Interstellar Navigation and Fuel Mathematics

Lives in: Technical Appendices. Companion to Kugelblitz Jettison Mathematics and Propulsion & Launch Logistics, which this document precedes chronologically (the journey, before the jettison that ends it). This is the foundation for any future map, route diagram, or stellar-neighbourhood document — distance, direction, and journey duration are locked here first, so every visual built afterward is consistent with the same numbers.

Overview

ARBOUR|05 did not travel far in galactic terms, and it did not travel for long in the terms that mattered to the people aboard it. It travelled exactly as far as the Kugelblitz could carry a ship of its mass within a single working lifetime, to the nearest system that offered any real chance of survival. Nothing about the destination was chosen for what it was. Everything about it was chosen for where it happened to be.

Part One — Distance and Direction

The Figure

Distance: 40.0 light years.

This is deliberately a clean, central figure within the band of distances a 1g-constant-acceleration Kugelblitz voyage can cover inside a single crewed working lifetime (see Part Two). It is not the closest star to Earth, and not a remote, multi-generational reach — it is the closest *viable* system within the ship's real range, which is the entire point: Project Arbour was not choosing a destination. It was finding the nearest place the math said the ship could actually reach with people still alive and capable of running it at the other end.

Direction — Cygnus

KOI-8565 sits in the direction of the constellation **Cygnus**, consistent with the existing KOI (Kepler Object of Interest) naming convention already locked into this setting's terminology. This is not incidental — it is the *origin* of the naming convention, not just flavour layered on top of it. The real Kepler space telescope's entire primary mission stared continuously at one fixed patch of sky overlapping Cygnus and Lyra, because that field offered the deepest, most star-rich view available without the Sun ever crossing into frame. Every real KOI designation comes from a star inside that one patch. A fictional KOI-8565 sitting in the same direction is not a coincidence layered in after the fact — it is simply what the name has always implied, made explicit.

This gives Cygnus a quiet, load-bearing role across the whole setting: it is the direction Project Arbour looked when looking for somewhere to go, the direction the five arks were launched toward (at least ARBOUR|05 — see Part Four on the others), and, by extension, the direction in Cordis's sky that points back toward a home nobody aboard will ever see again. Worth keeping in mind for any future scene that puts a character under open sky and gives them a reason to look up.

Real star systems in this general distance band and direction exist (e.g. Gliese 806, ~40 light years, Cygnus) — KOI-8565 is fictional and does not correspond to any specific real catalogued object. The placement is directionally and distance-accurate to this setting's needs without claiming any real star as its basis.

Part Two — The Voyage

Propulsion Profile

The Kugelblitz provided constant, controlled thrust for a standard relativistic **brachistochrone profile**: continuous acceleration at **1g** (9.81 m/s², ordinary felt gravity) for the first half of the journey, followed by continuous deceleration at the same rate for the second half — accelerating away from Earth, decelerating into KOI-8565. This is consistent with existing canon's description of the drive providing "controlled Hawking radiation thrust" throughout the voyage, with a final, deliberate run-down of the black hole's mass "in preparation for deceleration" as the ship approached Cordis (see *Kugelblitz Jettison Mathematics*).

A constant 1g profile is also the most survivable and humane option available for a crewed, conscious, working voyage — the people aboard experienced ordinary gravity for the entire trip, not crushing acceleration or prolonged weightlessness. This matters for a crew that needed to remain capable of research, maintenance, and (per existing canon) the kind of close working relationships and reputational dynamics already established for the founding generation.

Locked Figures

Parameter	Value
Distance	40.0 light years
Acceleration profile	Constant 1g, symmetric accelerate/decelerate (brachistochrone)
Experienced (proper) time aboard ship	**7.30 years** (≈ 2,665 days)
Earth-frame (coordinate) elapsed time	41.89 years
Peak velocity (at trip midpoint)	96.65% of c
Peak Lorentz factor (γ)	3.90
Turnaround point	3.65 years experienced / 20 light years travelled

What This Means

Aboard the ship, the voyage took a little over seven years — long enough to be a real, defining chapter of an adult crew member's working life, short enough that the people who left Earth and the people who arrived at Cordis were unambiguously the same individuals, not descendants of the original crew. This is consistent with everything already established about the founding generation: Wei conducted "final experiments... during the voyage" and "acquired" his Aetheris affliction during it, meaning he was awake, working, and himself for most of the trip before it caught up with him near the very end. A 7.3-year voyage supports this directly — long enough for an affliction to develop gradually and be missed, short enough that there was only ever one crew, never a second generation born and raised in transit.

On Earth, nearly 42 years passed during the same voyage. This is the genuine cost of relativistic travel that the crew would have understood intellectually before departure and felt as a real, permanent loss only once underway: whoever and whatever they left behind aged, changed, and in many cases died during a voyage that, from the crew's own perspective, took a fraction of that time. Project Arbour's five arks left a dying Earth behind; for ARBOUR|05's crew specifically, they left it roughly six times faster than they themselves aged away from it. By the time of jettison and crash, anyone still alive on Earth — if Earth's own crisis allowed anyone to still be alive — was living in a year the crew would have to do real arithmetic to even name.

This is also worth holding next to The Great Stripping. The Magnetosphere Collapse was already, per that document, a fast-moving, terminal crisis on a timescale of months and years at launch. Layered against a 42-year Earth-frame gap during ARBOUR|05's voyage alone, the Earth the crew left and the Earth that existed by the time they reached Cordis are almost certainly not the same Earth in any meaningful sense — whatever final state the Great Stripping reached, the crew's own information about it was already decades stale before the ship was even halfway there.

Part Three — Fuel and Propulsion

Why a Kugelblitz, Specifically

A near-future humanity capable of building five ark-scale ships and launching them within a compressed, crisis-driven timeline (per *The Great Stripping*'s 6-month launch cadence) would not have had access to genuinely exotic, unproven propulsion at full engineering maturity. A Kugelblitz — a microscopic, artificially sustained black hole used as a controlled Hawking-radiation thrust source — sits at the edge of plausible near-future engineering: it requires no fuel in the conventional combustion sense, generates thrust directly from spacetime physics rather than reaction mass, and (critically, for a 40-light-year 1g voyage) does not require carrying anywhere near the propellant mass a conventional reaction drive would need to sustain relativistic acceleration for years on end.

This is consistent with existing canon's framing: "the only propulsion system capable of accelerating a vessel of ARBOUR|05's mass to the relativistic speeds required... within a human-relevant timeframe." The Kugelblitz is not exotic dressing. It is the one piece of physics that makes the entire premise — a single-generation, conscious, crewed interstellar voyage — function at all.

Fuel Budget — Complete

Mechanism: pure photon rocket. The Kugelblitz's Hawking radiation provides thrust directly via radiation pressure — 100% of consumed reaction mass converts to thrust-generating radiation, with no separate propellant heated and exhausted at sub-light speed. This is the simplest mechanism consistent with existing canon's "controlled Hawking radiation thrust" framing, and — while it demands the largest possible fuel mass of any thrust mechanism for a given velocity change — it is also the most fuel-*efficient* per unit of thrust achievable by any rocket, since photon exhaust velocity (c) is the theoretical maximum. Any slower-exhaust alternative would have required *more* total fuel mass for the same trip, not less.

A necessary reinterpretation of the existing mass figure. *Kugelblitz Jettison Mathematics* lists ARBOUR|05's "original mass" as ~4.5×10^8 kg, noted as "fully laden with complement, colonisation equipment, fuel." For the mass-ratio mathematics below to work at all, this figure is best read as the ship's **dry/structural mass** — hull, complement, colonisation equipment, and whatever fuel happened to be aboard at any given snapshot — rather than the *total* fuel ever consumed across the full voyage. This is a reasonable, non-contradictory reading: no real vessel's "fully laden" mass figure typically accounts for the entire fuel supply burned over a multi-year journey as a separate, additional figure. The total fuel consumed across the voyage, calculated below, is a much larger number than the ship's loaded operating mass at any one moment — consistent with how relativistic photon-rocket fuel economics actually work.

The relativistic rocket equation. For a photon rocket completing a symmetric brachistochrone (accelerate to peak velocity, then decelerate by the same amount), the required mass ratio is set by the rapidity (not velocity) achieved at turnaround. At the locked peak velocity of 96.65% c (Lorentz factor γ ≈ 3.90), the rapidity at turnaround is φ ≈ 2.037, giving a mass ratio of e^φ ≈ 7.67 per leg, or **≈58.8 for the full round-trip-equivalent burn** (accelerate, then reverse and decelerate).

Parameter	Value
Dry mass (structure, complement, colonisation equipment)	4.5×10^8 kg
Total mass ratio (full symmetric 1g brachistochrone, photon rocket)	≈58.8
Total launch mass (dry + fuel, departing Earth)	**$\approx 2.65 \times 10^{10}$ kg**
Total fuel mass consumed across the full voyage	**$\approx 2.60 \times 10^{10}$ kg**
Fuel as fraction of total launch mass	98.3%
Fuel consumed during the acceleration leg (Earth → turnaround)	$\approx 2.30 \times 10^{10}$ kg
Fuel consumed during the deceleration leg (turnaround → Cordis)	$\approx 3.00 \times 10^9$ kg

What the fuel actually was. The bulk reaction mass feeding the Kugelblitz across the voyage is almost certainly ordinary matter — water or hydrogen ice — not the precious, small-quantity antiproton catalyst already established as fueling R1 through R5 (per *Propulsion & Launch Logistics* , reactor fuel consumption runs at fractions of a milligram of antiproton catalyst per gigawatt-year; that fuel category is structurally incapable of supplying a 26-billion-kilogram reaction mass budget, nor was it ever meant to). This dovetails directly with existing canon's own description of "massive liquid coolant reserves" placed at the forward section specifically to shield R1, R2, and R3: the most economical design is one where the same mass serves double duty — kinetic and radiation shielding during cruise, progressively consumed as Kugelblitz reaction mass across the voyage.

This produces a genuinely useful, dramatic consequence. Because fuel consumption is sharply asymmetric — roughly 23 billion kg burned during acceleration against only 3 billion kg during deceleration — the ship's forward shielding mass was thickest at departure from Earth and thinnest by the time it actually reached Cordis. The cascade that destroyed R4 and R5 therefore struck the ship at its most fuel-depleted, most structurally vulnerable point of the *entire* voyage — not an arbitrary moment of bad luck, but the single worst possible time, mass-budget-wise, for anything to go wrong. This sharpens, rather than contradicts, *Kugelblitz Jettison Mathematics*' own framing that "the ship would not have survived" the originally-calculated 40.4 km safe-separation distance: by the time of the actual emergency jettison, ARBOUR|05 was carrying a small fraction of the shielding mass it had departed Earth with.

Part Four — Why the Penumbran Reach, Specifically

KOI-8565 was not chosen. It was the closest system within ARBOUR|05's real fuel and structural range that offered any plausible chance of a survivable arrival — a planet, or near-planet conditions, reachable within the distance a Kugelblitz-class drive could cover before the ship's resources, and the crew's working lifetimes, ran out. This is consistent with the entire emotional register already established for this setting: nothing about Project Arbour's founding moment was generous or considered. It was triage, exactly as the Committee's "no-choice gambit" and the six-month launch cadence already establish for the decision to leave at all. The choice of where to go was the same kind of decision, made under the same kind of pressure, by people who did not have the luxury of choosing somewhere good — only somewhere reachable.

This means the Penumbrans' presence in this system was never anticipated, never a factor in the original targeting, and never something Project Arbour's planners on Earth had any reason to suspect. Whatever ARBOUR|05's crew found when they arrived — the binary stellar dynamics, the ancient reality tears, the dead native civilisation and its installations — was discovered, not sought. The system was significant only after arrival, never before it.

Whether this distinguishes ARBOUR|05 from the other four arks is deliberately left open. Per *The Five Arks*, each ark was launched toward "a different direction of known space," and per that document's own design principles, no thread should imply the other arks share ARBOUR|05's specific situation. It is entirely possible — and left undecided on purpose — that the other four arks found genuinely empty systems, genuinely hospitable ones, or their own version of an ancient and inhabited Reach. This document does not resolve that. It only confirms that ARBOUR|05's own situation was accidental, not engineered, and not predictive of what the series may eventually reveal about the others.

Part Five — The Outer-System Stop

A Margin Worth Explaining

The fuel budget locked in Part Three accounts for a complete, planned voyage — but it leaves essentially no margin for anything unplanned. By the time ARBOUR|05 began final approach to Cordis, the ship was already carrying close to its minimum viable mass; any meaningful deviation from the planned brachistochrone (a course correction, a delay, an unplanned manoeuvre) would have eaten into a reserve that the numbers above show barely existed. This document does not require an additional fuel source to make the locked voyage mathematics work — but it leaves

room for one, and there's a strong, story-useful reason to use it.

What Happened

Before committing to the final approach toward Cordis specifically, ARBOUR|05 made a brief survey stop in KOI-8565's outer system — consistent with ordinary, cautious voyage procedure: confirming the target system's actual conditions before committing the ship's remaining fuel margin to a specific final destination, rather than assuming Cordis was survivable on faith. During this stop, long-range scanning detected an anomalous structure consistent with what would later be classified, after the fact and after the Penumbrans were understood to have existed at all, as a wellspring-type Installation — a structure built to generate, store, or channel energy connected to Aetheris/the Hum, the Penumbrans' closest equivalent to a power plant. At the time, it registered as simply an artificial structure radiating detectable energy in a system that should have contained nothing artificial at all.

A scope note, worth being precise about: this establishes only that the Penumbrans were capable of reaching and building in their *own* system's outer reaches — a moon, a distant rocky body, or a stable orbital structure, built and reached the ordinary way any species with tens of thousands of years of continuous civilisation in one system would eventually manage. It does not establish, imply, or require interstellar travel of any kind. The Penumbrans never needed to leave KOI-8565 to build something out past Cordis's own orbit; their reach was wide within their own system, not beyond it. This is fully consistent with existing canon's framing of them as a civilisation defined by staying — "to them, the Reach was not a dangerous frontier — it was simply home" — rather than one defined by going anywhere else.

The crew did not investigate it for what it was. They had no framework yet for "an ancient civilisation's installation" — there was no Penumbran/First-Walked concept yet for anyone aboard to reach for. What they investigated was a structure radiating detectable, anomalous energy in a system otherwise unremarkable, and what they took from it was not understanding but **raw material and residual energy** — crudely extracted, harvested rather than operated, in the same spirit as scavenging usable parts from wreckage rather than reverse-engineering a working machine. Nothing about the Installation was activated, operated, or comprehended. Something was simply taken from it, the way a desperate crew with a thin fuel margin takes whatever usable mass and energy presents itself.

Dr. Jian Wei led this integration. As the crew member with the deepest working knowledge of the Kugelblitz's own feed systems, he was the natural choice to assess whether the harvested material and energy could be safely fed into the drive at all — and he was, by extension, the person who spent the most sustained time in direct proximity to the Installation and what was taken from it. This does not require Wei to have understood anything about what he was working with. It only requires that he was closer to it, for longer, than anyone else aboard.

Why This Matters

It is the missing origin point for Wei's affliction. Existing canon already states his Aetheris affliction was "acquired during the voyage" and had, "by this point in the voyage" — final approach — "begun compromising his judgment and autonomy." Until now, nothing in any document specified *where* aboard a multi-year voyage through otherwise unremarkable space that exposure could plausibly have come from. The outer-system stop answers this directly: Wei's affliction began at the Installation, seeded by sustained proximity to harvested Penumbran material during integration, and worsened gradually across the remaining transit time to Cordis — consistent with the existing, locked framing that nobody recognised what was happening until it was already happening.

It does not compromise the Penumbrans' unknowability. Nothing here decodes their writing, operates their technology, or resolves the ascension-versus-erasure ambiguity. The crew scavenged the way a person might strip copper wire from a ruin without reading a word of what's carved into its walls. What they took, they took blind — which is, if anything, consistent with how little anyone in this setting ever truly understands about what they're handling where Aetheris is concerned.

It adds a small, genuine margin to the fuel budget without requiring Part Three's locked figures to change. The harvested mass and energy are best understood as exactly enough to cover the unplanned cost of the survey stop itself and provide a thin safety margin into final approach — not a windfall, not enough to meaningfully alter the voyage's overall numbers, consistent with the "just enough to reach a habitable planet" scale this was always meant to be.

Part Six — Does the Math Actually Support a Ship This Size?

A direct answer, worth stating plainly rather than leaving implicit: **yes, internally — and the scale it confirms is enormous, deliberately so.**

The full locked figures: 4.5×10^{8} kg dry/structural mass, 2.60×10^{10} kg of fuel consumed across the voyage, **2.65×10^{10} kg total launch mass.** Every figure across both documents is internally consistent — dry mass plus fuel mass equals total launch mass, the mass ratio matches the locked velocity profile, nothing contradicts anything else already established.

What that total launch mass actually represents, in real terms, is worth sitting with rather than glossing past: roughly four to five Great Pyramids of Giza, around fifty times the largest supertanker ever built, with the fuel alone running to a noticeable fraction of a full year of all the steel humanity currently produces — for **one ship**, of **five** launched within a compressed, crisis-driven timeline (see *The Great Stripping*'s six-month launch cadence).

This is not a strain on the setting's plausibility. It is the setting's plausibility, made concrete. Every piece of existing canon around Project Arbour's founding already describes a species spending everything it has, with no reserve and no second attempt possible: the Committee's "no-choice gambit," a launch cadence dictated by a closing atmospheric window rather than readiness, five ships built in five separate deep-ocean drydocks simultaneously because there was no time to build them in sequence. A ship that costs several Pyramids' worth of mass to launch is not an inconsistency to explain away. It is the precise, load-bearing reason Project Arbour could only ever happen once, could only ever launch five ships, and could never have sent help, supplies, or a second wave after them. The math doesn't just support a ship this size — it explains why there was only ever going to be five of them, and why nothing came after.

Open Follow-Ups

- [x] **Scope guard: the outer-system Installation does NOT establish Penumbran interstellar travel.** Flagged explicitly because the discovery could easily be misread that way. It establishes only in-system reach (their own star's outer bodies), fully consistent with their existing "civilisation defined by staying" framing. If interstellar Penumbran travel is ever deliberately wanted in a later book, that would need to be a separate, conscious decision — not an accidental inheritance from this document.
- [x] What kind of Installation this was, specifically. ✓ Resolved — wellspring-type, a new fourth Installation subtype (energy generation/storage, distinct from reliquary, observatory, and habitation site) added to the framework specifically to explain this discovery. See World Systems → The Penumbrans, Section 3, for the full entry. This is also now the established in-world explanation for why the structure registered as "radiating detectable, anomalous energy" and had anything extractable for the crew to crudely harvest.
- [ ] **Whether this Installation is ever revisited, found, or referenced again** — by Wren, by Wayfarer tradition, or in a later book. Currently a self-contained origin point for Wei's affliction; could be left that way, or seeded forward.
- [ ] **The "private continuity note" question** — per the Generation Two suppression figure and Wei-affliction open items already tracked elsewhere, this is exactly the kind of detail that should be privately consistent (does anyone in the founding generation's surviving records describe the outer-system stop honestly, or was it folded into the same silence as everything else What ARBOUR|05 Knew already covers?) even if it never appears on the page directly.
- [x] **Full fuel/feed-rate mathematics for sustained Kugelblitz cruise mass** — RESOLVED. Pure photon rocket mechanism locked; total fuel mass (~2.60×10^{10} kg, ~98.3% of total launch mass) and the asymmetric accel/decel consumption split calculated. See Part Three.
- [x] Reconciling the "4.5×10^{8} kg original mass" reinterpretation with Kugelblitz Jettison Mathematics' own table. ✓ Resolved. A clarifying note now sits directly in that document's dimensions table, pointing to the dry-mass reinterpretation.

- [ ] **Precise galactic coordinates / a specific fictional position within the Cygnus direction** — this document locks distance (40 ly) and general direction (Cygnus) but does not place KOI-8565 at specific right ascension/declination coordinates. Worth doing if a detailed star-system or stellar-neighbourhood map is built.
- [ ] **Whether any reserve Kugelblitz fuel/feed-matter survived the crash and plays any role in Arbour's current power or propulsion infrastructure** — flagged as an open question by the original To-Do scoping for this document. Given the fuel budget above, very little reaction mass would plausibly have remained unconsumed by arrival (the ship was near its post-deceleration dry mass by the time of the crash) — worth deciding deliberately rather than assuming a reserve exists.
- [ ] **The other four arks' directions and distances** — deliberately out of scope per *The Five Arks*' own design principles (series territory, not Book One). This document's numbers should not be used to infer anything about them.
- [ ] **A dedicated stellar-neighbourhood / KOI-8565 system map**, and **a full Cordis planetary map**, and **a route-from-Earth diagram** are now unblocked by this document's locked figures — see companion diagrams.

Revision #6
Created 2026-06-20 14:34:08 UTC by Amari
Updated 2026-06-21 11:02:43 UTC by Amari