^\circ$), the engine maintains a constant thrust of 3500 kp. For steeper trajectories ($>24^\circ$), it initially operates at 3500 kp for 24 s before transitioning smoothly to 2000 kp. Propellant delivery is achieved via a turbopump unit comprising a gas generator, turbine, oxidizer pump, and fuel pump, all mounted on a common shaft. Hot gas produced by the gas generator drives the turbine, enabling high-pressure injection of both oxidizer and fuel into the combustion chamber. The combustion chamber is regeneratively cooled using oxidizer circulated through interjacket channels, while a film cooling layer is created by injecting fuel along the inner walls. A bipropellant injector head ensures proper mixing and

atomization of propellants. Thrust modulation is managed by a hydraulic regulator that controls oxidizer flow to the gas generator. A pre-receiver and associated valves ensure a smooth transition between thrust levels. Engine start-up is initiated by pyrovalves that trigger membrane rupture, allowing pressurization and propellant flow. A starting tank introduces a brief delay in fuel injection relative to oxidizer, promoting stable ignition. The pressurization system uses high-pressure compressed air stored in a spherical tank, reduced through a multi-stage system, and routed to the oxidizer and fuel tanks. It also powers auxiliary systems, including steering actuators and trajectory correction devices. Additional components, such as check valves and gas connectors, ensure operational integrity during stage separation and engine shutdown [91].

3.3. Missile Operation Considerations

According to the manual [89], the working diagram of the second stage of the SA-2 Dvina missile is presented in Figure 4.

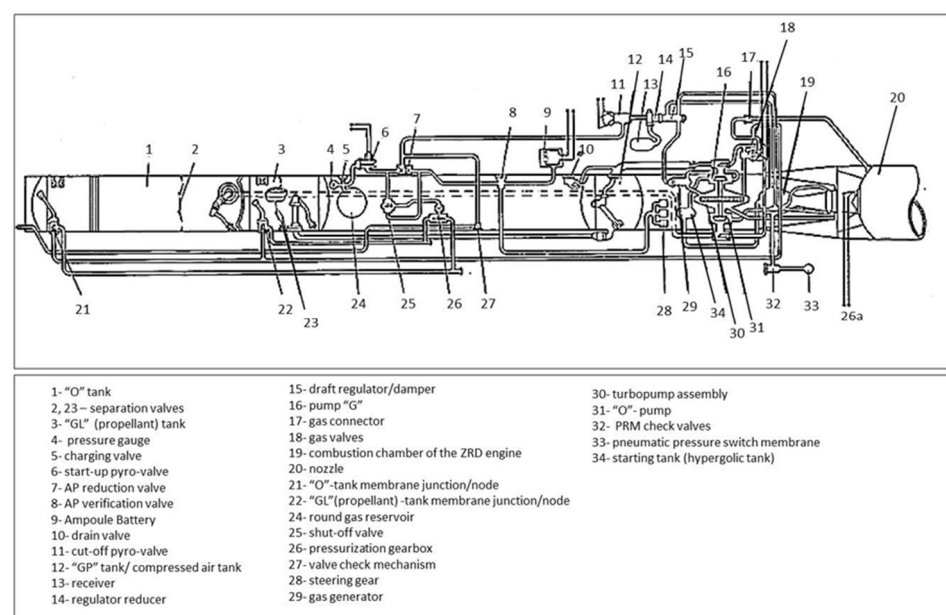


Figure 4. SA-2 Dvina second stage components, including the Isayev S2.20 engine (referred to as the ZRD engine in the manual [90]).

The missile had three operational modes, described below.

(a) The start-up sequence

At ignition, an electrical command triggers the activation of pyrocharges in the main start-up pyrovalve (6), releasing compressed air from the high-pressure cylinder into the air distribution system. This air is routed via the auto shut-off valve (25) into the repressurization manifold (26), where it is directed to the membrane assemblies of the oxidizer (tank O) and fuel (tank G) through dedicated check valves. These membranes maintain propellant pressurization in preparation for engine ignition. Simultaneously, air is supplied to the AP reducer (7), which distributes pressure to the steering actuators (component 28) and the ampoule battery system (9), setting them into operational readiness.

Air at 50 kg/cm² is delivered through a cut-off valve (11) to the thrust regulator (15), engaging the engine's first operational mode. Additional air flows to the sliding mechanism of the payload casing, initiating structural retraction procedures and configuring the missile for aerodynamic flight. Air at 10 kg/cm² is also routed through the APT check valves (8) to auxiliary systems, including stabilization and onboard electronics.

Following this, the propellant reserve devices (PRDs) are ignited. The resulting hot gases travel through the interstage gas connector (17) to the gas pyrovalve (18), which remains closed until sufficient pressure is reached. Upon activation, the gas pyrovalve triggers the rupture of membranes in the start valves of the oxidizer and fuel systems (O and G), enabling flow into the turbopump assembly (THA). The gas generator receives propellant flow and initiates turbine spin-up, thereby powering the oxidizer and fuel pumps. These pumps feed propellant to both the gas generator and combustion chamber. Exhaust gases from the turbine are expelled through a vent, marking the beginning of sustained engine operation.

(b) First operating mode ($T = 34.32 \text{ kN}$)

In the first mode, the engine delivers a constant thrust of $\sim 34 \text{ kN}$. This mode is automatically selected if the missile is launched at an inclination of less than 24° relative to the horizon. The thrust regulator (15), supported by the onboard pressure system, maintains chamber pressure and propellant flow rate to sustain this fixed thrust level. This configuration supports the initial acceleration phase and is maintained for up to 24 s after ignition.

(c) Second operating mode ($T = 19.61 \text{ kN}$)

If the launch angle exceeds 24° , or once 24 s have elapsed, the missile's onboard flight control system (PMK-60A) sends an electrical signal to detonate the pyrocharges in the cut-off valve (11). This action terminates the air supply to the thrust regulator, initiating a controlled transition from 34.32 kN to 19.61 kN. The regulator adjusts the oxidizer feed into the gas generator, reducing turbine power and engine output accordingly. This transition is gradual, ensuring stable engine behavior during trajectory correction or extended burn phases.

If the launch angle is less than 21° , the transition to the second operating mode is omitted entirely.

As the air cylinder pressure drops below 70 kg/cm^2 , the auto shut-off valve (25) engages, isolating the oxidizer and fuel tanks from further pressurization. From this point onward, the remaining air supply is reserved for terminal guidance and steering functions during the final phase of the missile's flight.

Unlike surface-to-air missile engines, which are designed for short-duration, high-thrust burns to rapidly accelerate an interceptor over a few tens of seconds, launch vehicle engines must sustain controlled thrust for several minutes under vacuum or near-vacuum conditions. This requires longer burn times, higher thermal management capacity, and precise throttling and restart capability. Missile engines typically prioritize compactness, storability, and rapid readiness, often relying on hypergolic propellants, while launch vehicle engines are optimized for efficiency, reliability, and structural robustness under prolonged operation. These distinctions underline the core challenge of conversion: adapting hardware originally built for brief, high-intensity operation into systems capable of sustained orbital insertion. The key transformation points discussed in Section 5—propellant substitution, remanufacturing of subsystems, and performance validation—are thus critical for bridging this functional gap.

4. Pillar I—Adoption of Cryogenic Propellants for Sustainable Conversion

4.1. Propellant Choice

Rocket engines are indispensable to space exploration but often depend on non-green propellants that pose significant environmental risks. Solid propellants containing ammonium perchlorate are widely used in systems such as the French M51 SLBM [89,92] and NASA's Space Shuttle SRBs, yet their combustion produces harmful byproducts, including hydrogen chloride (HCl) and aluminum oxide (Al_2O_3) particulates [93]. Hydrazine and its derivatives,

such as MMH and UDMH [94], remain common in satellite thrusters and interplanetary missions because of their storability and hypergolic ignition, typically paired with the toxic oxidizer nitrogen tetroxide (N_2O_4), as seen in the Titan II and Proton-K upper stages [95]. RP-1 kerosene, still standard in orbital-class rockets like SpaceX's Falcon 9 and Russia's Soyuz, generates carbon dioxide and black carbon emissions, with studies estimating current soot output at around 1 gigagram annually and projecting increases up to 10 gigagrams in the coming decades [96], exacerbating stratospheric warming and ozone disruption [97].

Hypergolic propellants, which ignite spontaneously upon contact between fuel and oxidizer, have played a critical role in both historical and contemporary spacecraft propulsion systems. Common hypergolic combinations include monomethyl hydrazine (MMH) with nitrogen tetroxide (NTO) and unsymmetrical dimethylhydrazine (UDMH) with NTO [98]. While MMH/NTO is typically preferred by the United States, UDMH/NTO remains widely used in Russian systems.

Numerous spacecraft have used hypergolic propellants for their reliability, storability, and restart capability. The Cassini mission to Saturn and the Dawn spacecraft [99], which studied Vesta and Ceres, employed hydrazine monopropellant for complex orbital maneuvers. The International Space Station (ISS) uses a bipropellant system of UDMH and NTO through two main and 16 auxiliary thrusters for attitude control beyond its Control Moment Gyroscopes [100]. The Apollo Lunar Module utilized Aerozine-50 with NTO in its reaction control and descent systems [101], while ESA's Orion European Service Module is also equipped with hypergolic engines [102].

Despite their effectiveness, hypergolic propellants pose serious health, safety, and environmental hazards. They are highly toxic, corrosive, and volatile, requiring strict handling protocols [103,104]. Their corrosive nature can degrade engine components, increasing the risk of malfunction or catastrophic failure, and accidental leaks or explosions at launch sites may release dangerous fumes, causing severe environmental contamination and costly cleanup. Consequently, hypergolic propellants are generally avoided in first-stage launch systems, with exceptions like Russia's Proton rocket, which continues to use UDMH/NTO in its core stages.

Nevertheless, hypergolic fuels remain valuable for in-orbit and deep-space applications due to long-term storability, multiple restart capability, and high specific impulse. Advanced space programs, including those in the United States, Japan, and South Korea, have conducted extensive research—such as drop tests [105,106] and impinging jet experiments [107]—to understand ignition characteristics and optimize injector design. South Korea's plans for a lunar lander by 2032 underscore the continued relevance of hypergolic propulsion in emerging programs.

While hypergolic propellants have enabled key milestones—satellite deployment, planetary landings, and manned missions—they raise growing environmental and safety concerns. Increasing global launch activity, especially in commercial and deep-space sectors, drives interest in green propulsion technologies, which are safer, cleaner, and more sustainable. Europe's REACH framework has classified hydrazine as a “substance of very high concern,” potentially leading to future bans without alternative solutions. Research into HAN- and ADN-based propellants shows promise for small satellite platforms, particularly CubeSats, where volumetric efficiency and compact system size are critical [108,109].

Nitrous oxide-based monopropellants are under review due to self-pressurization, which simplifies tank and feed systems for compact spacecraft designs [110]. Hydrogen-peroxide aqueous solutions (HPAS), particularly high-test peroxide (HTP), are recognized as green propellants for niche aerospace applications. H_2O_2 monopropellant systems provide moderate performance (~ 186 s Isp), excellent storage stability, and non-toxicity, making them suitable for low-to-medium thrust missions and secondary propulsion [111]. As an

oxidizer in bipropellant configurations, HPAS achieves higher performance (~ 325 s Isp) when combined with fuels like ethanol [112]. NASA, ESA, and aerospace startups are investigating H_2O_2 -based systems for small satellite attitude control, multi-mode spacecraft integration, and hybrid or green hypergolic propulsion, highlighting their continued relevance and environmental benefits [113–115].

Cryogenic propellants, particularly liquid hydrogen (LH_2) and liquid oxygen (LOX), are among the cleanest rocket fuels, producing only water vapor and offering high specific impulse for launch vehicles and deep-space missions [116]. However, they require specialized storage below 120 K to prevent boil-off and pressure buildup, adding complexity, mass, and cost [117]. In contrast, hypergolic propellants (e.g., MMH/NTO, UDMH/NTO) are storable at ambient temperatures, ignite on contact, and support compact spacecraft designs, making them ideal for reaction control systems and planetary probes. Their high toxicity and corrosiveness, however, pose serious environmental and safety risks. Consequently, green propellants have emerged as alternatives, combining storability, safety, and adequate performance while mitigating the drawbacks of both cryogenic and hypergolic systems. As a result, green propellants have emerged as a promising alternative, offering a balance of storability, safety, and performance while addressing the drawbacks of both cryogenic and hypergolic systems. A clear demonstration of these advantages can be seen in the Saturn V rocket [118] and NASA's SLS [119], both of which utilize cryogenic propellants to enable high-performance missions to the Moon and Mars. In Europe, the Vulcan 2 engine [120], used on the Ariane 5 and the upcoming Ariane 6, serves as the main propulsion system for lifting heavy payloads into geostationary transfer orbit (GTO) and supporting scientific missions. Japan's LE-7A engine [121], powering the H-IIA and H3 rockets, enables Earth observation, scientific exploration, and international satellite deployment. Additionally, the possibility of in-situ resource utilization (ISRU)—producing cryogenic fuels on the Moon or Mars [122]—further enhances the appeal of cryogenic propulsion for sustainable space exploration.

As regulations tighten and launch rates rise, green propellants are poised to become the default choice for a wide array of space missions—from CubeSat constellations to robotic deep-space explorers. Other promising propellants are Energetic Ionic Liquids (EILs) [123]—notably AF-M315E, a hydroxylammonium nitrate (HAN) blend—and LMP-103S, an ammonium dinitramide (ADN) solution. Their advantages include higher volumetric impulse (e.g., $\sim 50\%$ higher than hydrazine) and room-temperature stability, replacing hazardous SCAPE-suited fueling operations with standard lab attire [124]. The NASA GPIM mission, launched in 2019, is a landmark demonstration showing that these green fuels can reliably perform orbital maneuvers while significantly lowering personnel risk and ground processing time [125–127].

Parallel to the development of green propulsion technologies, there is also renewed focus on repurposing legacy hardware for modern applications. In particular, efforts have increased to reconvert missile engines and other terrestrial propulsion systems for use in cryogenic space missions. Many Cold War-era missile programs developed high-thrust engines with robust structural designs, offering a valuable foundation for adaptation. Through the modification of fuel systems, injector heads, and cooling mechanisms, these engines can be repurposed to operate with cryogenic propellants, such as LH_2 and LOX, which offer significantly higher specific impulse compared to the storable hypergolic propellants originally used. This approach allows agencies and private companies to leverage existing manufacturing infrastructure and proven designs, reducing development costs and timelines. For example, the RD-0120 [128,129], originally designed for the Soviet Energia launch vehicle, has been studied as a model for reconversion due to its LOX/ LH_2 cycle and high performance.

Similarly, programs like India's CE-20 [130] and China's YF-75D [131] have built on heritage engine technologies to produce modern cryogenic upper-stage engines.

Reconversion not only supports cost-effective development but also facilitates the transition toward cleaner and more efficient propulsion systems aligned with current sustainability goals. A key aspect of this transition is the replacement of traditional propellants with greener alternatives, not only to mitigate environmental and safety hazards but also to enhance engine performance. By adopting propellants with higher specific impulse and lower toxicity, propulsion systems can achieve better efficiency while reducing harmful emissions. Table 2 presents a comparative overview of the theoretical specific impulse values for various oxidizer–fuel combinations, highlighting the performance potential of these environmentally conscious alternatives.

Table 2. Characteristic data of different propellants [132–137].

Oxidizer	Fuel	Propellant Type	Isp (Vacuum)	Isp (Sea Level)	O/F Ratio	Fuel Density (kg/m ³)	Toxicity/ Environmental Impact
LOX	LH ₂	Cryogenic	~450 s	~380 s	~6:1	~71	Clean (water vapor only)
LOX	LCH ₄	Cryogenic	~370 s	~320 s	~3.5:1	~420	Cleaner than RP-1, some CO ₂
LOX	RP-1 (Kerosene)	Semi-cryogenic	~330 s	~295 s	~2.7:1	~820	CO ₂ and soot production
N ₂ O ₄	UDMH/MMH	Hypergolic	~320 s	~285 s	~2.0:1	~793	Highly toxic, carcinogenic
MON-3	MMH	Hypergolic	~315 s	~280 s	~1.9:1	~880	Toxic, used in spacecraft propulsion
HAN (AF-M315E)	Ionic Liquid	Green mono-propellant	~255–265 s	-	-	~1350	Low toxicity, safer handling
ADN (LMP-103S)	Ionic Liquid	Green mono-propellant	~265–270 s	-	-	~1450	Low toxicity, low environmental impact
H ₂ O ₂ (90%+)	RP-1 or Alcohol	Green (if highly pure)	~250–300 s	~200–260 s	~7:1 (varies)	~800 (RP-1)	Biodegradable, low-toxicity in dilute form

A promising option for reconverting the Isayev S2.720 engine is the LOX–LCH₄ (liquid oxygen–liquid methane) propellant combination, which is preferred over LOX–LH₂ and LOX–kerosene due to its advantageous engineering, economic, and operational characteristics. Among these are a higher density impulse, simplified handling and storage, enhanced reusability, reduced environmental impact, and the potential for in-space production. LOX–LCH₄ provides a compelling balance between density and specific impulse, resulting in more compact tanks and improved mass ratios. Although LOX–LH₂ achieves the highest specific impulse (~450 s in vacuum), its very low density demands much larger tanks, thereby increasing vehicle complexity and dry mass. In contrast, LOX–LCH₄ achieves a better balance of efficiency and practicality, as shown in Figure 5 and Table 1.

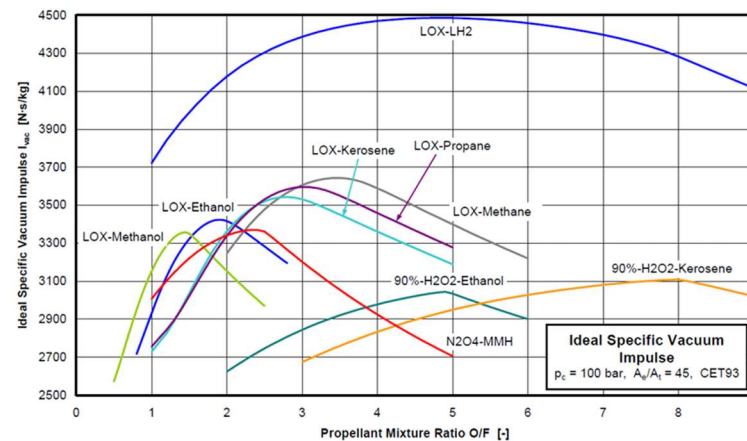


Figure 5. Ideal specific impulse of various propellant combinations [138].

This transition is particularly relevant given the limitations of the original Isayev S2.720 engine, which operated on hypergolic propellants: AK20-K as the oxidizer and TG-02 as the fuel. Due to the severe health, safety, and environmental risks associated with these substances, as well as their performance limitations, the reconversion project includes replacing them with a cleaner and more efficient alternative. The goal is to employ a “green” propellant, such as LOX–LCH₄, to improve engine performance while significantly reducing environmental and handling hazards. Theoretical comparisons in Table 1 demonstrate the superior specific impulse and environmental benefits of these new propellant combinations, making them more suitable for future reusable or in-space applications.

The optimum propellant replacement for the LRE will establish the trade-off between engine performance, costs, and the impact on future engine development actions. The propellant choosing mechanism should follow an established decision matrix, according to the scheme illustrated in Figure 6, where each criterion is represented by a dimensionless number from 1 to 5 (lowest to highest value in the scoring mechanism). These values represent a rating of the compatibility with European standards; REACH regulations and industry best practice determined from literature reviews. The results of this study must contain the new propellant alternative and a broad idea of the changes needed to be conducted in terms of engine component structure and design to fit with the envisioned solution of the “green” LRE.

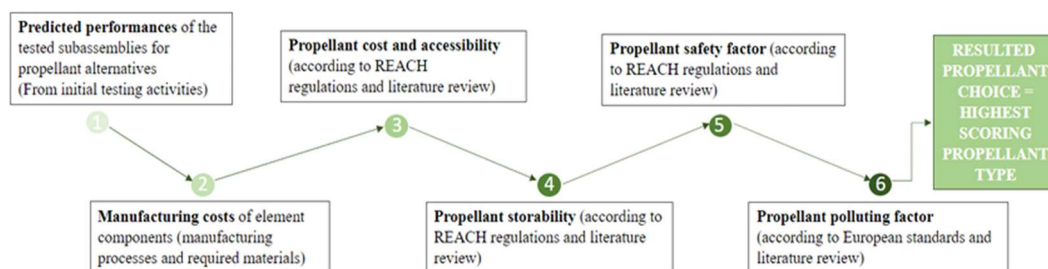


Figure 6. Selection mechanism for the propellant type.

The methodological steps outlined above are directly aligned with the subject of this paper: the ISAYEV S2.720 liquid rocket engine can be effectively reconfigured to operate with a higher-performance, environmentally sustainable propellant. The central hypothesis is that replacing the original hypergolic propellants with a green alternative—such as LOX–LCH₄—will not only improve specific impulse and operational safety, but also significantly reduce lifecycle environmental impact. Furthermore, these actions support the other conversion pillars, which are further described. The choice of propellant is therefore not merely a design decision but a strategic lever in validating both the technical and ecological

hypotheses that define the paper's innovative perspective. The new working cycle of the Isayev S2.20 functioning on cryogenics is depicted, on a hypothetical level, in Figure 7.

A central hypothesis of this paper is that the LOX–LCH₄ propellant combination offers the optimal trade-off between performance and system-level feasibility for converting legacy propulsion systems such as the ISAYEV S2.720 engine. This formulation is posited as superior to both LOX–LH₂ and LOX–kerosene, not only from a thermodynamic standpoint but also when considering engineering constraints, operational handling, environmental sustainability, and potential for in-situ resource utilization. While LOX–LH₂ is known to yield the highest specific impulse (~450 s in vacuum), it is hypothesized that the volumetric penalties associated with its low density offset much of its theoretical advantage, especially in compact or reusable launch systems. In contrast, LOX–LCH₄ is expected to deliver a more favorable balance between specific impulse and propellant density, leading to reduced tank volume requirements, simplified thermal management, and improved mass ratios. This hypothesis should be assessed through comparative performance analysis and subsystem-level redesign, with reference data illustrated in Figure 4 and Table 1.

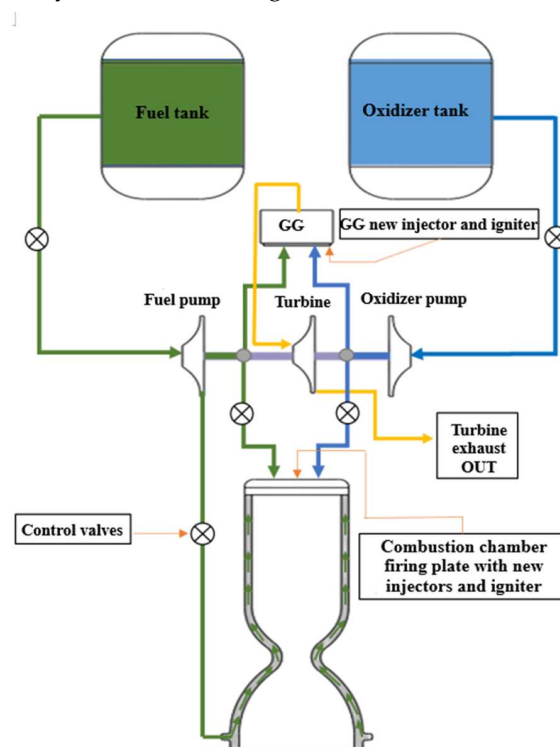


Figure 7. Concept operating cycle of the Isayev S2.720 (LOX–LCH₄ propellant).

The second criterion is the handling, storage, and cryogenic complexity. LOX–LH₂ has an extremely low boiling point (−253 °C) [139], making hydrogen difficult to store long-term without excessive boil-off, requiring highly insulated tanks, significantly increasing the mass and complexity of the propulsion system. Another issue with LOX–LH₂ is the high leakage factor, which can easily happen through seals due to its molecular size, increasing safety risks, and can also cause hydrogen embrittlement in metals, demanding specialized materials for long-term reliability.

Some advantages arise here for LOX–LCH₄, which presents a higher boiling point (−161 °C) [140], reducing insulation and minimizing boil-off losses. Proves to be easier to store and transfer than LH₂, making it ideal for long-duration space missions and reusability. It also does not cause embrittlement issues and allows for the use of conventional high-strength materials.

Another alternative would be LOX-kerosene, which is mostly used in lower stages due to its storability at ambient temperatures and established infrastructure, while being easier to handle than both methane and hydrogen, but has an inferior Isp, as presented in Figure 4. Another issue with the LOX-kerosene alternative is the carbon residue left after the combustion, which can degrade the engine performance in the case of multiple uses and presents a higher environmental impact. Coking can also happen in the cooling channels, increasing thermal stress [141].

While Figures 2 and 6 share a similar layout, they represent two different operating cycles. Figure 2 depicts the baseline Isayev S2.720 engine, operating with its original hypergolic propellants as integrated in the S-75 Dvina system. Figure 6, by contrast, illustrates a conceptual adaptation cycle showing how the same architecture might be recon-figured for cryogenic propellants such as LOX–LCH₄. The similarity in structure is intentional, as it highlights continuity while emphasizing the key changes in propellant feed, ignition, and cooling strategy required for conversion to space-grade use.

4.2. Environmental and Operational Conditions

Several environmental and operational conditions are taken into account when choosing a new propellant, as follows:

1. LOX-Kerosene produces soot and CO₂ emissions, contributing to air pollution and carbon buildup;
2. LOX-LCH₄ burns cleaner and emits only water (H₂O) and carbon dioxide (CO₂), with significantly less unburnt hydrocarbons and particles;
3. A methane-based engine is less prone to carbon fouling, meaning less downtime and lower refurbishment costs;
4. Unlike kerosene, methane is non-toxic and does not require complex cleaning procedures, making ground handling safer and easier.

There are also a few structural and vehicle design considerations worth mentioning:

1. Hydrogen requires much larger tanks due to its low density, increasing vehicle size and drag;
2. Methane's higher density allows for more compact tankage, improving mass efficiency and structural integrity;
3. Methane is more thermally stable than hydrogen, reducing boil-off risks and making it easier to integrate into long-duration missions;
4. Kerosene, though dense, requires separate pressurization systems, while methane is more compatible with autogenous pressurization (using its own vapor for pressurization), simplifying vehicle design.

Other important aspects are cost and economic viability

1. LOX-LH₂ requires extremely high insulation costs and suffers from rapid boil-off, making long-term storage expensive;
2. LOX-Kerosene engines require frequent maintenance and cleaning, increasing turnaround times and operational costs;
3. Methane is widely available, inexpensive, and can be produced synthetically, making it economically attractive for large-scale space operations.

For these reasons, LOX–LCH₄ has become the preferred choice for next-generation reusable rockets and deep-space exploration missions (such as SpaceX's Starship, Blue Origin's BE-4, and NASA's Artemis), replacing older LOX–kerosene designs while avoiding the complexity of LOX–LH₂ systems.

Historically, the development and demonstration of such propulsion systems have followed a non-linear process, exemplified by programs like JAXA's 30 kN LE-8 engine, which used LNG and liquid oxygen as propellants. The core design challenges were addressed over several years, from 2003 to 2009, with development continuing until 2013 [142]. Similarly, the VEGA-E LOX/LCH₄ engine underwent preparatory demonstrations between 2007 and 2014, culminating in preliminary firing tests in 2018 [143].

4.3. Economic Aspects and the Possibility of a Drastic Timeframe Reduction

The conversion of a missile engine into a cryogenic space propulsion system generally offers a cost-effective and time-efficient solution when compared to the ground-up development of a new propulsion system. Leveraging existing missile technology can significantly reduce development costs and timelines. The modifications required might be extensive, and can include changes to fuel tanks, fuel delivery systems, and combustion chambers, but they are envisioned to be generally faster and less expensive than building a new system from scratch. However, this approach also carries risks, as missile engines were not originally designed for the long-duration, low-thrust requirements of space propulsion, potentially limiting their efficiency and reliability. Figure 8 presents a time frame development of the JAXA's LE-8 engine, to serve as an example for the unpredictability of developing a complex new propulsion system.

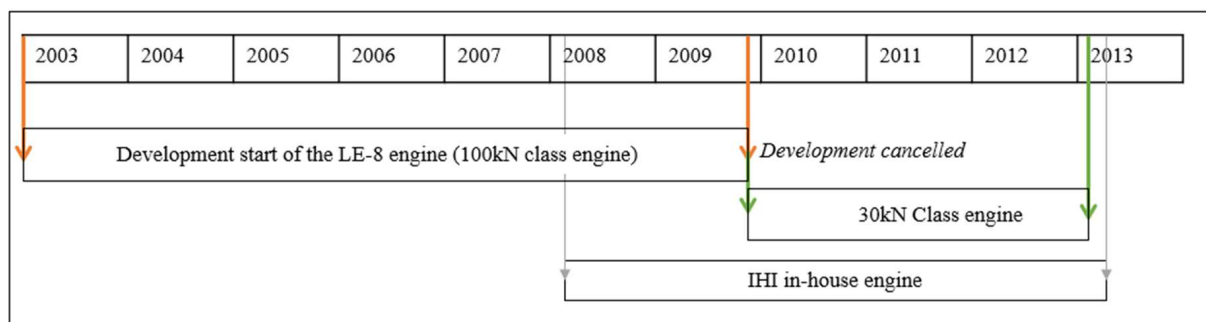


Figure 8. Timeframe development of the JAXA's LE-8 engine [142].

In Figure 9, the diagram of the most common rocket engine development process is compared to the perspective of a conversion plan. Several development steps can be reduced or eliminated because of the advanced starting point of the conversion's development plan and time-saving optimized manufacturing process.

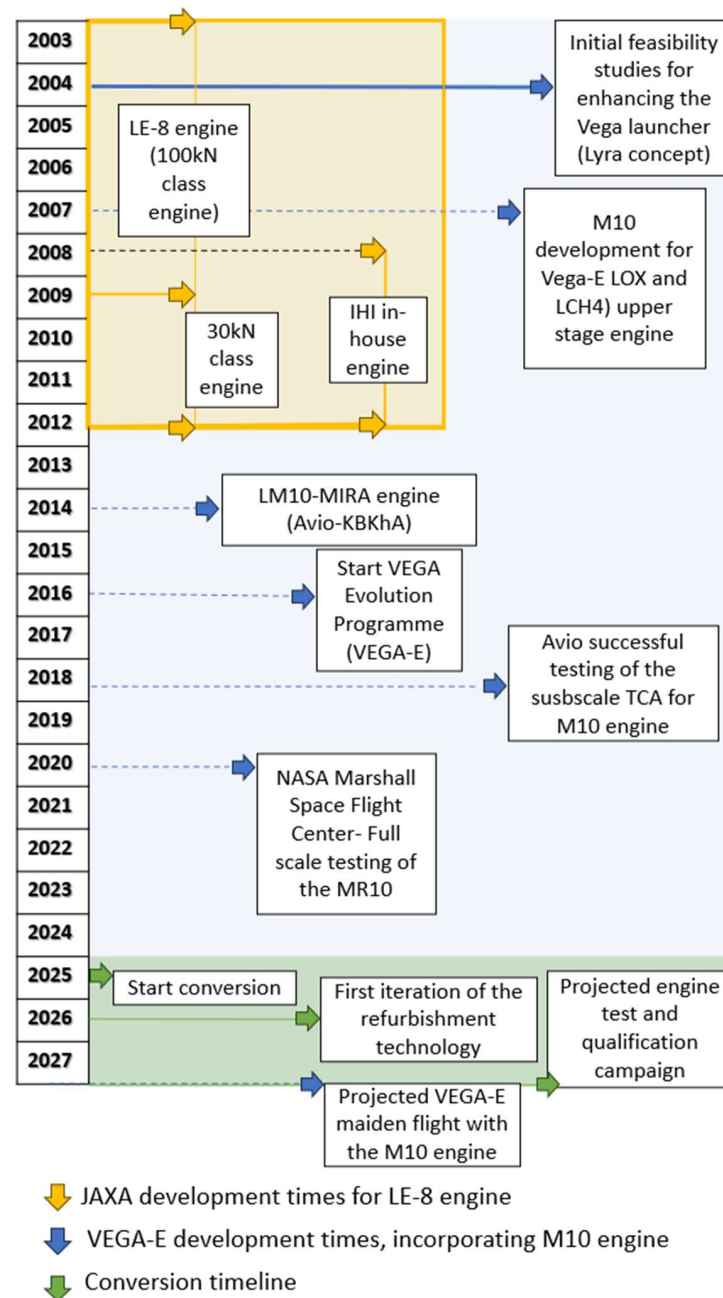


Figure 9. Timeframe development of the JAXA's LE-8 [142] engine and VEGA-E's M10 [144] vs. the proposed conversion.

In contrast, developing a new cryogenic propulsion system from scratch typically requires 5–10 years of research, prototyping, and testing. This approach can lead to severely increased expenses due to the need for new materials, advanced technologies, and the extensive certification process for space applications. Systems like NASA's Space Launch System (SLS) exemplify the costs and time involved in ground-up development, with an estimated total cost of \$23 billion and a timeline extending over a decade [145,146]. The Space Shuttle program also faced challenges with engine refurbishment, which led to rising costs and operational delays, demonstrating the risks of adapting existing missile systems [147]. On the other hand, companies like SpaceX, through their Starship development, have shown how starting fresh can push the boundaries of space technology, even though this comes with its own set of risks and expenses [148,149].

Table 3 compares the costs and timeframes involved in converting a missile engine into a cryogenic space propulsion system versus developing a new cryogenic propulsion system from the ground up.

Table 3. Comparison of cost and timeline.

Aspect	Missile Engine Conversion	Ground-Up Development (Cryogenic Space Propulsion)
Initial Cost	Lower (leverage existing technology)	Higher (full design, materials, R&D)
Time to Develop	~Shorter (3–6 years)	Longer (5–10 years)
Testing and Validation	Extensive (cryogenic testing, safety, reliability)	Extensive (cryogenic conditions, space-specific testing)
Performance	Medium (limited by missile design, not optimized for space)	High (fully optimized for space conditions, Isp, efficiency)
Technological Risk	Medium to High (unproven adaptation)	High (new systems and technologies)
Reliability	Medium (dependent on successful conversion)	High (designed for space missions)
Mission Suitability	Limited (best for smaller, short-duration missions)	High (optimized for long-term space missions)
Long-Term Sustainability	Medium (limited by aging missile tech)	High (designed for space with long operational life)

5. Pillar II—Remanufacturing of Key Components

The remanufacturing of key components for the envisioned converted engine should follow an iterative optimization loop. This process, illustrated schematically in Figure 10, outlines the sequential adaptation of components to meet the new operational requirements.

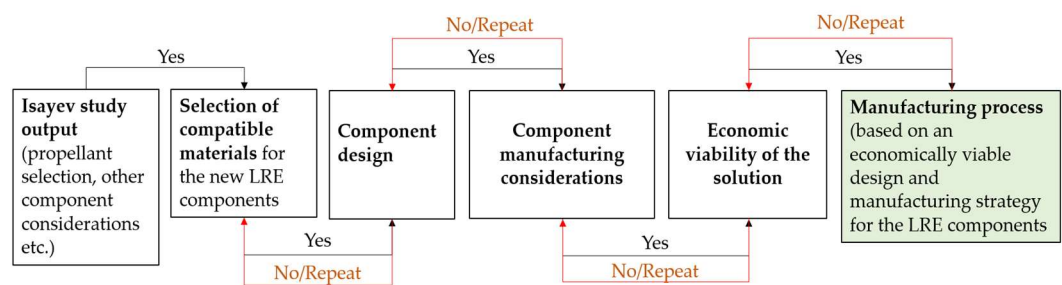


Figure 10. Optimization loop for the manufacturing process.

The remanufacturing process of missile engine components can be significantly enhanced through the integration of artificial intelligence (AI), particularly in supporting complex decision-making tasks. Recent technical advances can significantly contribute to the optimization of the manufacturing process, especially when combined with AI-driven tools. These advances enable the analysis of large datasets collected during component disassembly, inspection, and material characterization, allowing for accurate prediction of failure modes and assessment of component reusability. Machine learning models and digital twin systems can simulate multiple repair scenarios, guiding the selection of the most efficient and reliable restoration paths. This not only improves performance and reduces costs but also supports traceability, quality assurance, and compliance with emerging standards, ultimately accelerating the industrialization of remanufacturing workflows.

The optimization loop for the manufacturing process of targeted components of the Isayev S2.720 missile engine can also benefit from valuable input from a reliability

assessment conducted using Virtual Physics-of-Failure principles [150,151], modelling, and simulations introduced by NASA for their missions. This engineering-based approach uses modelling and simulation to qualify a design and manufacturing process with the intent of eliminating failures early in the design process by addressing the root cause. The physics of failure analysis can be conducted to incorporate reliability into the new design process of the turbopump, gas generator, feed-system pipelines, and the modified combustion system (incorporating the existing thrust chamber and the potential firing plate), by establishing a scientific basis for evaluating the new materials chosen for manufacturing, the new engine components structures and the technologies used for manufacturing.

Table 4 outlines the components identified as requiring remanufacturing or redesign, based on their functional criticality, potential material degradation, and the necessity to meet updated performance and safety standards for space applications. The baseline assumption is minimal redesign wherever possible. Turbo-pump and gas generator modifications are not presupposed; instead, they will be validated through testing of existing hardware, with redesign proposed only if test data confirm the necessity.

Table 4. Expected level of modification for Isayev S2.720 subsystems under LOX–LCH₄ conversion (conceptual perspective).

Subsystem	Expected Modification Level	Notes
Feed system (tanks, pressurization, lines, valves)	Minor to moderate adaptation	Material compatibility checks; sizing/pressure-drop verification.
Turbo-pump unit	Testing first; redesign only if required	Differences in propellant density/viscosity may necessitate re-tuning or partial redesign, to be confirmed experimentally.
Gas generator	Testing first; redesign only if required	New injectors may be needed; chamber volume and stability to be assessed in test campaigns.
Combustion chamber	Moderate adaptation	Injector and cooling approaches may need updating for cryogenics.
Ignition system	New concept required	Hypergolic start cannot be retained; alternative ignition to be introduced.

The reuse of compatible components from the available S2.720, while only modifying the necessary components, will be one of the major drivers to enable the economic viability of the conversion concept in the face of the extremely competitive nature of the global micro-launcher market. Thus, the new manufacturing routes in conjunction with the advanced design and simulation capabilities can contribute to delivering a new, fast-to-achieve low-cost space transportation solution for Europe’s access to space and, thus, support Europe’s launcher industry.

Development costs can be reduced by reusing, testing, and validating existing components, as well as by leveraging advanced manufacturing technologies such as additive manufacturing (AM), which enables the customization and rapid production of redesigned parts with significantly shorter development cycles compared to conventional methods, as illustrated in Figure 11.

Several specialized component geometries can serve as a guideline for the design of improved parts. Figures 12 and 13 present the existing geometries of the gas generator and the combustion chamber.



Figure 11. Comparison of traditional manufacturing evolution (cost in US\$, 2020 equivalent, credits NASA) [152].



Figure 12. Section through the Isayev S2.720 gas generator.

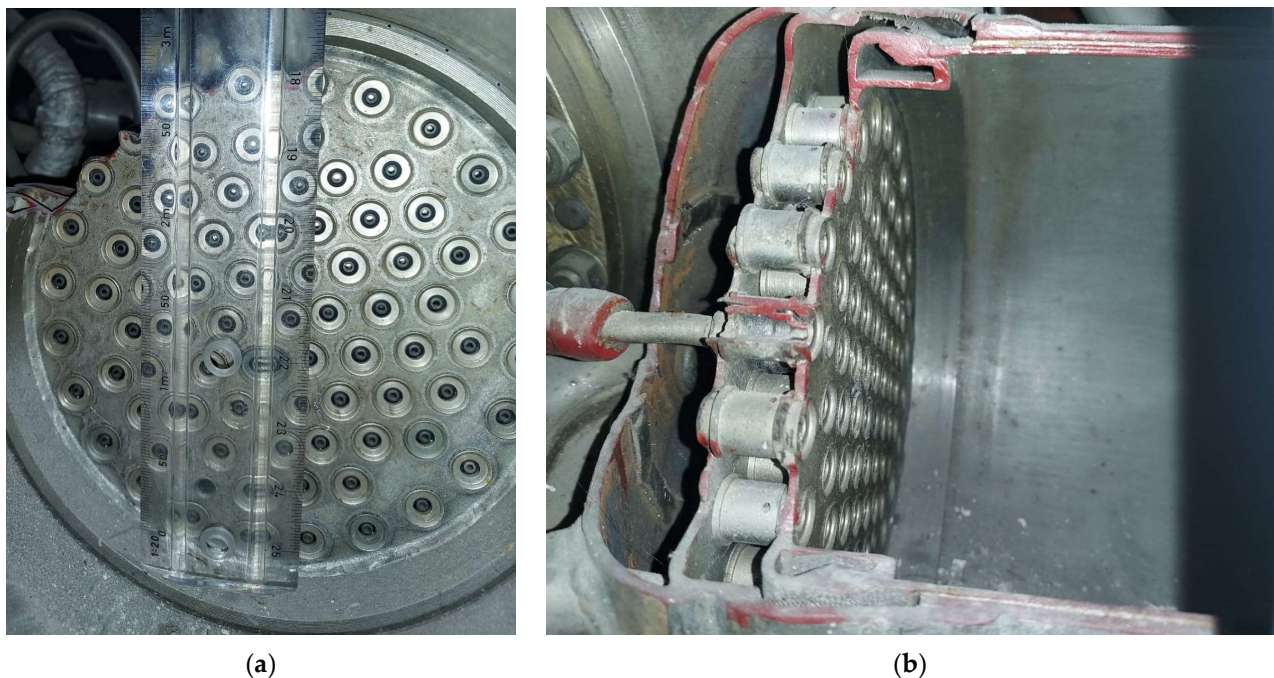


Figure 13. (a) Isayev S2.720 injection plate—frontal view, (b) section through the Isayev S2.720 combustion chamber, revealing the cooling jacket and injector geometry.

The remanufacturing of engine components, as outlined in the table, can effectively leverage additive manufacturing (AM), AI-driven inspection, and digital engineering to enable

cost-effective restoration and functional reuse. For components such as gas generator, turbopump elements, and interconnecting mounts—marked for manufacturing but not redesign, geometry-preserving repair using Directed Energy Deposition (DED) [153] or cold spray AM allows precise restoration of worn areas without producing entirely new parts. Propellant tanks, spanning concept development through testing, are ideal candidates for hybrid manufacturing: legacy tanks can be scanned, evaluated via AI-enabled non-destructive evaluation (NDE), and repaired or modified with AM to integrate new interfaces or accommodate different fluids. Thrust chambers and combustion injection systems, which include concept development and design, can be remanufactured using AM-enabled topological optimization and AI-informed flow modeling to redesign internal channels and regenerate cooling systems. The propellant feeding system and controls/valves, requiring revalidation through testing, can benefit from digital twins and condition monitoring models to ensure system integrity. In all cases, AI-supported decision tools analyze material degradation, stress paths, and mission compatibility to determine whether full restoration, partial reuse, or responsible recycling is appropriate, maximizing material value while supporting net-zero and circularity goals.

Recent developments in AM have enabled the direct fabrication of liquid rocket engine combustion chambers, significantly accelerated production timelines, and enabled design freedom that is unachievable with traditional subtractive methods. A notable example is NASA's work with GRCop-84 and C-18150 copper alloys [154], where bimetallic, channel-cooled combustion chambers were successfully manufactured using a hybrid approach: powder bed fusion for the copper liner and DED for the Inconel 625 structural jacket. The parts were manufactured on the LT4300 Hybrid Manufacturing Machine, illustrated in Figure 14, with the purpose of emphasizing the important advancements in the field of AM. These chambers were subsequently hot-fire tested with LOX/RP-1, demonstrating structural integrity and regenerative cooling performance comparable to conventional chambers. Similarly, the U.S. Air Force Research Laboratory has demonstrated a large-scale thrust chamber printed in a single piece via DED, confirming the viability of AM for full-scale hardware in high-pressure environments [155].



Figure 14. Virgin Orbit LT4300 Hybrid Manufacturing Machine [154].

Commercial ventures have also adopted AM in propulsion hardware. Launcher Inc. [156], for instance, developed the E-2 engine featuring a single-piece copper-alloy

combustion chamber produced using advanced LPBF systems, which was hot-fire tested successfully at NASA's Stennis Space Center at 100 bar. Complementary to these efforts, Kerstens et al. [152] present a comprehensive end-to-end evaluation of the AM process for thrust chambers, from design through hot-fire testing, highlighting the importance of thermal performance validation and post-processing, such as hot isostatic pressing (HIP) and machining. These examples collectively underline the maturity of AM in rocket propulsion applications and serve as a relevant technological baseline for the conversion strategy proposed by this paper.

In 2019, engineers from DLR (German Aerospace Center) and ArianeGroup under ESA successfully 3D-printed and hot-fired a full-scale combustion chamber demonstrator, known as BERTA, on the P8 test stand at Lampoldshausen [157–159]. The chamber, built using Laser Powder Bed Fusion (LPBF) from a copper–chromium–zirconium alloy, featured intricate, integrally printed regenerative cooling channels. During 14 hot-fire tests totaling approximately 560 s, the demonstrator achieved stable, reliable performance at a reference thrust of around 2.5 kN, validating both the manufacturing technique and thermal management design. This campaign confirmed that additively manufactured thrust chambers can meet rigorous engine requirements and significantly reduce production complexity relative to traditional fabrication methods. Meanwhile, research at DLR focused on establishing the AM techniques for manufacturing a variety of rocket engine components from turbo-pump parts to injectors and new designs of Copper Liners. One of such liners, printed together with the German company AMCM[®] on a large-scale LPBF setup M4K in the project 3D-LoCos (3D-printing for Low-Cost Rocket Engines), included improved internal fuel flow structures that were designed with the help of AI, considering the particulars of LPBF manufacturing and its inherent high surface roughness. These developments, conducted alongside the establishment of DLR's Liquid Upper Stage Demonstrator Engine (LUMEN) test platform [160]—which allows testing and operation of a complete engine with all components in a ground facility—highlighted the potential of additive manufacturing for space propulsion. Notably, the LPBF copper liner, generating 25 kN of thrust, successfully completed 29 hot-fire tests under varying conditions, with a cumulative burn time of 1147 s [160].

In Italy, ASI and AVIO have contributed to the development of MPGE (MultiPurpose Green Engine), based on H₂O₂ and kerosene propellants. The engine is manufactured by Sophia High Tech company using additive manufacturing with a specialized copper-alloy blend. Figure 15 shows the sketch of the engine and the first ignition test [161].

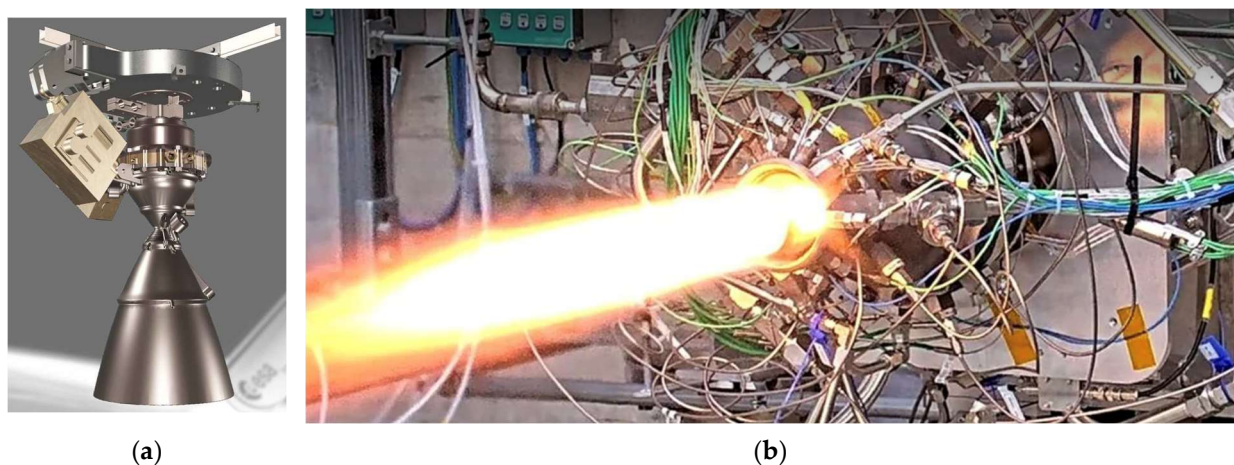


Figure 15. ASI/AVIO/Sophia High Tech (a) MPGE Engine sketch and (b) ignition test [161].

An important step in the adaptation of a legacy liquid rocket engine (LRE) combustion chamber is the evaluation of heat flux loads on both the chamber walls and the firing plate. This analysis is essential not only for guiding the design of a new injector head but also for determining the necessity and extent of protective coatings on the thrust chamber.

An increasingly promising approach to managing high local heat fluxes is the integration of transpiration cooling structures via additive manufacturing, as demonstrated in [160]. In this method, coolant passes through a porous wall, cooling the structure internally and forming a protective surface film. LPBF enables the direct fabrication of metallic porous regions with locally tailored permeability, achieved by adjusting manufacturing parameters. This allows smooth transitions between dense, load-bearing areas and porous, coolant-permeated zones within a single structure. For legacy combustion chamber upgrades, AM-based transpiration cooling offers a cost-effective means to boost thermal performance and extend service life with minimal changes to the overall geometry. However, if the thermal relief achieved through transpiration cooling alone proves insufficient, protective coatings will still be required to ensure adequate heat shielding in the most highly stressed regions.

The decision to apply coatings depends largely on the cooling channels' thermal efficiency. If simulations indicate sufficient heat removal, coatings may only be applied selectively, targeting thermally stressed regions. Conversely, if thermal performance is inadequate, full internal and external surface coverage may be required.

To support this process, advanced computational fluid dynamics (CFD) simulations will be required, focusing on reactive flow behavior and heat transfer under high-pressure, cryogenic combustion conditions. Validated 3D models will capture the interaction between fuel injection, mixing, combustion, and wall heat flux, leveraging symmetrical features of the remanufactured engine. These simulations, based on existing numerical methods and chemical kinetic schemes developed for oxygen–hydrocarbon propellant pairs, will generate detailed insight into combustion behavior. The outcomes will support both the optimization of the injector head and the performance verification of the regenerative cooling system.

In previous projects, such as HYPROB (managed by CIRA) [162], validated simulation frameworks have successfully been used to compare three-dimensional CFD results with experimental data from hot-fire campaigns involving breadboards, injector heads, and full demonstrator thrust chambers. Building on this state of the art, the present perspective explores how similar methodologies can be applied to remanufactured liquid rocket engines (LREs). In particular, three-dimensional simulations can leverage the symmetry of legacy chamber geometries—such as those repurposed from decommissioned missile engines—when coupled with redesigned injector heads. Established chemical kinetic schemes for methane/oxygen combustion, along with verified numerical procedures, offer a reliable foundation for investigating injection dynamics, flame structure, and wall heat flux loads. These insights are critical for evaluating cooling jacket performance and informing decisions on whether additional protective coatings or design adaptations are required in the remanufactured system.

Figure 16 illustrates a qualitative validation of CFD predictions through direct visual comparison between simulated exhaust flow fields and experimental observations. The contour lines represent temperature or velocity distributions obtained from three-dimensional reactive flow simulations, while the background image captures the actual exhaust plume during TEST06 of the HYPROB FSBB [162] test campaign by CIRA/AVIO, recorded using a high-speed imaging system. The good correlation between the predicted plume shape, expansion structure, and shear layer features with the captured image demonstrates the reliability of the numerical model in replicating key flow characteristics. This level of agree-

ment reinforces confidence in the simulation approach, which can be applied to support the redesign, optimization, and heat flux estimation of remanufactured propulsion systems.

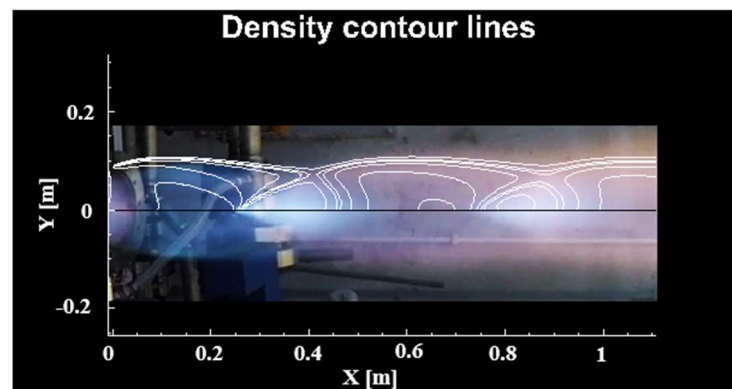


Figure 16. Density contour lines of the exhaust gases (plume) from the HYPROB FSBB test campaign, captured using a high-speed camera [162].

6. Pillar III—Testing

In the context of converting the Isayev S2.720 engine to operate with cryogenic propellants, a targeted component-level testing campaign would be necessary to assess the suitability and adaptability of legacy hardware. While no new conceptual design is being developed for the turbopump propellant-feed system or gas generator, these components must undergo rigorous functional validation. Cold-flow testing will simulate the performance of these units under inert fluid flow to evaluate their behavior in terms of rotational dynamics, flow stability, and mechanical wear, particularly under pressure and temperature regimes approximating cryogenic operation.

The propellant tanks, which are central to this conversion, should be tested for both structural integrity and compatibility with LOX or methane. This would involve cryogenic proof testing, cyclic pressure loading, and compatibility checks with proposed internal coatings, especially in light of material embrittlement risks and the need for corrosion resistance. The associated propellant feeding system, such as manifolds, flex lines, and connectors, will undergo pressure drop assessments, vibration testing, and leak detection to confirm performance under modified routing and thermal cycling conditions.

Control and valve systems, expected to be reused with only minor modifications, must demonstrate reliable actuation under cryogenic conditions. Testing will verify their sealing behavior, cycle endurance, and response time when exposed to thermal shocks and low-temperature fluid dynamics. For the thrust chamber, despite being reused structurally, hot-fire testing is essential to validate regenerative cooling performance, nozzle expansion behavior, and combustion stability with the new propellant pair.

The combustion chamber injection and ignition system, being redesigned to accommodate LOX–methane combustion, requires dedicated testing for spray dynamics, ignition reliability, and injector-cooling compatibility. Finally, interconnecting mounts and structural elements, although not planned for full-scale testing, may be subjected to mechanical testing to ensure that thermal contraction, dynamic loads, and modified interfaces do not compromise engine integrity during firing or integration. Together, these tests form the foundation for safely repurposing the S2.720 engine architecture for modern, sustainable propulsion applications.

In summary, the strategic repurposing of legacy missile propulsion systems represents a technically viable and economically attractive pathway for addressing the growing demand for sustainable space transportation. By combining cryogenic propellant retrofitting,

precision remanufacturing, and rigorous component-level testing, this approach enables the extension of existing aerospace assets into new, environmentally conscious applications. The use of additive manufacturing and data-driven validation not only reduces material and energy consumption but also supports faster iteration cycles and design adaptability. When reinforced by systematic LCA and LCC analyses, this methodology offers a compelling framework for advancing circularity, resilience, and innovation in European space propulsion development.

Ultimately, the decision between converting missile engines and developing new propulsion systems depends on the specific mission requirements, budget, and timeline. If the goal is to quickly deploy a system for small-scale or interim missions, missile engine conversion could be a viable and cost-effective solution. However, for long-term, high-performance missions, especially those involving multiple space cycles or large payloads, a ground-up development would likely be the better option for optimal performance, reliability, and long-term sustainability. The choice should align with mission priorities, whether focusing on cost-efficiency or advanced capabilities for more complex space missions. Table 5 compares the costs and timeframes involved in converting a missile engine into a cryogenic space propulsion system versus developing a new cryogenic propulsion system from the ground up.

Table 5. Comparison of Costs and Time [67,75,127,145,148].

Aspect	Missile Engine Conversion	Ground-Up Development (Cryogenic Space Propulsion)
Initial Cost	Lower (leverage existing technology)	Higher (full design, materials, R&D)
Time to Develop	~Shorter (3–6 years)	Longer (5–10 years)
Testing and Validation	Extensive (cryogenic testing, safety, reliability)	Extensive (cryogenic conditions, space-specific testing)
Performance	Medium (limited by missile design, not optimized for space)	High (fully optimized for space conditions, Isp, efficiency)
Technological Risk	Medium to High (unproven adaptation)	High (new systems and technologies)
Reliability	Medium (dependent on successful conversion)	High (designed for space missions)
Mission Suitability	Limited (best for smaller, short-duration missions)	High (optimized for long-term space missions)
Long-Term Sustainability	Medium (limited by aging missile tech)	High (designed for space with long operational life)

It should be emphasized that the analyses presented in Sections 5 and 6 are conceptual in nature, consistent with the scope of a Perspective article. The primary aim is to outline possible pathways for converting legacy missile engines (covering aspects such as propellant substitution, remanufacturing of subsystems, AI-supported inspection, advanced cooling concepts, and component testing) rather than to deliver detailed engineering case studies. Technical analyses of combustion processes, ignition transients, spray dynamics, and material compatibility under LOX–LCH₄ operation, as well as implementation details for AI algorithms, dataset design, and digital twin integration, are recognized as necessary follow-up research directions. Similarly, while additive manufacturing-based transpiration cooling and systematic test schemes are identified as promising approaches, their validation requires dedicated CFD studies, experiments, and structured test campaigns that extend beyond the present work. The focus here is therefore on framing the methodological approach

and identifying the critical areas where detailed technical and experimental validation will be required in future studies.

7. Potential European Missiles for Reconversion into Space Propulsion Systems

The need for European launcher autonomy has become increasingly critical, especially in light of Russian engine bans and growing competition from private companies like SpaceX. Europe's reliance on Russian-made engines, such as the RD-170/191 engines [163] used in the Soyuz launch vehicle, has posed significant risks to its space launch capabilities. Following the geopolitical tensions resulting from Russia's actions in Ukraine, European nations have had to reevaluate their reliance on Russian propulsion technologies, prompting European nations to accelerate efforts to achieve greater self-sufficiency in their space programs.

In response, the European Space Agency and Arianespace have expedited the development of indigenous engines, such as the Vinci engine for Ariane 6 [164] and the Prometheus engine [165,166], a cutting-edge liquid-fueled engine that aims to reduce launch costs by a factor of ten while also promoting green propulsion [167]. These developments represent a key strategy for ensuring that Europe is not only independent of Russian propulsion systems but also competitive in the global space launch market.

However, the rise of SpaceX as a dominant force in the space industry has added pressure to European efforts. With its reusable Falcon 9 [67] and Starship rockets [148], SpaceX has dramatically lowered the cost and increased the frequency of space launches. This has set new industry standards, making it challenging for traditional European space providers to compete both on price and in terms of turnaround time. In response, Europe is focusing on innovative technologies such as green propellants and reusable rocket stages to enhance its space capabilities and ensure long-term competitiveness.

In addition to these efforts, missile-to-space conversion could emerge as a potentially viable path to further strengthen European launcher autonomy. While missile-to-space conversions are more commonly explored in countries like the U.S. (e.g., the Minuteman missile), certain European missile systems hold the potential for modification into space propulsion platforms. Systems like Ariane [8] and Vega rockets [144], which use cryogenic propellants (liquid hydrogen and liquid oxygen) in their upper stages, represent European launch vehicles that have been designed from the ground up with space propulsion in mind. These systems benefit from established cryogenic technology but are not the result of missile-to-space conversion. However, their use of military-grade propulsion technology and their proven reliability in space applications could inspire future reconversions of military missile engines for space propulsion, especially when adapting them to more sustainable, green propellants. European missile systems like the Aster family, Storm Shadow (SCALP EG), and the M51 SLBM offer promising starting points.

On the missile front, the Aster missile family (Aster 15 and Aster 30) offers a high-performance, high-thrust solution [168]. Developed by MBDA (France/Italy), these surface-to-air and anti-aircraft missiles are optimized for supersonic flight and harsh environmental conditions. However, their solid-propellant propulsion systems [169] would need to be significantly reworked for liquid cryogenic fuels. The overall structure, particularly the thrust-to-weight ratio, is promising for space propulsion applications, but substantial modifications to the combustion chamber, fuel systems, and nozzle design would be necessary.

The Storm Shadow (or SCALP EG) long-range cruise missile, a joint Franco-British design, uses a turbojet engine for high-speed, long-range operation [170]. Originally designed for atmospheric flight, this missile's propulsion system could potentially be adapted for space missions with cryogenic or green propellants. The modifications would

require substantial changes to the engine's nozzle design, insulation, and fuel systems to function effectively in space's vacuum environment. Despite these challenges, the Storm Shadow has a solid operational track record with air forces like the Royal Air Force and the French Air Force, having seen active service in conflict zones such as Iraq, Libya, and Syria.

Another possibility is that the M51 SLBM (Submarine-Launched Ballistic Missile), used by the French Navy, is powered by liquid-fueled engines (kerosene/LOX) capable of delivering high thrust [171]. Though originally designed for nuclear deterrence missions, its propulsion system has the potential to be adapted for space launches with green or cryogenic propellants. However, converting it to operate in space would require significant adjustments not only to the engine but also to the guidance system and payload integration. Given its high-thrust capability, the M51 could be a candidate for future space propulsion if its military mission requirements can be adapted to meet the needs of space missions.

By combining these missile-to-space conversion possibilities with ongoing developments in indigenous space technologies like Prometheus, Europe could strengthen its autonomy in space propulsion and gain a competitive edge against emerging commercial players. The fusion of military-grade propulsion technology and innovative space technologies presents a strategic opportunity for Europe to accelerate its space ambitions, ensuring both security and independence in an increasingly dynamic space race.

8. Policy, Security, and Ethical Dimensions

8.1. Policy Framework

Missile reconversion programs present a unique opportunity to transform decommissioned military missile systems into valuable civilian assets, supporting national goals in space exploration, technological innovation, and nonproliferation. These programs repurpose retired military platforms for peaceful applications such as satellite launch, hypersonic research, or dual-use technology demonstrators. In doing so, they contribute to the reduction of military stockpiles while fostering innovation and industrial competitiveness. However, such efforts must be managed responsibly within a secure and transparent framework that addresses complex legal, technical, strategic, and ethical implications.

The intersection of dual-use technologies for missile reconversion to space propulsion, particularly with cryogenic propellants, sits at the intersection of international defense policy, space exploration, and export control regimes. While the EU and NATO support peaceful space development, missile reconversion raises serious nonproliferation and strategic stability concerns.

The European Union Dual-Use Regulation (428/2009) [172] controls the export, transit, and brokering of dual-use goods. This regulation governs the transfer of technologies that have both military and civilian applications, such as missile technology, space-related technologies, and cryogenic propellants. The goal is to prevent sensitive technologies from falling into the hands of hostile nations or organizations that could use them for military purposes in violation of international law. In parallel, the EU Common Position on Arms Export Control [173] provides guidelines on exporting military technologies, while considering the broader implications for peaceful space exploration. These guidelines ensure that missile technology, when reconverted for space propulsion, does not undermine regional security or fuel the militarization of space.

NATO, as an intergovernmental military alliance, also has policies on dual-use technologies, though its focus is often on military cooperation and interoperability among member states. However, NATO's Science and Technology Organization (STO) [174] and the Cooperative Cyber Defense Centre of Excellence (CCDCOE) [175] are involved in dual-use technologies research and development, which sometimes overlaps with space and missile technologies. NATO members are also bound by international arms control

agreements, such as the Missile Technology Control Regime (MTCR) [176], which restricts the proliferation of missile systems capable of carrying payloads of over 500 kg for 300 km or more [177]. Leading among the governing instruments, the MTCR seeks to prevent the spread of missile technologies capable of delivering weapons of mass destruction. Although the MTCR allows for the transfer of space technologies for peaceful use, it imposes strict limits on systems capable of carrying large payloads over long distances. As such, reconverted missile platforms—particularly those with performance characteristics similar to ballistic missiles—fall under intense scrutiny due to their potential reversibility for military use. This introduces strategic ambiguity, which can erode trust in arms control regimes and contribute to inadvertent militarization of space.

The Wassenaar Arrangement [178] is another crucial international export control regime that includes 42 countries, among them EU and NATO members. Its aim is to prevent the proliferation of dual-use technologies that could have military applications, including missile technologies and space propulsion systems. Cryogenic technologies used in missiles and space systems are of particular concern, as they can be adapted for both long-range military missile systems and space launch vehicles. The Wassenaar Arrangement provides a multilateral framework to ensure that the export of such technologies is carefully controlled, reducing the risks associated with military misuse or proliferation. The European Space Agency (ESA) promotes the development and use of advanced propulsion systems, including cryogenic propellants, and supports private sector collaboration to enhance European space launch capabilities. Programs such as Prometheus and Ariane 6 exemplify this direction. Although NATO does not maintain its own civilian propulsion programs, it oversees space-related defense initiatives, particularly in satellite-based surveillance and communication. These initiatives may involve dual-use technologies, including cryogenic systems.

8.2. Security Implications

The militarization of space remains a highly sensitive issue, and great care must be taken to ensure that converted technologies do not inadvertently contribute to geopolitical instability or an arms race in space.

The development and transfer of cryogenic propulsion systems represent a key security concern due to their potential use in strategic delivery vehicles such as ICBMs. These high-performance systems are closely monitored under national and international export control frameworks. Even among allies, there is no automatic clearance for such transfers. Instead, they require individual export licenses, end-use verification, and often government-to-government arrangements. National agencies like BAFA (Germany) [179] and DGA (France) [180] ensure compliance with these frameworks and evaluate potential proliferation risks on a case-by-case basis.

To address these challenges, national governments must establish a centralized compliance authority responsible for coordinating export licensing, tracking converted systems, and ensuring transparency throughout the technology transfer process. Reconversion efforts must be integrated into broader industrial, defense, and space policies, with oversight mechanisms that balance innovation with strategic and regulatory discipline.

Security must be a central pillar of reconversion governance. Public and private actors must operate within robust legal and operational frameworks to protect sensitive technologies. This includes cybersecurity and IP protection to defend against data theft and espionage, physical security of production, storage, and testing facilities, to prevent sabotage or unauthorized access, end-use assurance mechanisms, such as export licenses, end-user certificates, and post-delivery monitoring to prevent diversion to unauthorized military uses.

At the same time, missile reconversion programs can catalyze industrial development. By involving SMEs through grants, tax incentives, and regulatory simplification, these initiatives can accelerate innovation in propulsion, guidance systems, and advanced materials. Public R&D funding should target dual-use technologies with both strategic and commercial applications, reinforcing domestic aerospace capabilities and securing resilient supply chains.

Clear legal and governance frameworks are also required to manage public-private partnerships effectively. These should include transparent intellectual property arrangements, milestone-based public investment, and third-party oversight mechanisms to ensure alignment with national objectives, particularly in areas such as nonproliferation, transparency, and peaceful use.

8.3. Ethical Dimensions

In addition to legal and technical oversight, missile reconversion programs raise significant ethical considerations. These initiatives operate at the intersection of defense, science, and commercial innovation, where the dual-use nature of technologies—especially cryogenic propulsion—creates ethical ambiguity. While such systems can power peaceful missions, they may also be redirected toward strategic military applications. As government and private entities engage more deeply in space-related R&D, it becomes increasingly difficult to distinguish legitimate scientific progress from latent military capability. This blurring of civilian and military lines can fuel international mistrust, undermine arms control efforts, and increase the risk of conflict.

The potential misuse of launch systems originally designed as weapons platforms presents a moral hazard. Without strict oversight and transparent governance, reconverted systems may be used to circumvent disarmament treaties, serve as covert weapons development platforms, or provoke strategic escalation. The integration of civilian research institutions and commercial actors into defense-related programs also raises societal concerns about academic independence, the ethics of public funding, and the normalization of militarized space development.

Therefore, there is a moral imperative to ensure that space remains a demilitarized and cooperative domain. This includes enforcing ethical safeguards in technology transfer and export, promoting transparency in program goals and outcomes, and embedding peaceful-use and nonproliferation principles in all PPP governance structures.

The use of cryogenic propellants—such as liquid hydrogen and liquid oxygen—is critical in both military missile systems and space launch vehicles due to their high specific impulse and performance efficiency. Because of the significant technological overlap, particularly in propulsion, guidance, and structural components, the reconversion of missile systems—especially intercontinental ballistic missiles—into space launch platforms presents a complex dual-use challenge. Table 6 outlines some of the major overlapping systems. Cryogenic propulsion systems used in launch vehicles like the Ariane series or Falcon 9 [65] must comply not only with national export control regimes, but also with international treaties governing space activity—particularly the Outer Space Treaty. Any conversion of military missile systems into civilian SLVs must ensure transparency, civilian intent, and strict adherence to peaceful-use norms in order to remain compliant with both arms control obligations and space law. This layered governance structure is designed to prevent the misuse of peaceful exploration as a cover for space militarization, reinforcing international trust.

Table 6. Overlapping systems.

System	Missile Purpose	Space Purpose
Cryogenic engines	High-thrust launch of warheads	High-impulse space launch
Guidance control	Target acquisition	Precise orbital insertion
Airframe and structure	Reentry durability	Payload fairing for satellites

Within this regulatory and technical context, key players in Europe’s missile reconversion and dual-use technology governance include Airbus, ArianeGroup, and CNES (Centre National d’Études Spatiales)—each playing a critical role at the intersection of aerospace innovation, security regulation, and space policy. Airbus and its joint venture ArianeGroup are foundational industrial actors in Europe’s launch vehicle ecosystem, with deep involvement in both civilian missions (e.g., Ariane 5 and the upcoming Ariane 6) and military aerospace programs. Their dual competencies uniquely position them as central stakeholders in missile reconversion, particularly in adapting technologies such as guidance systems, structural composites, and cryogenic propulsion for civilian use. They also lead major R&D programs like Vulcain 2 [120], the main stage engine of Ariane 5/6 [7,8], and Prometheus [166], a next-generation reusable engine designed for flexibility and cost reduction. Airbus and ArianeGroup exemplify effective public-private synergy, working closely with European governments and agencies to ensure that innovation aligns with national security, nonproliferation, and export control obligations.

Meanwhile, CNES, France’s national space agency, functions both as a technical authority and a regulatory body. It plays a crucial role in shaping and enforcing national space policy, overseeing industrial partnerships, and ensuring compliance with international frameworks such as the MTCR, the Outer Space Treaty, and EU dual-use regulations. CNES also fosters an innovation ecosystem by linking startups, academia, and major aerospace firms to drive forward responsible R&D in areas like mini-launchers, space situational awareness, and advanced propulsion technologies. Serving as France’s liaison with the European Space Agency, CNES helps align national priorities—such as missile reconversion—with broader strategic goals laid out in the EU Strategic Compass and ESA’s exploration roadmap.

9. Conclusions

The conversion of decommissioned missile propulsion systems into sustainable, space-grade engines represents both a technical opportunity and a strategic imperative. As shown through the model case of the Isayev S2.720 engine, such transformations are becoming increasingly feasible due to advancements in manufacturing technologies, particularly additive processes, and the growing maturity of testing and qualification infrastructures.

This article proposed a structured methodology based on three foundational pillars: (1) the adoption of cryogenic or green propellants to align with environmental and safety standards; (2) the remanufacturing and targeted redesign of critical engine components to ensure compatibility with spaceflight requirements; and (3) rigorous component-level testing to validate performance under representative mission conditions. Together, these pillars offer a practical route for repurposing legacy systems in a way that significantly reduces development time, costs, and environmental impact. Remanufacturing components from old rocket engines and repurposing parts or whole systems may open up new opportunities for a new emerging market that aims at achieving a more sustainable economy.

Moreover, the broader assessment of potential European missile systems reveals an underexplored inventory of high-precision hardware that could be integrated into future space transportation architectures. However, technical feasibility alone is not sufficient. The successful implementation of such conversion strategies will require coherent policy frame-

works, transparent security protocols, and ethical oversight to ensure that remanufacturing aligns with both civilian goals and non-proliferation commitments.

Ultimately, this perspective argues that legacy missile engines should not be seen merely as relics of the Cold War, but as dormant assets with renewed relevance in the era of sustainable and sovereign access to space. Through a careful combination of engineering innovation, testing, and regulatory foresight, Europe can take a leadership role in developing circular pathways for strategic aerospace hardware.

10. Patents

A patent application entitled ‘Conversion of the Isayev S2.720 Engine for Cryogenic Propellants and Small Launch Vehicle Applications’ is currently in preparation and will be filed with the Romanian State Office for Inventions and Trademarks (OSIM) within the 12-month grace period granted after public disclosure, in accordance with national legislation.

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Abbreviations

The following abbreviations are used in this manuscript:

ADN	Ammonium Dinitramide
AI	Artificial Intelligence
AM	Additive Manufacturing
Al ₂ O ₃	Aluminum Oxide
CALLISTO	Cooperative Action Leading To Launcher Innovation For Stage Toss-Back Operations
CCDCOE	Cooperative Cyber Defense Centre Of Excellence
CNES	Centre National D’études Spatiales
CMG	Control Moment Gyroscopes
CO ₂	Carbon Dioxide
DED	Directed Energy Deposition
EIL	Energetic Ionic Liquids
ESA	European Space Agency
GEO	Geostationary Orbit
GG	Gas Generator
H ₂ O	Water
HAN	Hydroxylammonium Nitrate
HC	Hydrocarbons
HCl	Hydrogen Chloride
HPAS	Hydrogen-Peroxide Aqueous Solutions
HTP	High-Test Peroxide
HYPROB	Hydrocarbon Propulsion Bench
ICBM	Intercontinental Ballistic Missile
ISS	International Space Station
ISRU	In-Situ Resource Utilization

kp	Kilopond (Also Known As A Kilogram-Force, Older Unit Of Force)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LEO	Low Earth Orbit
LH ₂	Liquid Hydrogen
LOX	Liquid Oxygen
LOX–CH ₄	Liquid Oxygen–Methane
LPBF	Laser Powder Bed Fusion
LRE	Liquid Rocket Engine
LUMEN	Liquid Upper Stage Demonstrator Engine
MMH	Monomethyl Hydrazine
MPGE	Multipurpose Green Engine
MTCR	Missile Technology Control Regime
N ₂ O ₄	Nitrogen Tetroxide
NDE	Non-Destructive Evaluation
NTO	Nitrogen Tetroxide
OMS	Orbital Maneuvering System
PSLV	Polar Satellite Launch Vehicle
R&D	Research and Development
RCS	Reaction Control Systems
RP-1	Kerosene
SLBMs	Submarine-Launched Ballistic Missiles
SLV	Space Launch Vehicles
SoC	System-On-Chip
SPS	Service Propulsion System
SPTF	Space Propulsion Test Facility
SRB	Solid Rocket Boosters
THA	Turbopump Assembly
UDMH	Unsymmetrical Dimethylhydrazine
VTVL	Vertical Take-Off/Vertical Landing
mos	Months

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