

H350-64 Rigid Airship Concept Study

Version 1.0 – Preliminary Design Review Baseline

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18. September 2026

Zusammenfassung

Version 1.0 friert den bisherigen H350-64-Vorentwurf als **interne Preliminary-Design-Review-Baseline** ein. Der Schwerpunkt verschiebt sich von zusätzlichen Einzelrechnungen auf Nachweisführung und Rückverfolgbarkeit: 65 Systemanforderungen, 34 Lastfälle, 22 FHA-Fehlerzustände, 30 FMEA-Einträge, zehn kontrollierte Interface-Control-Documents, 15 externe CFD/URANS-Fälle, zehn externe FEA-Fälle und 13 Hardware-/Fahrzeugtests werden gegen eine einheitliche 350-m-Konfiguration verwaltet. Die Designmasse bleibt **604,14 t**, davon **47,42 t** explizite Entwicklungsreserve. v1.0 ist ausdrücklich **kein Behörden-PDR, keine Zulassung und keine Baufreigabe**. Das Ergebnis ist ein bedingter interner PDR-Freeze: Requirements, Interfaces, Risiken und Verifikationspläne sind kontrolliert; Behördenabstimmung, High-Fidelity-CFD/FEA und kritische Hardwaretests bleiben offene Gate-Items.

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1 PDR-Zweck, Bewertungsmaßstab und Disposition

NASA beschreibt den Preliminary Design Review als den Punkt, an dem der vorläufige Entwurf die Systemanforderungen mit akzeptablem Risiko erfüllen und die Grundlage für die Detailkonstruktion bilden soll; Requirements, Interfaces, Verifikationsmethoden und Risiken müssen ausreichend definiert sein [6]. Für H350 wird dieses Prinzip als internes Engineering-Gate benutzt, nicht als Behördengenehmigung.

v1.0-Disposition: CONDITIONAL PDR BASELINE FREEZE. Die Baseline darf für Detailed-Design-Arbeiten verwendet werden. Nicht geschlossen sind (1) die mit der zuständigen Behörde abgestimmte Zertifizierungsbasis, (2) die externe High-Fidelity-CFD/FEA-Kampagne und (3) die kritischen Hardware-Sicherheitsversuche. Deshalb ist v1.0 weder ein formaler EASA/FAA-PDR-Pass noch ein Zertifizierungsnachweis.

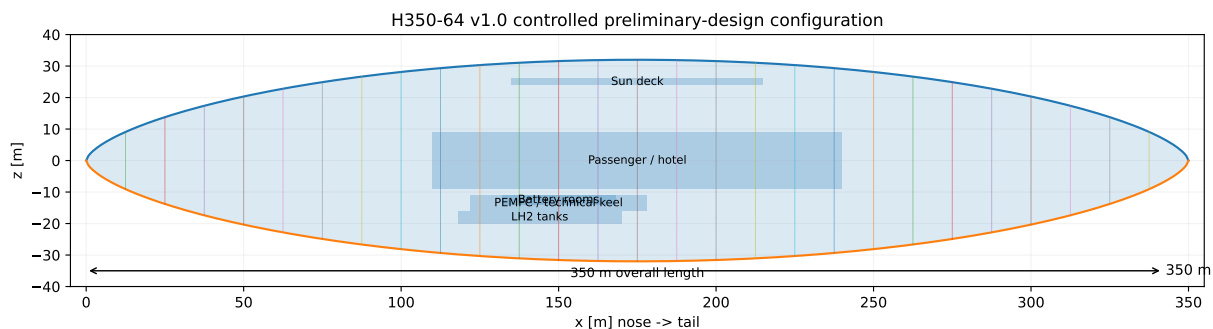


Abbildung 1: Kontrollierte H350-64-v1.0-Konfiguration.

2 Eingefrorene Systembaseline

Tabelle 1: H350-64 v1.0 Kernparameter.

Parameter	Freeze-Wert
Länge / Maximaldurchmesser	350 m / 64 m
Designmasse	604,14 t
Explizite Entwicklungsreserve	47,42 t
Schwerpunkt	x=174,99 m; z=-2,87 m
Primärstruktur	27 Ringe / 24 Longerons / 26 Sekundärhoops
Traggas	48 unabhängige Niederdruck-H ₂ -Zellen
Passagiere	60 Doppelkabinen / 120 Gäste / 10 Evakuierungskerne
Propulsion	8 × 0,75 MW elektrische Pods
PEMFC	7 × 0,75 MW = 5,25 MW installiert
Batterie	4 × 250 kWh LFP = 1,0 MWh nominal
HV	zwei segmentierte 1.500-VDC-Längsbusse
Brennstoff	2 × 4 t LH ₂

Die gemeinsame Geometriereferenz ist als parametrische JSON-Definition sowie als neutrale GLB- und STL-Geometrie freigegeben. Das Koordinatensystem ist verbindlich: Ursprung Bug-Mittellinie;

x zum Heck, y steuerbord positiv, z nach oben. Die Neutralform dient Konfigurationskontrolle und Solver-Handoff; sie ist kein produktionsreifes natives CAD-Modell.

3 Zertifizierungs- und Sicherheitsrahmen

EASA führt *SC GAS – Gas Airships, Issue 01* weiterhin als nicht superseded [1]. Die FAA Hydrogen-Fueled Aircraft Safety and Certification Roadmap von Dezember 2024 behandelt unter anderem Storage, Leaks, Ventilation, Fire/Explosion und Materials als zentrale Wasserstoff-Zertifizierungsthemen [2]. Für die System-Safety-Methodik wird FAA AC 25.1309-1B als aktueller Referenzrahmen herangezogen [3]; Composite-Strukturthemen stützen sich auf die weiterhin aktive AC 20-107B [4], Batterien auf AC 20-184 [5].

Diese Dokumente werden **nicht** als automatisch anwendbare endgültige Zertifizierungsbasis des H350 interpretiert. Die konkrete Basis und Means of Compliance müssen mit der zuständigen Behörde vereinbart werden. Genau deshalb bleibt REQ-CER-001 offen.

4 Requirements- und Compliance-Matrix

Jede v1.0-Anforderung besitzt ID, Fachgebiet, Verifikationsweg, Evidenzpfad, Status und Owner. Es gibt keine unzugeordneten offenen Anforderungen. Der Status bedeutet:

- **CLOSED_PDR**: für den internen PDR-Freeze ausreichend definiert und mit vorläufiger Evidenz geschlossen;
- **PARTIAL**: Design/Evidenz vorhanden, aber High-Fidelity-, Test- oder Behördenschritt offen;
- **OPEN**: erforderliche Substantiierung steht noch aus.

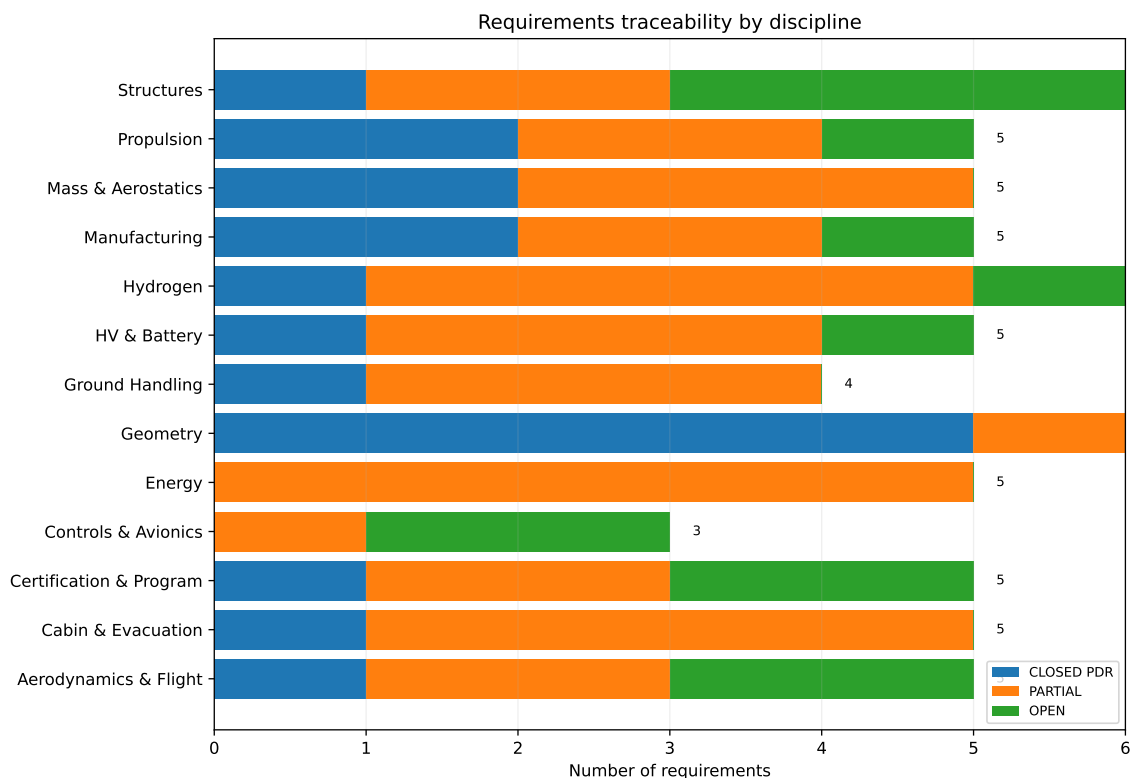


Abbildung 2: Requirements-Status nach Fachgebiet.

Tabelle 2: Requirements-Zusammenfassung.

Fachgebiet	Closed	Partial	Open	Gesamt
Aerodynamics & Flight	1	2	2	5
Cabin & Evacuation	1	4	0	5
Certification & Program	1	2	2	5
Controls & Avionics	0	1	2	3
Energy	0	5	0	5
Geometry	5	1	0	6
Ground Handling	1	3	0	4
HV & Battery	1	3	1	5
Hydrogen	1	4	1	6
Manufacturing	2	2	1	5
Mass & Aerostatics	2	3	0	5
Propulsion	2	2	1	5
Structures	1	2	3	6
Gesamt	18	34	13	65

5 Lastfallkatalog

Der Lastfallkatalog trennt bereits gescreente Fälle von extern zu rechnenden Fällen. Er umfasst Aerostatik, Flug, Böen, Propulsionsausfälle, Mooring, lokale Modul-/Strukturlasten, Wasserstoff, Batterie/HV, Thermal, Cabin Fire/Evacuation, Lightning/EME und Whole-Ship-Proof.

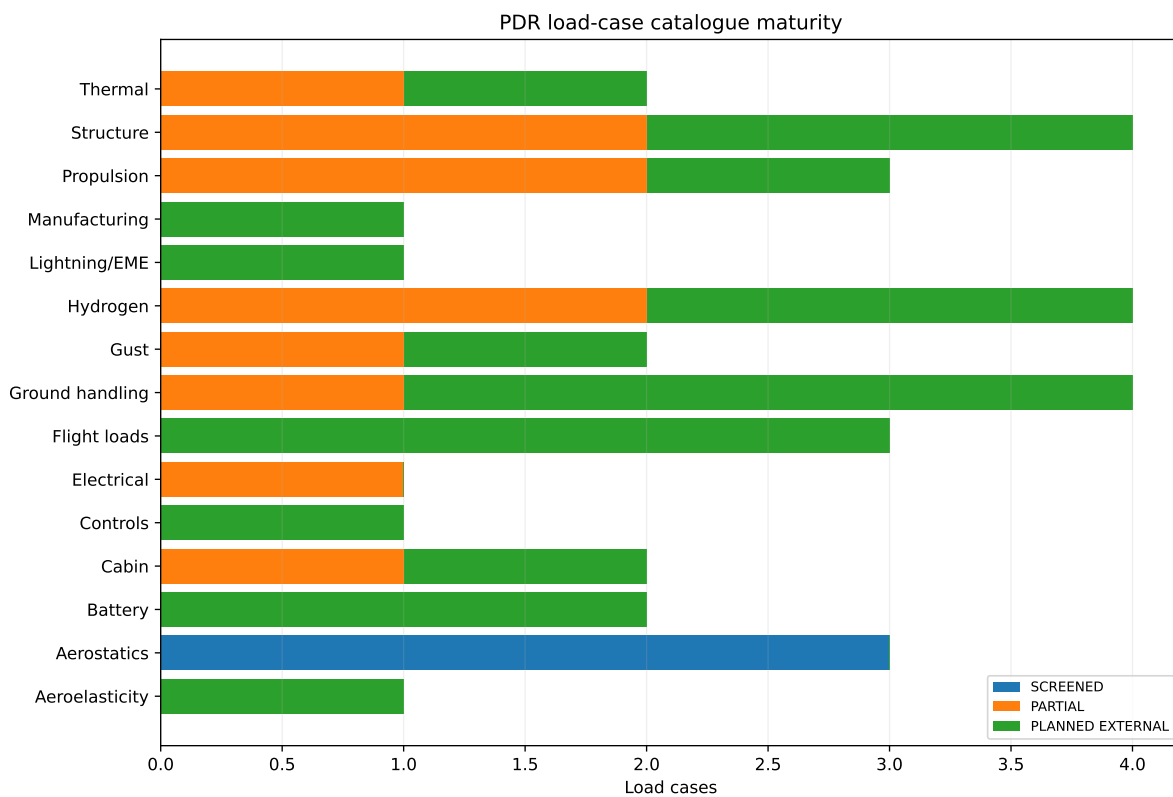


Abbildung 3: Reifegrad der 34 kontrollierten Lastfälle.

Besonders wichtig ist die Trennung von *Normalbetrieb* und *Abnormal-/Emergency-Fall* beim Ground Handling: 20 m/s bei ausgerichtetem Weather-Vaning ist ein normal zu substantiierender Grenzfall; 20

m/s broadside bei ausgefallenem Weather-Vaning wird als abnormaler Lastfall geführt und darf nicht stillschweigend zur normalen Terminalbetriebsannahme werden.

6 Preliminary FHA und FMEA

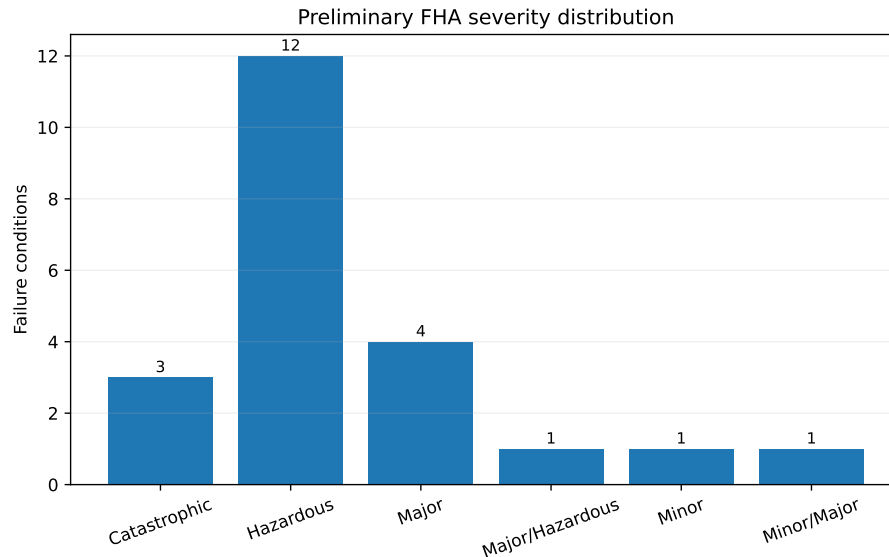


Abbildung 4: Verteilung der vorläufigen FHA-Schweregrade.

Die FHA-Klassifikationen sind **vorläufig** und dienen der Architektur-/Verifikationsplanung. Wahrscheinlichkeitsziele und endgültige Klassifizierung werden erst nach abgestimmter Zertifizierungsbasis festgeschrieben. Besonders hoch priorisiert bleiben: H₂-Zündung in Traggaszone, unzureichende LH₂-Reliefkapazität unter Fire Case, Common-Mode-HV/Propulsion-Verluste, Weather-Vane-/Mooring-Fehler, kritische Strukturknoten und Lightning/ESD-Pfade.

Die FMEA zerlegt diese Fahrzeugfehler auf Komponentenebene. Sie zeigt für jedes Element lokale und Fahrzeugwirkung, Detection und Design Control. v1.0 beansprucht noch keine SSA; die FMEA ist der Startpunkt für PSSA/SSA und das Hardware-Fehler-Injection-Programm.

7 Interface Control und Konfigurationsmanagement

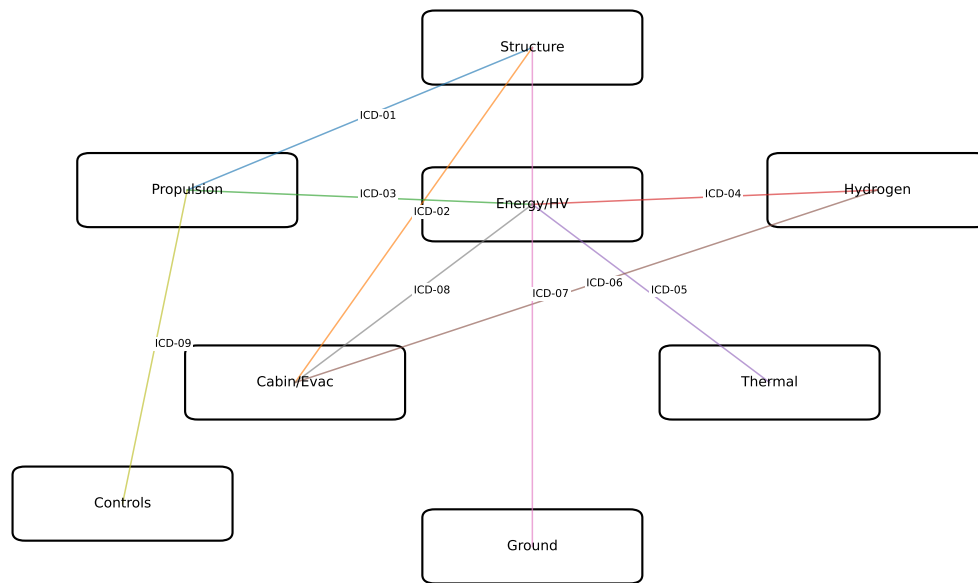


Abbildung 5: Kontrollierte Subsystem-Interfaces der v1.0-Baseline.

Zehn ICDs regeln Struktur/Propulsion, Struktur/Cabin, Energy/HV, LH₂/PEMFC, PEMFC/Thermal, H₂-Safety/Cabin, Ground Systems/Structure, Evacuation/Routing, Flight Controls/Propulsion-Tail sowie Configuration/All Systems. Jedes ICD besitzt Scope, kontrollierte Grenzwerte und Verifikationsweg. Änderungen an einem Freeze-Wert erfordern einen Requirements-/Safety-/Mass-/CG-/Interface-Impact-Check.

8 Externe CFD/URANS- und FEA-Kampagne

Verification campaign frozen at PDR - evidence still to be executed

CFD / URANS	FEA	Hardware tests
15 controlled cases	10 controlled cases	13 controlled cases
• Cruise / max speed • yaw & pitch derivatives • pod/hull/tail interaction • gusts / mooring / dispersion	• global shell/beam • mooring nonlinear • nose/pylon/hardpoint/tail • modal/aeroelastic / damage tolerance	• coupon -> element • subcomponent nodes/hardpoints • battery/HV/H2/thermal rigs • ground system -> whole ship -> flight

Abbildung 6: v1.0-Verifikationskampagne: geplant und kontrolliert, noch nicht ausgeführt.

Die Kampagne ist solver-ready, aber nicht als erledigte Evidenz verbucht. Für CFD/URANS werden 15 Cases definiert: Cruise/Max Speed, Yaw/Pitch-Derivatives, Pod-Hull-/Tail-Interaction, Control Deflections, Mooring-Wind, Gusts und H₂/Battery-Dispersion. Projektinterne Konvergenzkriterien verlangen bei zentralen stationären Fällen typischerweise maximal 2 % Änderung des Drag und 3 % der integrierten Momente zwischen den letzten beiden Meshstufen; unsteady Peak-Loads müssen bei Zeit-/Mesh-Verfeinerung innerhalb 5 % liegen. Diese Grenzen sind Projekt-Gates, keine gesetzlichen Werte.

Die zehn FEA-Cases decken Global Shell/Beam, nonlinear Mooring, Nose Capture, Gas-Cell/Panel, Pylon Root, Hardpoints, Tail Root, Evacuation-Cutouts, Modal/Aeroelastic und Damage Tolerance ab. Ein Case darf erst von PLANNED_EXTERNAL auf VERIFIED wechseln, wenn Inputdeck, Materialkarten, Meshstatistik, Konvergenzgeschichte und Postprocessing archiviert sind.

9 Hardware- und Fahrzeug-Testprogramm

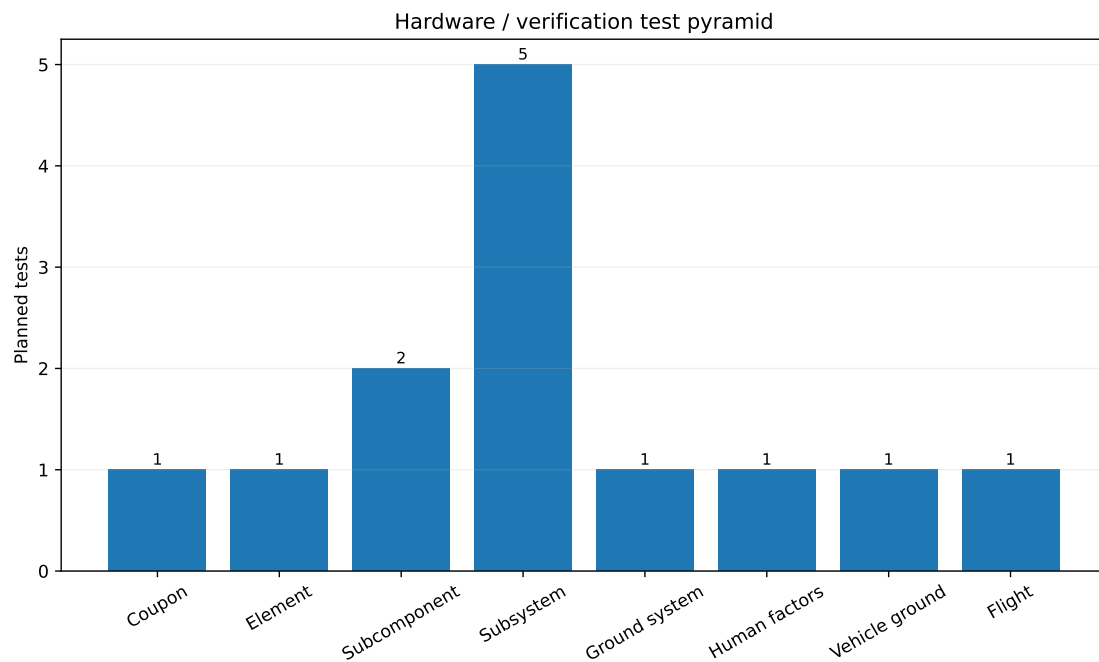


Abbildung 7: Testpyramide von Coupon bis Flight Test.

Die Testpyramide beginnt bei Composite-Coupons und Bond-/Bolted-Joint-Elementen, geht über Ring- und Longeronknoten in Originalgröße und Hardpoints zu Batterie-, HV-, LH₂-, H₂-Detection-, PEMFC-/Thermal- und Mooring-Rigs. Vor dem Erstflug ist ein Whole-Ship-Ground-Proof mit Struktur, Leak, Electrical, Geometry und Controls vorgesehen. Flight Tests sind ausdrücklich der letzte Buildup-Schritt und ersetzen keine Ground Qualification.

10 Risiko- und Open-Action-Register

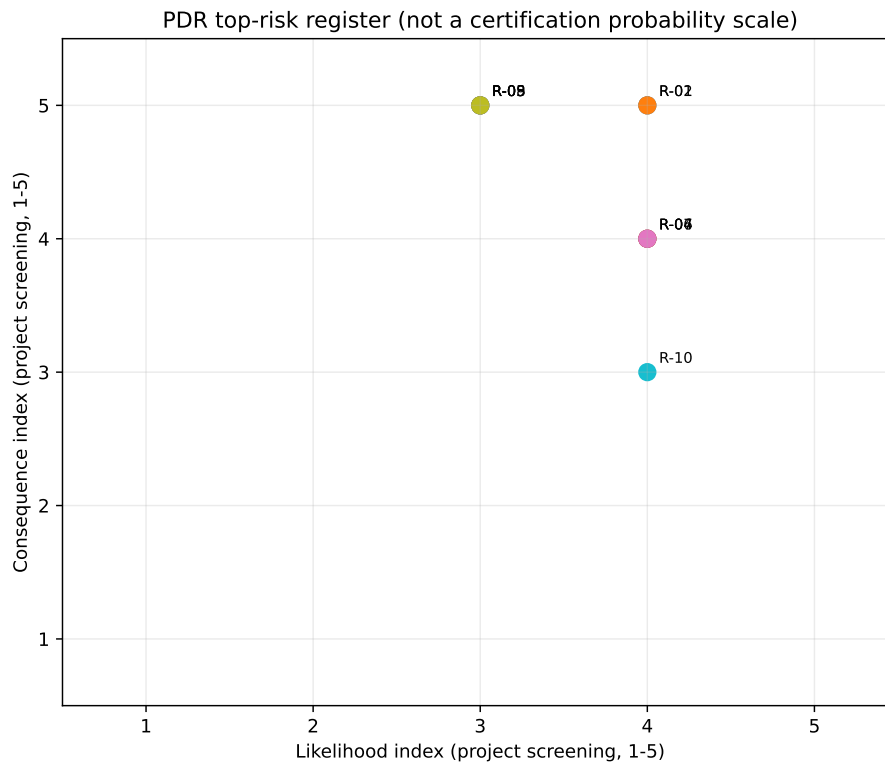


Abbildung 8: Top-Risiken. Die 1–5-Indizes sind internes Priorisierungs-screening, keine Zertifizierungs-Wahrscheinlichkeiten.

Die zehn Top-Risiken sind Ground Handling und Mooring, zweiphasige LH₂-Relief- und Fire-Loads, H₂-Leak und Ignition, Composite-Joints und Allowables, Battery Thermal Runaway, Hot-Day Thermal Rejection, Pod-Hull-Tail-Interaktion, Flight Control und Flexible Coupling, Evacuation/Human Factors und Industrialization. Alle besitzen Owner und konkrete Mitigation/Verification Paths.

11 PDR-Exit-Kriterien und nächster Gate

Die v1.0-Baseline erfüllt die internen Kriterien für Configuration, Traceability, Interfaces, Mass und CG, Reserve, Lastfälle, Preliminary Safety, Risk Ownership, Verification sowie Manufacturing. Drei Gate-Items bleiben bewusst offen: Behördenabstimmung der Zertifizierungsbasis, Ausführung der externen CFD- und FEA-Kampagne und kritische Hardware-Safety-Tests.

Damit lautet der technische Schluss: **Detailed Design darf auf dieser Baseline beginnen, aber kein Zertifizierungs-, Bau- oder CDR-Status darf daraus abgeleitet werden.** Der nächste Release soll ein Action-Closure-Stand sein, in dem externe Solverruns und erste kritische Rig-Tests echte Evidenz liefern.

A Vollständige Requirements-Matrix

ID	Fachgebiet	Anforderung	Verification	Status
REQ-GEO-001	Geometry	Overall length shall be 350 m.	Inspection	Closed
REQ-GEO-002	Geometry	Maximum hull diameter shall be 64 m.	Inspection	Closed
REQ-GEO-003	Geometry	Primary structure shall use 27 primary ring stations and 24 primary longerons.	Inspection	Closed
REQ-GEO-004	Geometry	Lift gas shall be segmented into 48 independent low-pressure cells.	Inspection	Closed
REQ-GEO-005	Geometry	Passenger baseline shall provide 60 double cabins for 120 guests.	Inspection	Closed
REQ-GEO-006	Geometry	Emergency egress architecture shall include 10 gas-free evacuation cores independent of the boarding lift.	Inspection + evacuation test	Partial
REQ-MAS-001	Mass & Aerostatics	Design mass shall not exceed 604.15 t at v1.0 freeze.	Analysis	Closed
REQ-MAS-002	Mass & Aerostatics	Explicit development reserve shall remain ≥ 40 t at PDR freeze.	Analysis	Closed
REQ-MAS-003	Mass & Aerostatics	Longitudinal CG shall remain within 174.5-175.5 m in the reference mission states.	Analysis	Partial
REQ-MAS-004	Mass & Aerostatics	The vehicle shall retain positive static buoyancy capability at the defined 50 C extreme-day screening condition.	Probabilistic analysis	Partial
REQ-MAS-005	Mass & Aerostatics	Routine operation shall not require lift-gas venting.	Analysis + demonstration	Partial
REQ-STR-001	Structures	Longeron baseline section shall be 500 x 280 x 4 mm CFRP with 20-ply symmetric / balanced laminate screening definition.	Analysis	Closed
REQ-STR-002	Structures	Primary structural sizing shall retain ≥ 1.5 screening margin for defined PDR load cases.	Analysis	Partial
REQ-STR-003	Structures	Composite design shall include damage tolerance, bonded-joint and manufacturing qualification evidence.	Test + analysis	Open
REQ-STR-004	Structures	Cabin / battery / fuel-cell mounts shall transfer load through dedicated Ti / CFRP hardpoints into ring / longeron nodes.	Analysis + test	Partial
REQ-STR-005	Structures	Mooring nose, pylon roots, tail roots and evacuation cutouts shall receive nonlinear shell / solid substantiation.	External FEA	Open
REQ-STR-006	Structures	First flexible modes shall be separated from flight-control and propulsor forcing bands by project-defined margins.	Modal FEA + GVT	Open
REQ-PRO-001	Propulsion	Propulsion shall use 8 independently controllable electric pods, 0.75 MW installed each.	Inspection	Closed
REQ-PRO-002	Propulsion	Reference propeller shall be approximately 10 m diameter / 6 blades.	Analysis	Closed
REQ-PRO-003	Propulsion	One-pod loss shall not produce an uncontrollable yaw transient.	6-DOF analysis + flight test	Partial
REQ-PRO-004	Propulsion	Installed propulsion shall provide ≥ 6 MW total shaft capability.	Inspection + bench test	Partial
REQ-PRO-005	Propulsion	Propeller / hull / tail interaction shall be substantiated with RANS / URANS and model / ground test correlation.	External CFD + test	Open
REQ-ENE-001	Energy	PEM fuel-cell installation shall provide 5.25 MW installed and ≥ 4.50 MW after loss of one module.	Inspection + bench test	Partial

ID	Fachgebiet	Anforderung	Verification	Status
REQ-ENE-002	Energy	Battery installation shall provide 1.0 MWh nominal energy and 4 MW short-time discharge capability.	Bench test	Partial
REQ-ENE-003	Energy	Loss / isolation of one battery subpack shall not collapse both HV buses.	FHA + HIL test	Partial
REQ-ENE-004	Energy	Thermal system shall reject reference continuous heat load with one cooling module unavailable.	Analysis + thermal rig	Partial
REQ-ENE-005	Energy	No single electrical fault shall disable all propulsors and all essential hotel / safety buses.	FHA / FMEA + HIL	Partial
REQ-HV-001	HV & Battery	Main HV distribution shall be nominal 1500 VDC with sectionalized protection.	Inspection	Closed
REQ-HV-002	HV & Battery	Prospective fault current shall be interrupted by coordinated primary protection before thermal damage propagates to adjacent zones.	Analysis + HIL	Partial
REQ-HV-003	HV & Battery	Battery thermal-runaway products shall be contained or vented through dedicated paths away from occupants and H2 vents.	Test + inspection	Partial
REQ-HV-004	HV & Battery	Maintenance of main HV buses shall use verified de-energized state and interlocked isolation.	Demonstration + procedure review	Partial
REQ-HV-005	HV & Battery	Partial-discharge, insulation coordination and altitude derating shall be validated for the 1500 V installation.	Test	Open
REQ-H2-001	Hydrogen	Lift hydrogen and fuel hydrogen systems shall remain physically and functionally separated.	Inspection	Closed
REQ-H2-002	Hydrogen	Fuel hydrogen shall be stored as two independently isolatable 4 t LH2 tank systems.	Inspection + tank qualification	Partial
REQ-H2-003	Hydrogen	Each LH2 tank shall have two independent 100 mm emergency relief risers plus normal BOG venting.	Analysis + test	Partial
REQ-H2-004	Hydrogen	Two-phase relief, fire exposure, backpressure and dispersion shall be substantiated before CDR.	External multiphysics + test	Open
REQ-H2-005	Hydrogen	Hydrogen detection shall cover tank, transition, technical-keel and vent-adjacent zones with fault monitoring.	Inspection + leak test	Partial
REQ-H2-006	Hydrogen	No normal vent outlet shall discharge into passenger, intake, battery vent or ignition-source zones.	Geometry inspection + dispersion	Partial
REQ-AER-001	Aerodynamics & Flight	Reference cruise speed shall be 80-100 km / h.	Analysis + flight test	Partial
REQ-AER-002	Aerodynamics & Flight	Maximum study speed shall not exceed 120 km / h before aeroelastic / CFD substantiation.	Analysis	Closed
REQ-AER-003	Aerodynamics & Flight	Three-fin trihedral tail shall provide positive static / dynamic directional and pitch stability over the operational envelope.	External CFD + 6-DOF + flight test	Open
REQ-AER-004	Aerodynamics & Flight	8 m / s lateral gust screening case shall remain controllable without loss of envelope.	6-DOF analysis	Partial
REQ-AER-005	Aerodynamics & Flight	CFD drag and stability derivatives shall demonstrate mesh / time-step independence to project convergence criteria.	External CFD	Open
REQ-GND-001	Ground Handling	Normal terminal operation shall use free / controlled weather-vaning rather than broadside restraint.	Analysis + demonstration	Partial

ID	Fachgebiet	Anforderung	Verification	Status
REQ-GND-002	Ground Handling	Mooring system shall tolerate the defined 20 m / s screening wind case without structural overload when weather-vaning is available.	Multibody + FEA + ground test	Partial
REQ-GND-003	Ground Handling	Broadside 20 m / s weather-vane-failure case shall be treated as an abnormal / emergency condition, not a normal design operating state.	Safety assessment	Closed
REQ-GND-004	Ground Handling	Mast, nose capture and trolley interfaces shall have defined load, travel, release and fail-safe limits.	ICD + rig test	Partial
REQ-CAB-001	Cabin & Evacuation	Boarding lift shall not be credited as the sole emergency egress path.	Inspection + evacuation test	Closed
REQ-CAB-002	Cabin & Evacuation	Evacuation architecture shall demonstrate acceptable egress time with representative blocked-exit cases.	Simulation + full-scale drill	Partial
REQ-CAB-003	Cabin & Evacuation	Passenger occupied zones shall be gas-tight separated from lifting / fuel H2 zones.	Inspection + leak test	Partial
REQ-CAB-004	Cabin & Evacuation	Fire / smoke zones shall prevent a single cabin / technical fire from disabling all egress paths.	FHA + smoke / fire test	Partial
REQ-CAB-005	Cabin & Evacuation	Sun deck shall be inhibited above project-defined relative-wind and operating-state limits.	Software / ops inspection + demonstration	Partial
REQ-CTL-001	Controls & Avionics	Flight-control architecture shall tolerate a single actuator or sensor failure without loss of controlled flight.	FHA + HIL + flight test	Open
REQ-CTL-002	Controls & Avionics	Lightning / ESD bonding shall provide continuous controlled current paths across composite structural joints and service zones.	Analysis + high-current test	Open
REQ-CTL-003	Controls & Avionics	Hydrogen and battery safety sensors shall be electrically segregated from single common-cause power loss.	FHA + inspection	Partial
REQ-MFG-001	Manufacturing	Primary rings shall be manufacturable as 24 controlled sectors with full material / process traceability.	Process qualification + inspection	Partial
REQ-MFG-002	Manufacturing	Final integration facility envelope shall accommodate 350 m vehicle, tooling and safe access.	Facility study	Partial
REQ-MFG-003	Manufacturing	Critical bonded joints shall have qualified processes, witness coupons and NDI acceptance criteria.	Process qualification + test	Open
REQ-MFG-004	Manufacturing	Configuration-controlled master geometry shall define common datums and controlled coordinates for all major systems.	Inspection	Closed
REQ-MFG-005	Manufacturing	Every released PDR artifact shall carry version, checksum and evidence mapping.	Inspection	Closed
REQ-CER-001	Certification & Program	Certification basis shall explicitly map H350 requirements against EASA SC GAS and agreed special conditions / means of compliance.	Authority review	Open
REQ-CER-002	Certification & Program	System safety process shall use FHA / PSSA / SSA progression and controlled assumptions.	Review	Partial
REQ-CER-003	Certification & Program	Hydrogen certification plan shall address storage, leak / ventilation, fire, materials and operations.	Review + authority coordination	Partial
REQ-CER-004	Certification & Program	PDR exit shall leave no unowned open requirement, interface or top risk.	Review	Closed

ID	Fachgebiet	Anforderung	Verification	Status
REQ-CER-005	Certification & Program	External CFD / FEA and hardware test evidence shall be completed before declaring detailed-design / qualification readiness.	Review	Open

B Open-Action-Register

Action	Quelle	Closure Action	Owner
ACT-001	REQ-STR-003	Composite design shall include damage tolerance, bonded-joint and manufacturing qualification evidence.	Structures
ACT-002	REQ-STR-005	Mooring nose, pylon roots, tail roots and evacuation cutouts shall receive nonlinear shell / solid substantiation.	Structures
ACT-003	REQ-STR-006	First flexible modes shall be separated from flight-control and propulsor forcing bands by project-defined margins.	Aeroelasticity
ACT-004	REQ-PRO-005	Propeller / hull / tail interaction shall be substantiated with RANS / URANS and model / ground test correlation.	Aerodynamics
ACT-005	REQ-HV-005	Partial-discharge, insulation coordination and altitude derating shall be validated for the 1500 V installation.	Electrical
ACT-006	REQ-H2-004	Two-phase relief, fire exposure, backpressure and dispersion shall be substantiated before CDR.	Hydrogen Safety
ACT-007	REQ-AER-003	Three-fin trihedral tail shall provide positive static / dynamic directional and pitch stability over the operational envelope.	Flight Dynamics
ACT-008	REQ-AER-005	CFD drag and stability derivatives shall demonstrate mesh / time-step independence to project convergence criteria.	Aerodynamics
ACT-009	REQ-CTL-001	Flight-control architecture shall tolerate a single actuator or sensor failure without loss of controlled flight.	Flight Controls
ACT-010	REQ-CTL-002	Lightning / ESD bonding shall provide continuous controlled current paths across composite structural joints and service zones.	EME
ACT-011	REQ-MFG-003	Critical bonded joints shall have qualified processes, witness coupons and NDI acceptance criteria.	Manufacturing
ACT-012	REQ-CER-001	Certification basis shall explicitly map H350 requirements against EASA SC GAS and agreed special conditions / means of compliance.	Certification
ACT-013	REQ-CER-005	External CFD / FEA and hardware test evidence shall be completed before declaring detailed-design / qualification readiness.	Chief Engineer
ACT-014	PDR-10	Certification basis agreed with authority	Chief Engineer / discipline lead
ACT-015	PDR-11	High-fidelity aero / structural evidence completed	Chief Engineer / discipline lead
ACT-016	PDR-12	Critical hardware safety tests completed	Chief Engineer / discipline lead

C Lastfallkatalog

Case	Domain	Phase	Beschreibung	Status
LC-001	Aerostatics	Ground	Reference ISA-like neutral buoyancy	Screened
LC-002	Aerostatics	Ground	Hot-day buoyancy	Screened
LC-003	Aerostatics	Ground	Extreme hot-day buoyancy	Screened

Case	Domain	Phase	Beschreibung	Status
LC-004	Flight loads	Cruise	Reference cruise	Planned ext.
LC-005	Flight loads	Cruise	Low cruise	Planned ext.
LC-006	Flight loads	Envelope	Maximum study speed	Planned ext.
LC-007	Gust	Flight	Lateral gust	Partial
LC-008	Gust	Flight	Vertical gust	Planned ext.
LC-009	Controls	Flight	Maximum tail control input	Planned ext.
LC-010	Propulsion	Flight	One pod failed	Partial
LC-011	Propulsion	Flight	Two non-adjacent pods unavailable	Planned ext.
LC-012	Propulsion	Ground	Maximum static thrust	Partial
LC-013	Ground handling	Mooring	20 m / s headwind aligned	Partial
LC-014	Ground handling	Mooring	20 m / s broadside emergency	Planned ext.
LC-015	Ground handling	Mooring	Mast release transient	Planned ext.
LC-016	Ground handling	Taxi / tow	Rear trolley asymmetric resistance	Planned ext.
LC-017	Structure	Ground	Local module downward inertial load	Partial
LC-018	Structure	Ground	Local module forward inertial load	Partial
LC-019	Structure	Flight	Gas-cell differential pressure envelope	Planned ext.
LC-020	Structure	Flight	Single lift-cell loss	Planned ext.
LC-021	Hydrogen	Ground / Flight	Normal LH2 BOG	Partial
LC-022	Hydrogen	Emergency	External heat input	Partial
LC-023	Hydrogen	Emergency	Fuel H2 leak	Planned ext.
LC-024	Hydrogen	Emergency	Lift H2 cell tear	Planned ext.
LC-025	Electrical	Ground / Flight	1500 V bus bolted fault	Partial
LC-026	Battery	Ground / Flight	Single subpack thermal runaway	Planned ext.
LC-027	Battery	Ground / Flight	Battery vent discharge	Planned ext.
LC-028	Thermal	Flight	One cooling module unavailable	Partial
LC-029	Thermal	Hot day	Maximum hot-day rejection	Planned ext.
LC-030	Cabin	Emergency	Blocked exit evacuation	Partial
LC-031	Cabin	Emergency	Passenger-zone smoke / fire	Planned ext.
LC-032	Lightning / EME	Flight / Ground	Lightning attachment / bonding	Planned ext.
LC-033	Aeroelasticity	Flight	Flexible-mode excitation	Planned ext.
LC-034	Manufacturing	Proof	Whole-ship ground proof	Planned ext.

D Preliminary FHA

ID	System	Failure Condition	Severity	Status
FHA-01	Flight control	Loss of commanded yaw / pitch control authority	Hazardous	Open
FHA-02	Propulsion	Loss of one propulsor	Major	Partial
FHA-03	Propulsion	Multiple common-bus propulsor loss	Hazardous	Open
FHA-04	Fuel cell	Loss of one PEMFC module	Minor / Major	Partial
FHA-05	Electrical	Main HV bus fault	Hazardous	Partial
FHA-06	Battery	Thermal runaway in one subpack	Hazardous	Open
FHA-07	Battery	Undetected battery venting into occupied zone	Hazardous	Open
FHA-08	Fuel H2	LH2 feed leak	Hazardous	Open
FHA-09	Fuel H2	Relief / vent path unavailable during heat input	Catastrophic	Open
FHA-10	Lift H2	Single gas-cell leak / tear	Major	Open
FHA-11	Lift H2	Ignition in lifting-gas zone	Catastrophic	Open
FHA-12	Thermal	Loss of one cooling module	Major	Partial
FHA-13	Thermal	Common coolant trunk failure	Hazardous	Open
FHA-14	Ground handling	Weather-vane mechanism jam	Hazardous	Open
FHA-15	Ground handling	Uncommanded mast release	Hazardous	Open
FHA-16	Structure	Critical ring / longeron node failure	Hazardous	Open
FHA-17	Structure	Cabin / battery hardpoint local failure	Major / Hazardous	Partial
FHA-18	Cabin	Fire / smoke blocks evacuation route	Hazardous	Open
FHA-19	Cabin	Boarding lift unavailable	Minor	Closed
FHA-20	Lightning / ESD	Bonding discontinuity near H2 zone	Catastrophic	Open
FHA-21	Avionics	Common erroneous air-data / state estimate	Hazardous	Open
FHA-22	Ballast	Trim-water transfer stuck / runaway	Major	Partial

E Preliminary FMEA

ID	Item	Failure Mode	Vehicle Effect	Status
FMEA-01	Propulsor pod	motor / inverter trip	yaw / thrust deficit	Partial
FMEA-02	Propulsor pod	vector actuator jam	control asymmetry	Open
FMEA-03	PEMFC module	module trip	reduced power margin	Partial
FMEA-04	PEMFC module	H2 internal leak	hazardous local H2	Open
FMEA-05	Battery subpack	contactor fails open	reduced peak support	Partial
FMEA-06	Battery subpack	contactor fails closed	fault propagation risk	Open
FMEA-07	Battery subpack	thermal runaway	fire / toxic / flammable hazard	Open
FMEA-08	HV bus	bolted short	loss of bus / fire risk	Partial
FMEA-09	HV bus	insulation / PD degradation	latent fire / EMI risk	Open
FMEA-10	Cooling module	fan / pump loss	thermal derate	Partial
FMEA-11	Cooling trunk	major leak	multi-module overtemp	Open
FMEA-12	LH2 tank	vacuum degradation	pressure / vent demand	Open
FMEA-13	LH2 feed	line rupture	fire / explosion hazard	Open

ID	Item	Failure Mode	Vehicle Effect	Status
FMEA-14	Vaporizer / regulator	stuck high flow	PEMFC / manifold upset	Open
FMEA-15	Relief riser	blocked	tank overpressure risk	Open
FMEA-16	Lift cell	membrane tear	trim / control upset	Open
FMEA-17	Gas detector	fails low	hazard escalation	Open
FMEA-18	Tail actuator	jam	control authority reduction	Open
FMEA-19	Flight-control computer	single lane loss	degraded control	Open
FMEA-20	Mooring mast	rotation jam	broadside load growth	Open
FMEA-21	Rear trolley	wheel / steer jam	yaw / load transient	Open
FMEA-22	Nose capture	lock release	ground excursion	Open
FMEA-23	Evacuation core	one portal blocked	longer evacuation	Partial
FMEA-24	Cabin fire zone	barrier breach	multiple-route impairment	Open
FMEA-25	Trim ballast	pump fail off	slow trim limitation	Partial
FMEA-26	Trim ballast	valve fail open	CG excursion	Open
FMEA-27	Ring-longeron node	bond / fastener degradation	structural redistribution	Open
FMEA-28	Cabin hardpoint	pin / clevis damage	local cabin support degradation	Partial
FMEA-29	Lightning bond	strap discontinuity	arcing near sensitive zone	Open
FMEA-30	Essential sensor bus	power common-mode loss	reduced hazard detection	Open

F ICD-Register

ICD	Interface	Kontrollierte Limits	Verification
ICD-01	Structure <-> Propulsion	x / y / z hardpoint datums; 0.75 MW / pod; 10 m prop clearance	Pylon FEA + installation survey
ICD-02	Structure <-> Cabin	4 hardpoints / module; no primary load into weather skin	Hardpoint rig + geometry inspection
ICD-03	Energy <-> HV	1500 V nominal; dual buses; 4 sections / bus	Power HIL + fault test
ICD-04	LH2 <-> PEMFC	2 x 32 mm LH2 feeds; 100 mm GH2 manifold	Cold-flow + leak / pressure test
ICD-05	PEMFC <-> Thermal	5 cooling modules; N+1 reference design	Thermal loop rig
ICD-06	H2 Safety <-> Cabin / Avionics	no shared H2 / battery vent; gas-free occupied cores	Leak / dispersion + zonal inspection
ICD-07	Ground Systems <-> Structure	weather-vane normal mode; broadside abnormal	Multibody / FEA + mooring rig
ICD-08	Evacuation <-> Systems Routing	>=2 m edge clearance project rule; 10 cores	3D clash + full-scale mockup
ICD-09	Flight Controls <-> Propulsion / Tail	8 pods + 3-fin tail; single-failure reallocation	HIL + 6-DOF + flight test
ICD-10	Configuration <-> All Systems	single v1.0 baseline manifest + SHA256	CM audit

G Top-Risk Register

ID	Risiko	L	S	Index	Owner
R-01	Ground handling / mooring loads	4	5	20	Ground Systems
R-02	Two-phase LH2 relief and fire exposure	4	5	20	Hydrogen
R-03	Hydrogen leak / ignition in large composite hull	3	5	15	Hydrogen Safety
R-04	Composite joints / allowables / damage tolerance	4	4	16	Structures
R-05	Battery thermal runaway containment	3	5	15	Battery Safety
R-06	Thermal rejection at hot-day / low-speed	4	4	16	Thermal
R-07	Pod / hull / tail aerodynamic interaction	4	4	16	Aerodynamics
R-08	Flight-control derivatives / flexible coupling	3	5	15	Flight Controls
R-09	Evacuation / fire human factors at 120 guests	3	5	15	Cabin Safety
R-10	Industrialization / 350 m assembly facility	4	3	12	Manufacturing

H CFD/URANS-Kampagne

Case	Solver	Zweck	Projekt-Gate
CFD-01	RANS	Reference cruise	last two mesh levels: drag $\leq 2\%$ change; integrated moments $\leq 3\%$
CFD-02	RANS	Low cruise	same convergence criteria
CFD-03	RANS	Max study	same convergence criteria; no unresolved separation sensitivity
CFD-04	RANS sweep	Yaw derivatives	fit residual $\leq 5\%$ over local derivative band
CFD-05	RANS sweep	Pitch derivatives	fit residual $\leq 5\%$ over local derivative band
CFD-06	MRF / actuator disk	Pod-hull interaction	thrust / power convergence $\leq 3\%$
CFD-07	MRF / actuator disk	Static thrust interaction	no unquantified recirculation at critical intakes / decks
CFD-08	RANS sweep	Tail control	moment convergence $\leq 3\%$
CFD-09	RANS	Mooring aligned wind	force convergence $\leq 3\%$
CFD-10	RANS	Single pod out asymmetry	stable numerical solution and mapped 6-DOF derivatives
URANS-01	URANS	Lateral gust	time-step refinement changes peak $\leq 5\%$
URANS-02	URANS	Vertical gust	time-step refinement changes peak $\leq 5\%$
URANS-03	URANS	Weather-vane transient	loads mapped to multibody model
CFD-11	RANS / dispersion	Fuel-H2 vent / leak	grid / domain sensitivity documented; keep-outs updated
CFD-12	RANS / dispersion	Battery vent release	no unmitigated occupied-zone accumulation in design case

I FEA-Kampagne

Case	Modell	Zweck	Projekt-Gate
FEA-01	Global shell / beam	Cruise distributed aero + buoyancy + mass	mesh-refined displacement $\leq 5\%$; forces $\leq 5\%$; project margins ≥ 1.5
FEA-02	Global nonlinear	20 m / s mooring emergency / broadside transient envelope	converged solution; no progressive instability before emergency limit
FEA-03	Local shell / solid	Nose capture / mooring fitting	no local project allowables exceedance; joint test correlation
FEA-04	Local shell / membrane	Gas-cell pressure / ring-longeron panel	buckling factor $\geq$ project gate after knockdowns
FEA-05	Local shell / solid	Propulsor pylon root max static / dynamic thrust	project margin ≥ 1.5 ; test-correlated
FEA-06	Local shell / solid	Cabin / battery / PEMFC hardpoint	project margin ≥ 1.5 incl. knockdowns; rig correlation
FEA-07	Local shell / solid	Tail root max control load	project margin ≥ 1.5 ; no local instability
FEA-08	Local shell / solid	Evacuation-core cutout	margin ≥ 1.5 ; geometry updated if not
FEA-09	Modal / aeroelastic	Whole vehicle modes	mode / control / prop forcing separation documented; GVT correlation plan
FEA-10	Damage tolerance	Representative impact / delam at node / longeron	residual strength criteria to be authority-agreed

J Hardware-Testprogramm

Test	Level	Artikel	Zweck	Gate
TEST-01	Coupon	CFRP laminate coupons	B-basis / hot-wet / static / fatigue material allowables	Before CDR
TEST-02	Element	Bonded / bolted CFRP joint elements	bearing / net / shear-out / bond defect sensitivity	Before CDR
TEST-03	Subcomponent	Full-size ring-longeron node	multi-axial node strength / buckling / damage tolerance	Before CDR
TEST-04	Subcomponent	Cabin / battery / PEMFC hardpoint rig	pin / lug / bearing / bond load path	Before CDR
TEST-05	Subsystem	250 kWh battery compartment representative	thermal runaway containment / propagation / venting	Before CDR
TEST-06	Subsystem	1500 V dual-bus HIL rig	fault detection / sectionalization / 3 ms trip logic	Before CDR
TEST-07	Subsystem	LH2 tank / valve / vent cold-flow rig	normal BOG and emergency relief behavior	Before CDR
TEST-08	Subsystem	Hydrogen leak / detection / ventilation rig	detector coverage, ventilation and dispersion	Before CDR
TEST-09	Subsystem	PEMFC + radiator module thermal rig	N+1 heat rejection / derate logic	Before CDR
TEST-10	Ground system	Nose mast + trolley dynamic rig	capture / release / weather-vane / jam cases	Before CDR
TEST-11	Human factors	Full-scale evacuation / smoke mockup	120-guest blocked-exit / fire-zone drills	Before certification design freeze
TEST-12	Vehicle ground	Whole-ship structural / systems proof	distributed proof, leak, electrical, geometry and controls checks	Before first flight
TEST-13	Flight	Envelope expansion vehicle	handling, engine-out, gust, thermal, power and H2 behavior	Flight test

K PDR-Exit-Kriterien

Gate	Kriterium	Status	Evidenz
PDR-01	Configuration baseline uniquely identified	MET	v1.0 manifest + master geometry
PDR-02	Requirements traceable to verification method / owner	MET	requirements_v10.csv
PDR-03	Major subsystem interfaces controlled	MET	10 ICDs
PDR-04	Mass / CG / reserve baseline closed for preliminary design	MET	604.14 t; 47.42 t reserve
PDR-05	Preliminary load-case catalogue established	MET	34 load cases
PDR-06	Preliminary FHA / FMEA completed	MET	22 FHA + 30 FMEA rows
PDR-07	Top technical risks identified with owners / mitigations	MET	10-risk register
PDR-08	Verification program defined	MET	CFD / FEA + 13 hardware tests
PDR-09	Manufacturing / assembly concept exists	MET	v0.9 modular assembly baseline
PDR-10	Certification basis agreed with authority	Open	EASA SC GAS referenced; authority agreement not obtained
PDR-11	High-fidelity aero / structural evidence completed	Open	external CFD / FEA campaign planned, not executed
PDR-12	Critical hardware safety tests completed	Open	test program defined, not executed

L Reproduzierbare Artefakte

Die vollständige Datenbasis liegt als CSV/JSON/Markdown im Rechenpaket. Die kontrollierten Kerngruppen sind: Requirements/Loads/Safety (requirements_v10.csv, load_cases_v10.csv, fha_v10.csv, fmea_v10.csv), Interfaces/Risks/Actions (icd_register_v10.csv, risk_register_v10.csv, open_actions_v10.csv), Verification (cfid_campaign_v10.csv, fea_campaign_v10.csv, hardware_test_program_v10.csv) sowie Geometry/Campaign-Manifests (master_geometry_definition_v10.json, analysis_campaign_manifest_v10.json). Das A3-Masterblatt wird separat ausgeliefert.

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