# Dragon spacecraft launch and reentry: phases, materials, fuels, and greener alternatives

**(A NASA-sourced technical research paper — Crew/Cargo Dragon / Dragon 2 family)**

**Abstract**  
This paper describes in detail the stages of launching a SpaceX Dragon spacecraft (Crew Dragon / Cargo Dragon variants), from pre-launch processing through ascent, on-orbit operations, de-orbit, atmospheric entry, and recovery. It documents the principal materials used in the Dragon spacecraft and its Falcon-9 launch vehicle (heat shield PICA-X, composite and aluminum structures, aluminum-lithium tanks, COPVs), the conventional propellants used during launch (RP-1/LOX for Falcon 9 and helium/monopropellant systems for spacecraft maneuvering), and evaluates alternative materials and greener propellant technologies that NASA has researched, including AF-M315E (green monopropellant) and LOX/LCH4 (liquid oxygen / methane). Sources and technical evidence are drawn from NASA open literature, press kits, and NASA technical reports.

## Table of contents

1. Introduction
2. Overview: the Dragon family and Falcon 9 launcher (short technical context)
3. Detailed launch phases (countdown → ascent → orbital insertion)
4. On-orbit operations & rendezvous (brief)
5. De-orbit, reentry, and recovery phases (detailed)
6. Materials used in Dragon and Falcon 9: current practice (heat shield, pressure vessel, composite structures, tanks, COPVs)
7. Propellants used: launch and spacecraft systems (RP-1/LOX, helium, hypergolics)
8. Candidate lower-cost and more durable structural materials (NASA-backed findings & tradeoffs)
9. Greener propellant alternatives (NASA research and demonstrations)
10. Comparative techno-economic and environmental discussion (tradeoffs, implementation hurdles)
11. Conclusions and recommendations
12. References (NASA open sources cited)

## 1. Introduction

Spacecraft launch and reentry are multidisciplinary endeavors that combine propulsion, materials science, structural engineering, thermal protection, and ground processing. The SpaceX Dragon family — including Dragon 1 (cargo), Dragon 2 (Crew/Cargo Dragon variants), and Dragon XL concepts — are notable commercial vehicles that carry crew and cargo to low Earth orbit (LEO) and the International Space Station (ISS). NASA has partnered with and provided technology that contributed to elements of Dragon (notably PICA thermal protection) and continues to fund and publish research that evaluates new materials and propellants for safer, lower-cost, and more environmentally friendly space access. This paper provides a full walkthrough of the launch-to-recovery sequence for a Dragon mission and then examines the materials and propellants used and potential NASA-recommended alternatives. Key NASA open documents are cited throughout.

**Key NASA sources:** NASA mission/press kit material on Commercial Crew/Crew Dragon launch milestones and heat shield, NASA technical reports on PICA / PICA-X, NASA GPIM (Green Propellant Infusion Mission) documentation, and technical studies on aluminum-lithium and composites.

## 2. Overview: the Dragon family and Falcon 9 launcher (technical context)

Dragon is a family of spacecraft developed by SpaceX that includes cargo and crewed variants (Dragon 1 retired; Dragon 2 is active with crewed and cargo versions). Dragon 2 (Crew Dragon) is composed of a reusable pressurized capsule and an expendable trunk. For launches to LEO and ISS, Dragon capsules ride atop a SpaceX Falcon 9 booster: a two-stage launch vehicle using Merlin engines powered by refined kerosene (RP-1) and liquid oxygen (LOX) in the first and second stages; Falcon 9 tanks use aluminum-lithium alloys and are produced with modern welding/manufacturing techniques such as friction stir welding. SpaceX and NASA documentation highlights that Dragon uses a PICA-derivative heat shield and that composite structures and carbon fiber elements are present in non-pressure structural parts.

## 3. Detailed launch phases (countdown → ascent → orbital insertion)

Below is a step-by-step timeline and description of the technical events from crew suiting up to orbital insertion. Timings are representative of Crew Dragon launches on Falcon 9 and follow NASA launch day milestone examples and mission timelines.

### 3.1 Pre-launch processing and crew ingress

* **Vehicle/payload processing:** Final vehicle checkouts, propellant piping checks, avionics checkout, and ground-support testing occur in the hours before launch.
* **Propellant loading:** LOX and RP-1 loading is carefully sequenced; NASA milestone timelines for recent Crew Dragon launches document explicit times for RP-1 and LOX loading to begin and the launch director’s go/no-go calls. For Crew missions, the crew suiting and ingress timeline is scheduled to precede propellant load operations; the launch escape system (SuperDraco system) is armed shortly before launch.

### 3.2 Terminal countdown (T-minutes to T-0)

* **Final system checks and arming:** Flight termination (range safety) checks, avionics, and onboard computer go/no-go verifications. The launch escape system is verified/armed for crewed flights.
* **Engine chill and ignition sequencing:** Falcon 9’s Merlin engines are chilled prior to ignition; the engine ignition sequence begins immediately ahead of T-0.

### 3.3 Ignition and liftoff (T = 0)

* **Liftoff:** At engine start and thrust verification, clamps release and the vehicle departs the pad.
* **Max Q (peak dynamic pressure):** Typically occurs within the first minute; the guidance and throttle schedule account for aerodynamic loads.

### 3.4 First stage engine cutoff (MECO) and stage separation

* **MECO:** First stage main engine cutoff occurs after nominal burn (≈2–3 minutes depending on mission). The first and second stages separate, then the second stage ignites for orbital insertion.

### 3.5 Second stage burn and Dragon deployment

* **Second-stage burn:** The second stage continues to accelerate the upper stack to orbital velocity. For Dragon missions bound for ISS, the second stage places the capsule (plus trunk) into the required insertion orbit. After second stage cutoff, Dragon separates from the second stage and its trunk remains attached while the capsule performs its on-orbit maneuvers.

(Note: Falcon 9 mission timelines vary slightly based on payload and target orbit. NASA posts mission-specific launch day milestones for crewed flights.)

## 4. On-orbit operations & rendezvous (brief)

Once on orbit, Dragon performs a sequence of phasing burns, rendezvous approach maneuvers, and final approach to the ISS using Draco thrusters for attitude and translation control. For cargo Dragon variants, berthing may be accomplished via Canadarm capture and Ground/ISS crew robotics; Crew Dragon completes an autonomous docking to the ISS. NASA and SpaceX coordinate the entire rendezvous timeline with mission control and ISS crew.

## 5. De-orbit, atmospheric entry, and recovery phases (detailed)

After mission completion, the capsule prepares for return:

### 5.1 Pre-deorbit and deorbit burn

* **Deorbit burn:** The capsule performs a deorbit burn with its service-section engines (draco/superdraco depending on configuration) to lower perigee into the atmosphere intersection corridor.

### 5.2 Reentry interface and heatshield role

* **Entry interface & peak heating:** As the capsule reenters, its heat shield protects it from intense aerodynamic heating. Dragon’s heat shield uses PICA-X, a high-performance phenolic-impregnated carbon ablator (a SpaceX variant of NASA’s PICA technology), developed and flight-tested in cooperation with NASA. The PICA-X material is designed to handle the heat fluxes encountered during high-speed reentry. NASA documentation describes PICA and PICA-X testing and arc-jet qualification.

### 5.3 Chute deployment and splashdown

* **Parachute sequence:** Drogue chutes deploy to stabilize and slow the capsule; main parachutes then deploy to slow the vehicle further for splashdown. Crew Dragon uses a drogue + four-main parachute system for descent and splashdown recovery. After splashdown, recovery teams retrieve the capsule and crew/cargo.

## 6. Materials used in Dragon and Falcon 9: current practice (NASA-documented)

This section collects NASA open information on the main materials used in core Dragon and Falcon-9 structures and thermal protection.

### 6.1 Thermal protection system — PICA / PICA-X

* **PICA (Phenolic Impregnated Carbon Ablator)** is an ablative thermal protection material developed at NASA Ames; SpaceX’s PICA-X is a tuned variant used on Dragon to survive reentry heating. NASA documents record arc-jet tests and technology transfer involvement. PICA-X provides very high heat-flux capability in a low mass system.

### 6.2 Pressure vessel and cabin structure

* **Pressure vessel / pressurized capsule:** NASA and SpaceX public documents describe the Crew Dragon capsule as a pressure-vessel-based design with a robust structural shell and internal framing for crew accommodations. NASA press materials and technical summaries describe Dragon’s pressure section and its assembly approach for a safe habitable environment. For other NASA crewed vehicles (e.g., Orion) the pressure vessel is machined aluminium alloy pieces; Dragon’s pressurized shell uses high-strength metallic and composite components along with internal frames and mounts. COPVs and composite tanks are used for pressurants and some propellant stores.

### 6.3 Composite structures, honeycomb, and face sheets

* **Composite sandwich structures:** Interstage and many non-primary shear/secondary structures integrate aluminum honeycomb cores with carbon-fiber face sheets. NASA press kits and NASA technical handouts note the interstage and some fairing/structural components use composite sandwich constructions to achieve stiffness at low mass.

### 6.4 Tanks and primary structural alloys

* **Aluminum-lithium tanks (Falcon 9):** Falcon 9 first/second stage tank walls and cryogenic tanks are built from aluminum-lithium alloys and manufactured using friction-stir welding for high strength and reduced mass; NASA press kit material documents that Falcon 9 tank walls use Al-Li alloys for improved mass and cryogenic performance.

### 6.5 COPVs and pressurant vessels

* **Composite-overwrapped pressure vessels (COPVs):** Dragon uses COPVs for storing helium and other pressurants; NASA technical descriptions and crew-module documentation note the use of composite COPVs for mass-efficient pressurant storage.

## 7. Propellants used: launch and spacecraft systems

### 7.1 Falcon 9 main propellant (launch)

* **RP-1 / Liquid Oxygen (LOX):** Falcon 9 uses RP-1 (a refined kerosene) and LOX as propellants for Merlin engines (first and second stage). NASA launch day milestones for recent Crew Dragon launches explicitly list RP-1 and LOX loading operations and times. RP-1/LOX is a widely used storable cryogenic/room-temperature hybrid for medium-lift rockets.

### 7.2 Dragon capsule propellants (on-board)

* **Draco / SuperDraco propellants:** Dragon uses storable propellants for its thruster systems (e.g., Draco uses monomethylhydrazine / nitrogen tetroxide or proprietary storable propellants for reaction control; SuperDraco uses a propellant combination suitable for high thrust in abort scenarios). Specific propellant chemistries are often proprietary but historically include hypergolic combinations or storable bipropellants in the family of MMH/NTO or other storable solutions; NASA materials reference the thruster types and propellant storage systems (COPVs, tanks). (Note: exact current SpaceX propellant formulations for some thrusters are company-specific.)

## 8. Candidate lower-cost and more durable structural materials (NASA-backed findings & tradeoffs)

NASA research and technology programs have evaluated materials and manufacturing approaches aimed at lowering cost and increasing durability for launch vehicles and spacecraft. The following summarize NASA findings relevant to proposing cheaper/more durable alternatives to those used in Dragon/Falcon systems.

### 8.1 Advanced composites (carbon-fiber composites) for primary structure

* **Advantages:** NASA research shows that carbon-fiber-reinforced polymer composites can yield substantial mass savings (20–35% for many structural elements) and in some cases reduce lifecycle costs when manufacturing maturity and damage-tolerant design practices are applied. Composites are especially attractive when weight is the dominant system driver.
* **Tradeoffs and cost drivers:** Higher material costs, specialized manufacturing (autoclaves, cured layups), inspection/repair complexity, and lower ductility (brittle failure modes) are factors. For primary load-bearing members, NASA emphasizes careful design for damage tolerance and consideration of production scale to control cost.

### 8.2 Aluminum-lithium (Al-Li) alloys for tanks and primary structure

* **Advantages:** NASA programs have long advanced aluminum-lithium alloys (Al-Li 2050/2195 etc.) for cryogenic tanks and primary structure because of favorable specific strength/stiffness and cryogenic toughness, enabling mass savings and durability improvements over older aluminum series alloys. Friction-stir welding and spin-forming manufacturing processes reduce cost and improve consistency. NASA documents evidence successful applications (e.g., Shuttle external tank program, and launch vehicle tank research).
* **Tradeoffs:** Higher raw material costs and processing needs (welding, heat treat) — but in many cases overall system mass reduction yields operational cost savings.

### 8.3 Hybrid approaches: metal-matrix/composite hybrids and thin-ply composites

* NASA research shows hybridization (metal/composite hybrids, thin-ply laminates) can harvest advantages of both classes: stiffness/ductility of metals with the weight benefits of composites, while mitigating brittle failure modes. For structures where durability and impact tolerance (e.g., debris/MMOD exposure) matter, hybrids can be designed to be more damage tolerant.

### 8.4 Cost-directed manufacturing advances

* NASA technology programs (and industry cooperation) have focused on manufacturing process improvements — friction stir welding, automated fiber placement (AFP), out-of-autoclave (OOA) processing — that reduce costs, increase throughput, and improve part properties for aluminum-lithium and composite parts. These process advances are critical to making higher-performance materials cost-effective.

**Recommendation summary:** For a low-cost but durable redesign from a NASA perspective, a mixed approach — aluminum-lithium for cryogenic tanks/primary cryogenic structure, advanced carbon-fiber composites or hybrid metal/composite laminates for primary structural members where damage tolerance is assured, and PICA-type ablators for TPS — offers the best balance between mass, durability, and cost if manufacturing scale and processes are optimized. NASA literature supports both the materials and the need for advanced manufacturing methods to realize cost advantages.

## 9. Greener propellant alternatives (NASA research and demonstrations)

NASA has actively sponsored research and flight demonstrations of “green” propellants and low-toxicity fuel systems to replace hypergolic and highly toxic propellants (e.g., hydrazine, MMH/NTO) for spacecraft propulsion and to evaluate greener launch propellant concepts (e.g., methane).

### 9.1 Green monopropellant: AF-M315E / GPIM

* **Green Propellant Infusion Mission (GPIM):** NASA’s GPIM validated AF-M315E (a hydroxylammonium nitrate / ionic liquid monopropellant variant) in orbit as a less-toxic, higher-density, and higher-specific-impulse alternative to hydrazine, with advantages in ground handling and safety. NASA documentation describes GPIM mission rationale: AF-M315E is less toxic, allows for simpler ground processing, and yields performance advantages (higher density and Isp) compared to hydrazine monopropellants. The GPIM flight demonstrated ground handling, on-orbit operations, and improved safety.

### 9.2 LOX / Methane (LCH4) — cryogenic bipropellant

* **LOX/CH₄ as a greener option for ascent & upper stages:** NASA technical studies identify LOX/methane as an attractive "greener" rocket propellant compared with RP-1 in some contexts because methane combustion produces less soot/black carbon and can be produced in situ (ISRU) on planetary bodies; methane offers higher specific impulse than RP-1 and simpler engine cooling patterns than hydrogen. NASA has invested in methane engine technology and cryogenic fluid management research (LOX/LCH4 studies). NASA technical reports examine the advantages of LOX/CH₄ for future launch and in-space propulsion, including reduced particulate emissions.

### 9.3 Environmental considerations and emissions

* **Soot and stratospheric impacts:** Recent NASA-affiliated technical analysis discusses launch-emitted black carbon and the potential climate/stratospheric impacts of soot from hydrocarbon fuels (RP-1). Methane/LOX also emits CO₂ and H₂O but tends to produce less black carbon compared with kerosene, potentially reducing some stratospheric radiative forcing effects. NASA studies and reports highlight that the environmental footprint of different rocket fuels varies and is an active area of research.

### 9.4 Other propellant technologies: electric propulsion and ISRU-produced propellants

* **Electric (high-ISP) propulsion** is another path to reduce the mass of propellant required for long-duration orbital maneuvers (useful for upper stages or stationkeeping), and NASA invests in electric propulsion research.
* **ISRU (in-situ resource utilization)** research indicates methane is attractive when refueling from local resources is possible (e.g., Mars). NASA reports discuss methane’s advantages for long-term exploration architectures.

**Recommendation summary:** For reducing environmental impact of launches and ground operations, NASA’s flight demonstration of AF-M315E (GPIM) supports replacing toxic hydrazine for spacecraft maneuvering systems. For ascent/main-propulsion, LOX/methane offers an intermediate "greener" option relative to RP-1 (reduced soot, higher Isp) and has been studied extensively in NASA research. However, implementing LOX/methane in medium-lift operational launch vehicles involves cryogenic storage and infrastructure changes which NASA technical research outlines as engineering hurdles to adopt at scale.

## 10. Comparative techno-economic and environmental discussion (tradeoffs, implementation hurdles)

Implementing more durable/cheaper materials and greener propellants is not purely a materials selection exercise — it requires system-level engineering, supply chain maturity, manufacturing capability, and regulatory/operations adaptation. Key tradeoffs include:

* **Manufacturing maturity vs unit cost:** Advanced composites can reduce mass but may increase unit manufacturing cost unless large production volumes and automated manufacturing processes (AFP, OOA curing) are used. NASA documents emphasize the importance of manufacturing innovations to realize cost advantages.
* **Operational complexity:** Switching the Falcon 9 family (or another medium-lift vehicle) from RP-1/LOX to LOX/methane would imply changes in ground support (cryogenic handling), tank insulation, and potential changes in engine architecture. NASA’s LOX/CH₄ studies discuss both the performance and operational implications.
* **Safety and ground processing:** Replacing hydrazine with AF-M315E reduces toxicity and simplifies ground processing for spacecraft systems (demonstrated by GPIM), potentially lowering ground processing costs and hazard mitigation overhead.
* **Environmental metrics differ:** While methane reduces soot emissions relative to RP-1, methane combustion produces CO₂ and water vapor; overall climate impacts depend on injection altitude, frequency of launches, and soot production behavior — NASA research stresses the need for comprehensive environmental modeling.

## 11. Conclusions and recommendations

1. **Launch & reentry phases for Dragon:** The Dragon family follows well-defined phases from ground processing and propellant load through ignition, ascent, stage separation, orbital insertion, rendezvous, deorbit, reentry (PICA-X heat shield protecting the capsule), parachute descent, and splashdown. NASA publishes mission-specific launch day milestones and technical documentation for crewed launches — these provide authoritative timelines.
2. **Materials:** Dragon’s thermal protection relies on NASA-derived PICA technology (SpaceX’s PICA-X variant). Structural use of aluminum honeycomb cores with carbon fiber face sheets, aluminum-lithium alloys in tanks, and COPVs for pressurants are documented in NASA/SpaceX press kits and technical reports. These materials balance mass, strength, and thermal performance.
3. **Greener propellants:** NASA’s GPIM validated AF-M315E as a viable less-toxic monopropellant alternative to hydrazine for spacecraft maneuvering. NASA technical studies also support LOX/methane as a promising "greener" alternative to RP-1 for some future launch/upper-stage architectures, but adoption involves engineering and ground-infrastructure changes.
4. **Cheaper & more durable materials:** NASA research indicates aluminum-lithium alloys and modern composite/hybrid structures provide reduced mass and improved mechanical properties; however, costs depend strongly on manufacturing methods. To achieve both lower cost and improved durability at scale, investing in advanced manufacturing (friction-stir welding, AFP, OOA) and damage-tolerant composite designs is essential (NASA programs support these directions).

**Practical next steps (for an engineering program):**

* Use AF-M315E (or ASCENT) as a near-term swap for toxic monopropellant systems when interface compatibility is resolved (GPIM demonstrates feasibility).
* For vehicle primary structure redesigns aiming at cost reduction and durability, adopt a hybrid architecture: Al-Li for tanks/cryogenic primary structure (manufactured with friction-stir welding) and targeted use of carbon-fiber composites for mass-sensitive primary structure where inspection/repairability is engineered in.
* For stepwise reduction of the launch emissions footprint, plan research and demonstration flights with LOX/methane upper stages or engines (NASA LOX/LCH4 studies provide groundwork) while fully assessing ground-infrastructure cost tradeoffs.

## 12. References (NASA open sources and related NASA technical reports cited)

(major NASA sources used in this report — all are NASA open documents or NASA press materials)

* NASA: “NASA’s SpaceX Crew-10 Launch Day Milestones” (blog/launch milestones).
* NASA: “NASA astronauts launch from America in historic test flight of SpaceX Crew Dragon” (news release, Demo-2).
* NASA: “PICA heat shield technology used by SpaceX” (image/article on PICA / PICA-X).
* NASA: SpaceX/Commercial press kits and COTS mission press kit (Dragon technical/press kit PDFs describing composite sandwich structure, thermal protection, and mission hardware).
* NASA NTRS / technical reports on PICA / PICA-X and TPS (Thermal Protection Systems — various NTRS items).
* NASA: “Green Propellant Infusion Mission (GPIM)” overview (AF-M315E / green monopropellant) and GPIM technical documents.
* NASA technical reports on LOX/CH₄ (LCH4) propulsion research and cryogenic fluid management (NTRS/technical publications).
* NASA documents on aluminum-lithium alloys, composite materials, and manufacturing (NTRS and TechPort entries — Al-Li alloy benefits, friction-stir welding, composites research).
* NASA mission press kits and descriptive material on Dragon and Falcon 9 (e.g., CRS mission press kits, Commercial Crew press kit).