HIGH FRONTIER

4 ALL | BY PHIL EKLUND

APPENDIX

BY PHIL EKLUND

V. Variants & Scenarios

Part of High Frontier 4 All - Core : SMG28-4 EAN: 653341041166
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These include game variants, and solitaire, cooperative and narrative scenarios. Variants are all structured in the same format. Any deviations from Core and/or Module rules are explicitly stated. Deviations can include changes to setup, changes to rules that govern gameplay and changes to game duration and victory conditions.

V1. Quick Start (by Phil Eklund)

This variant will accelerate the early phases of the game. It is recommended for games with larger numbers of players (4 or more), solitaire or cooperative games, or games with a turn length of 60 years or longer.

a. **Number of Players.** 1 or more.
b. **Setup.** As per Core rulebook **C**, with any Modules, with the following exceptions:
   - **Seniority Disks (C1)**. Place 4 *Seniority Disks* for a short game, 5 for an intermediate game or 7 if playing Futures.
   - **Starting Aqua (C5)**. Players start with 0 Aquas each.
c. **Special Rules.**
   - **1st Solar Cycle.** For the first 12 years, no ***operations, actions***, or events are undertaken. The only option available to a player in her ***player turn*** is to take the top card from any patent deck into her Hand. This selected card comes without ***bonus supports*** (**I2g**). The ***academia hand limit*** (**I2a**) is not in force during this process. In the last year, the ***sunspot cube*** is not moved (it should therefore be back on the start slot).
   - **Bonus Round.** When each player has obtained 12 cards, a bonus round applies. Each player may sell as many cards as she wishes in any order she chooses for one Aqua each, placing each on the bottom of the relevant patent deck as it is sold. The bonus round is conducted in normal player order. The ***sunspot cube*** is not moved.
   - **Start Core Game.** Once the bonus round is complete, Discard the first Seniority Disk and continue the game as normal. Do not place this disk into the assembly (**O6**) or perform *baton pass* **(O6a)**.
d. **Game End.** The game ends when the last Seniority Disk is removed.
e. **Victory Conditions.** Scoring as per Core rulebook **M**.

V2. Race To Saturn (by Phil Eklund)

The world governing body has sponsored a new technology competition intended to drive innovation: a race to Saturn and Back.

a. **Number of Players.** 2 or more, competitive.
b. **Setup.** As per Core rulebook **C** with any Modules.
c. **Special Rules.** None.
d. **Game End.** When someone wins the race.
e. **Victory Conditions.** Core rulebook **M** does not apply. The winner is the first to land a Crew on the surface of Titan (not the aerostat) and return them to LEO.

V3. Grand Tour (by Andy Graham)

Space exploration isn't about money; it's about discovery and glory.

a. **Number of Players.** 2 or more, competitive.
b. **Setup.** As per Core rulebook **C**, with any Modules, with the following changes:
   - **Seniority Disks (C1).** Place 2 *Seniority Disks* in the center of the Sunspot Cycle.
c. **Special Rules.** None
d. **Game End.** The game ends when the last Seniority Disk is removed.
e. **Victory Conditions.** In your *endgame score*, only earn Victory Points for *Claims* (**M2a)** and *glory chits* (**M2b**).

V4. Altruism (by Phil Eklund)

Go it alone or go it together, for the future of the species.

a. **Number of Players.** 1, alternatively 2 or more, cooperative.
b. **Setup**. As per Core rulebook **C**, with any Modules, with the following changes:
   - **Seniority Disks (C1).** Place 4 Seniority Disks for a short game, 5 for a medium game, or 7 if playing Futures.
   - **Patent Deck Setup (C4)**. Shuffle the patent decks as normal, then remove the bottom half of each deck (rounding up) from the game, sight unseen.

Example: The starting decks should consist of 6 thrusters, 6 robonauts, 6 refineries, 8 generators, 6 radiators, 6 reactors, 3 GW thrusters, 3 Freighters, 5 or 6 Bernals, & 9 Colonists.

   - **Faction Privilege (C5)**. In a solitaire game, if your chosen Faction has the Taxes, Secretary-General, or Felonious *faction privilege* **(B6a)**, additionally start with an additional 6 Aquas.
c. **Special Rule.**
   - **Research Auction Operation (I2).** Instead of the *research auction* (**I2g**), take the top card of a patent deck for your Operation, including *bonus supports* (**I2g**). This costs a number of Aquas equal to the number of cards taken. The *academia hand limit* **(I2a)** still applies to solitaire games. With the Marketeer *faction privilege*, during research auctons you are allowed to buy 3 cards for 2 aqua.

d. **Game End.** The game ends when the last Seniority Disk is removed.
e. **Victory Conditions.** Scoring as per Core rulebook **M**:
- **Solitaire.** Win if your score is 40+ Victory Points (short), 60+ Victory Points (medium), or 100+ Victory Points (Futures).
- **Cooperative.** Collectively win if each player scores 30+ Victory Points (short), 50+ Victory Points (medium), or 75+ Victory Points (Futures).

V5. Hermes Fall (by Phil Eklund)

Earth is threatened by the binary asteroid hermes (8:00?). Your mission is to reach hermes and build the infrastructure needed to deflect the asteroids -- Factories and embedded dirt thrusters that can use the asteroids' own regolith to deflect them from their current trajectory. Good luck and godspeed.

a. **Number of Players**. 1.
b. **Setup.** As per *Altruism* (**V4b**), with any Modules, with the following changes:
- **Seniority Disks**. Place 2 *Seniority Disks* in the center of the Sunspot Cycle.
- **Patent Deck Setup**. Set aside the Mass Driver thruster before setting up the Patent decks per **V4b**. Then add it to the five-card Thruster stack and reshuffle.
- **Faction Privilege**. See **V4b** and **V4c**.

c. **Special Rules.**
- **Research Auction Operation (I2)**. Do not perform auctions. Instead use **V4c** (special rule).
- **I6.** Prospecting is automatically successful on *hermes a* and *b*, using a robonaut of any ISRU.
- **I7.** To industrialize *hermes a* or *b*, you need to <u>additionally</u> Decommission an operational dirt rocket (gray thruster triangle).

d. **Game End.** The game ends when the second Seniority Disk is removed.
e. **Victory Conditions.** Industrialize both hermes sites before the end of the game.

V6. CEO (by Victor Caminha)

Every 12 years the Board meets to determine if the company's space program should continue or not based upon the achievements of the CEO. That's you. Make your company money. And don't bring any bad publicity in the process.

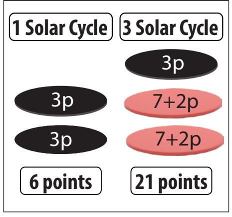
a. **Number of Players.** 1.
b. **Setup.** As per *Altruism* (**V4b**), with any Modules, with the following changes:
- **Seniority Disks.** Place 4 Seniority Disks for a short game or 7 if playing Futures.
- **Faction Privilege**. See **V4b** and **V4c**.

c. **Special Rules.** This variant can be played with Futures if using Modules 1 and 2. The following rules apply:
- **Fatality (E7).** Every time a Crew or Human Colonist is involuntarily *Decommissioned*, add a **fatality disk** (use a disk of an unused player color) to the **demand pile**.
- **Board Meetings.** Add the following steps to the *Sunspot Cycle Phase* (**D2**):
  - Upon passing the *seniority threshold* but before the Seniority Disk is removed in **D2b**, check to see whether the Board's **KPI** (Key Performance Indicator) has been met. Calculate the Board's KPI for that cycle as follows:
    - i. If there are any Seniority Disks in the demand pile, then the value of each disk is 7 plus the number of Seniority Disks in the demand pile. Accordingly, the KPI for one Seniority Disk is 8, for two Seniority Disks is 18, and for three Seniority Disks is 30.
    - ii. Additionally, each fatality disk in the demand pile is worth 3.
    - iii. The KPI is the sum of the value of all disks.
  - Remove all fatality disks from the demand pile.
  - Remove a Seniority Disk from the Sunspot Cycle and place it onto the demand pile.

REMEMBER. Because at the end of the first solar cycle it is likely that there are no disks yet in the demand pile, you usually don't have to meet any KPI until the end of the 2nd solar cycle. [V6c]

Example: At the end of the first Solar Cycle before a Seniority Disk is removed, the demand pile contains no Seniority Disks but two fatalities. The KPI is 6. After 36 years (3 cycles), at board meeting time there are two 2 Seniority Disks and 1 fatality disk in the demand pile. The board's KPI for the CEO is equal to 21.

EXAMPLE [V6c]

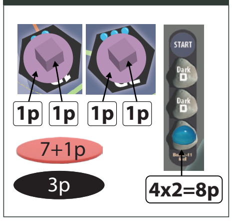


- **Research Auction Operation (I2).** Do not perform auctions. Instead use **V4c** (special rule).

d. **Game End.** The game ends when either of the following conditions are met:
- The last Seniority Disk is removed.
- The Board's KPI is not met at the end of a solar cycle. To meet the Board's KPI, you must have accumulated a number of victory points (**M2**) equal to at least the KPI value in the course of the game.

Example: The demand pile contains 1 Seniority Disk and 1 fatality disk. So far, the player has added two Claims and two Factories to his collection. The Claims and Factories are worth 1 Victory Point each and the Factories add an additional 8 Victory Points combined for being the third and fourth D Type Factories built. As such the player has accumulated 12 Victory Points so far, exceeding the Board's KPI of 11 (7+1 for the Seniority Disk+3 for the red disk). Play continues.

EXAMPLE [V6d]



e. **Victory Conditions, No Futures.** Score as per **M2**.
- 30-34: controversial
- 35-39: good
- 40-59: memorable
- 60+: legendary

f. **Victory Conditions, With Futures.** To succeed at the 7th and final board meeting, instead of Victory Points you must complete a Future. Then count your ***endgame score*** (**M2**):
- **0-77:** Controversial
- **78-94:** Good
- **95-114:** Memorable
- **115+:** Legendary

V7. Bios:Earth (by Phil Eklund & Paweł Garycki)

If you own the Bios trilogy (*Bios:Genesis, Bios:Megafauna* and *Bios:Origins*), you can play a full campaign and continue into *High Frontier 4 All.* Starting as a biochemical process (biont), develop into microorganisms, macro-organisms, and megafauna with emotions and communications, and finally as conscious intelligences heading to the beyond, settling the Solar System and exiting to the nearby stars. Here is the most up-to-date compilation of transition rules between the games, covering important nuances.

a. **Number of players.** 1 to 4 competitive. For solitaire play, use *Altruism* (**V4**) or *CEO* (**V6**).

b. **Setup.** As per Core rulebook **C**, with any Modules, except the end state of *Bios:Origins* determines the starting condition for *High Frontier*. Follow these steps (use these rules instead of **M** paragraph from *Bios:Origins*):

  i. **Starting Faction.** Choose Factions in the order of victory, with the highest scoring player choosing first. If your high score in *Bios:Origins* is political, preferably choose either yellow or purple. If it is cultural, preferably choose either white or green. If it is industrial, preferably choose either red or gray.

  ii. **Starting Politics.** The Active Law depends upon the ending Philosophy in *Bios:Origins:* "CENTRIST" if in the center or adjacent to the center, "UNITY" if to the right (pacifist or unity), "EQUALITY" if to the left (agnostic or equality), or "FREEDOM" if in abolitionist or freedom.

  iii. **Orbital Capacity.** Any player who has attained maritime 8 starts with double the usual Aquas.

  iv. **Nuclear Energy.** Any player who has attained energy 8 starts with a random starting thruster.

  v. **Bellwethers.** Normally players start with currency of the amount of Aquas equal to the amount of patent decks (6-9) Aquas. For each *Bellwether* a player has, he starts with one extra Aqua.

  vi. **Mars or Venus.** If playing on Mars or Venus, additionally see **V8**.

  vii. **Habitable Venus (optional).** You may optionally use the habitable Venus overlay card (**V8b**) for a different play experience.

c. **Special Rules.** If playing a full Campaign Game by continuing on from the Bios trilogy (*Bios:Genesis*, *Bios: Megafauna* and *Bios:Origins*), the following additional rules apply:

  i. **Starting Privilege.** Your Crew receives an additional Privilege determined by their species, as follows:
  - *Archetype.* None.
  - *Flyer. Mass 0.* (miniaturization)
  - *Burrower or Swimmer.* ISRU 3. (lichens)
  - *Armored. Rad-hardness +2.* (exoskeletal)

  ii. **Bonuses.** Depending on the technologies you <u>maxed</u> in *Bios:Origins,* start the game with the following, additional to orbital capacity and nuclear energy bonuses:
  - *Footprint.* Start with a random refinery.
  - *Energy.* All your thrusters except those on Human cards have at least 1 ballerina icon (**H4c**).
  - *Metallurgy*. Start with a random robonaut.
  - *Immunology.* Your Crew and Colonists are immune to CME Flare and Belt Rolls.
  - *Maritime.* Your additional starting cards start in LEO instead of Hand.
  - *Information.* Take a glory chit of your choice from the map, 1VP side up.

d. **Game End.** The game ends when the last Seniority Disk is removed.

e. **Victory Conditions.** The *High Frontier* score is per (**M2**). To evaluate the whole campaign, use *Bios:Origins* system (**C6i**):
  - **Victory Chits.** At the end of each of the games *(Bios:Genesis, Bios:Megafauna, Bios:Origins, High Frontier 4 All),* each player gains one victory chit (from *Bios:Origins*) for each opponent who has fewer VP in that game. The final winner is the one with the most chits, sharing victory if tied.

f. **Continuation into Interstellar (3rd edition).** For solo play, this requires completing an *ad astra future* (**1D1b**).

  i. **Card Translation.** You may opt to keep any cards you hold for Interstellar. Translate the cards into the closest equivalent 4th edition card.

  ii. **Ad Astra Exit**. If an *ad astra exit* has been used (**1D1b**) at least once in a game, a Sol Exit may be used in Interstellar. For the Jupiter Exit, in order to gather 2 steps of speed the thruster needs to be Operational after the first Belt Roll assuming thrust 0.

  iii. **Starship.** Except for solo play, start with either a random Purple-Side starship or a beehive (Operational TW thruster and promoted Bernal landed on a size 1 Synodic Comet).

  iv. **Futures Rewards.** If you used an ad astra exit, draw a random Colonist for each Future accomplished. Additionally: UPLIFT = may start politics at Robot Emancipation. BEEHIVE ARK = quick-start Beehive Ark. STARSHIP (AMMONIA or ENZMANN) = 2 more Colonists and either 1 factory or 10 fuel steps. PROTIUM = Protium Breakthrough. STAR WISP = free exploration up to 6 ly. EXOPLANET HUNT = free exploration.

  v. **Fuel.** Translate 1 isotope fuel to 1 fuel step in Interstellar, regardless of spectral type. Do not translate Aqua.

  vi. **Starting Politics** is determined by player color as follows: red = orange, white = upper white, yellow = lower white, purple = red, green = lower green, gray = upper green. The same applies to Crew political affinity.

  vii. **War of Independence** makes the SOS wisp inactive.

EASILY MISSED. The Oort Exit guarantees 1 step of interstellar speed. [V7fii]

viii. **Victory.** Add a victory chit for each victory level you achieve, starting with 1 chit at ZPG. If using Legacy Starshots variant, each next hop gives exactly 1 chit if at Linear Growth level. A final chit is awarded for exiting the map with Humans.

V8. Bios:Venus, Bios:Mars (by Paweł Garycki)

You started in the primordial soup in the (once) abundant oceans of Venus or Mars. Now it's time to expand as Venusians or Martians into the solar system before your oceans dry up. This contains optional perks if continuing a campaign game from *Bios:Genesis*, *Bios:Megafauna*, and *Bios:Origins*.

a. **Number of Players.** 1 to 4 competitive. For solitaire play, use *Altruism* (**V4**) or *CEO* (**V6**). All players start on the same planet as the same species.

b. **Setup.** As per Core rulebook **C**, with any Modules except Module 0, with the following changes:
- **Seniority Disks (C1).** Place 4 *Seniority Disks* for a short game, 5 for an intermediate game or 7 if playing Futures.
- **Earth/Venus Overlay Card** has Earth on one side, and Venus on the other. Use the Earth side if there are no Earthlings in the game. Use the Venus side if there are no Venusians in the game. In either case, lay this card directly upon the map to cover its planet.
- **Busted.** For the Venusians, aerostat-xity starts Busted **(I5a)** and you cannot pick up a glory chit there. For the Martians, Mars starts Busted and you cannot get a glory chit from any of its Sites. These Busted sites cannot be re-prospected using special Abilities.

c. **Special Rules.**
- **Ersatz LEO.** For the Venusians, LVO serves as LEO for all purposes: Aqua storage (**C5**), Crew Decommission location (**E7**), *free market* sales (**I3**), the location for *boosted* cards (**I4**), and *pad explosions/space debris* (**K2c**). Similar for the Martians and LMO.
- **Module 2.** Home Bernals may be Anchored on (Venus) the 4 spaces indicated on the Venus overlay card, or (Mars) Sol-Mars Lagrange points (L1, L2, L5) or the Lagrange Burn between the martian moons. Note that there are no Van Allen Belts (VAB) around Venus/Mars, so ignore any special rules associated with them. Note that Tourist Cycler still grants its ability. There is no *moon treaty* (*2Ba*).
- **Footfall and New Venus Futures** (Modules 1 and 2). These work as written, except the targets are switched: New Venus is now New Earth, and Footfall stomps Venus/Mars.
- **Moonlets Treaty.** If starting on Mars, Bernals cannot be anchored to phobos or deimos and a glory chit cannot be picked up there.
- **Space Elevators.** The Space Elevators depicted on the map at Earth and Mars can be built only by anchoring the *GEO Elevator Bernal* (**2B4i**) to the GEO Home Orbit (for Earth) or any Home Orbit in Mars (for Mars).

d. **Game End.** The game ends when the last Seniority Disk is removed.

e. **Victory Conditions.** As per Core rulebook **M2**. For Interstellar options, see **V7**.

f. **Campaign Transition Rules from *Bios:Genesis* to *Bios:Megafauna*.** If any macroorganisms which originated from extraterrestrial refugium are transferred to Bios:Megafauna, the game may start on a different planet than Earth (use both **K** and **L** rules). The choice depends on the refugium:
- Mars-Paleo Ocean = Mars
- Deep Hot Biosphere = Venus
- Interplanetary Dust = Mars, Venus or Earth with **K** and **L** rules (player's choice), if not already determined.
- Ties = the winner of the *Bios:Genesis* game decides how the tie is resolved.

RECOMMENDED. **In order to make Bios:Megafauna more likely to continue into Bios:Origins, remove the requirement of *population* being higher than the *heart limit* for execution of the raindance superpower. [V8f]**

g. **Campaign Transition Rules from *Bios:Megafauna* to *Bios:Origins*.**

i. **Alien Terrain.** Mars and Venus craton terrain is treated the following way:
- **Basin** is treated as sea.
- **Highland** is treated as a swamp if a green plant archetype is present (may place an unused burrower to further indicate this), or otherwise treated as weeds.

ii. **Climate Chit Transformation.** Replace the following on each craton in Mars solitaire/Venus multiplayer:
- **Mountain** (black disk) -> orange chit
- **Sea** (white disk) -> blue chit
- **Tubers Forest** (green burrower plant) -> green chit
- **Wasteland** (no green creeple and no disk) -> white chit

iii. **Alien America.** Add two additional Earth cratons as America to form a continent to the west of the Mars or Venus cratons. Cover Earth cratons entirely with random terrain chits and apply climate chits there according to the player count stars.

V9. The Sirens (by Paweł Garycki and Phil Eklund)

Carbon-based life that has gotten its start in the supercritical diamond oceans of Uranus. Because the surface gravity of Uranus is about the same as Earth's, intelligent beings called the Sirens have discovered rocketing solutions to the gravity well problem very similar to the liquid fuel boosters on Earth.[1] The players start as Sirenian Factions in the same manner as with terrestrial Factions, but with the Uranian moon cordelia being used instead of LEO.

1 SUPERCRITICAL DIAMONDS. Perhaps you are surprised that Sirens are subjected to crushing diamond-forming pressures while they walk on a 1 gravity world? Pressure is a function of the weight of the fluid column over your head, not surface gravity. Consider the 1000 atm pressure in the Mariana Trench, which is also at 1 gravity. Or consider worlds with a surface gravity less than Earth, like Titan and Venus, yet have considerably higher atmospheric pressure.

EASILY MISSED. You cannot play as the CEO of a Siren company. [V9b]

a. **Number of Players.** 1 or more, competitive.

b. **Setup.** As per Core rulebook **C**, with any Modules except Module 0, and except as follows:
   - **Seniority (C1).** Place 4 *Seniority Disks* for a short game, 5 for an intermediate game or 7 if playing Futures.
   - **Earthlings (C4)**.The players can all be "Siren" Factions, or 1 or 2 players can be "Earthling" Factions. If the latter, all patent decks (and the Colonist queue) are to be split into two, one for Earthlings and one for Sirens. Earthlings have no access to Siren decks, and vice versa, except during ***trade*** (next bullet & special rules) or ***negotiation***.
   - **Solitaire.** Use *CEO* (**V6**), but divide the patent deck between the Earthlings and Sirens per previous bullet except that the Sirens get all the **D** and **V** patents, and the Earthlings the remainder. The colonist queue remains split half to Earthlings, and half to Sirens.
     - *Trade.* If you land a Human on any **D** or **V** moon in the Uranian System, you may flip any white patent card in the landing stack to its Black-side.
     - *First Contact.* You automatically meet the board's KPI threshold during the Solar Cycle when your Humans first land on an Uranian moon (discovering the Sirenians).
   - **Busted.** Place Busted Claims disks on Luna, Uranus Aerostat, and Cordelia, which do not grant glory to their home species and cannot be re-prospected using special Abilities.

c. **Special Rules.** The following special rules apply:
   - **Research Auction Operation (I2).** If you are the only player in your species, so that you alone have access to the patent deck of your species, you do not perform auctions. Instead use **V4c** (special rule).
   - **Cordelia.** For the Sirens, this inner moon of Uranus acts as LEO for all purposes: Aqua storage (**C5**), Crew Decommission location (**E7**), *free market sales* (**I3**), the location for boosted cards (**I4**), and *pad explosions/ space debris* (**K2c**). You cannot pick up *glory* (**L**) on Cordelia or Uranus Aerostat.
   - **Diamonds Aren't Forever.**[2] Sirenian Crew and Colonists from the Siren queue (hereafter called "SIRENS") are considered rad-hard 0. If a Stack with Sirens suffers a Glitch, nothing happens if the Stack is on a Site, and the Sirens are Decommissioned if the Stack is in space.
   - **Heroism (Lc)**. If playing with Earthlings, if Humans and Sirens meet for the first time at the end of a Turn, give the player whose Turn it is one of the ***heroism chits*** (**C7**). Both Sirens and Humans can claim glory.
   - **Technology Trade**. If you are Earthling, you may take into your Hand one card from the top of a Siren patent deck if at the end of your Turn one of your Humans is colocated with a Siren. The same is true if you are a Siren and you end your Turn colocated with a Human.
   - **Promotion Colonies** (Modules 1 or 2). Regardless of its dome icon, Siren cards can only be promoted at *push colonies* (**2A3a**) or promoted and anchored Bernals (**2A3c**) (representing their need to enter into the inner solar system to meet their demands for solar energy).
   - **Sirenian Bernals.** The possible Home Orbits are indicated on the map, and any Bernal can go to any Home Orbit. Their dirtside hydration is not six, and instead depends upon the Hydration of the moons they are adjacent to. The Cycler Bernal allows safe passage through the "µ dust ring" Radiation Belt. Uranus Elevator can be built only by anchoring the *GEO Elevator Bernal* to any Home Orbit (**2B4i**).
   - **Footfall Future (1D5f)** can be directed to either Earth or Uranus, which removes either both Earthlings or the Sirens from the game. If more than 1 Faction survives, they continue with War of Independence.

d. **Game End.** The game ends when the last Seniority Disk is removed.

e. **Victory Conditions.** As per Core rulebook **M2**, except the ***bonus VP*** (**M2b**) for Siren domes is +3 if at Push Colonies (solar energy is important for the Sirens) or aerostats and +1 if anywhere else (including on Bernals).

V10. Red Giant (by Phil Eklund)

After a long (!) and moribund dark age, Earth-based astronomers of our future species belatedly discover that Sol is about to flash into a red giant.[3] This will turn Earth into a cinder and make the inner solar system uninhabitable. To survive this crisis, the Factions prepare to colonize the outer solar system, which will then become habitable.

a. **Number of Players.** 2 or more, competitive.

b. **Setup.** As per Core rulebook **C**, with any Modules.

c. **Special Rules.** The following special rules apply:
   - **Desiccation (B7a).** All Sites except for those in the Uranus and Neptune zones are one fewer in Hydration (to a minimum of zero) due to solar heating.
   - **Bright Future Sun (H3c).** Counterintuitively, as Sol burns up its nuclear fuel, it becomes brighter. Add +2 to the solar thrust modifier of each Heliocentric Zone (including Neptune). Cards limited to given Heliocentric Zones can make it 2 zones farther away.
   - **War of Independence** (see glossary) breaks out at the end of the 2nd Solar Cycle. This represents the breakdown of the governments of Earth.

d. **Game End.** As per Core rulebook **M1**.

e. **Victory Conditions.** As per Core rulebook **M2**, with the following exceptions:
   - Victory Points are not awarded for any ***glories***, Tokens, stock prices, or ***dirtside hydration*** except at Sites or Spaces within the Uranus zone or beyond.

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2 DIAMONDS are a quasi-stable crystalline form of carbon. Not to contradict James Bond, but the gem in a diamond ring will eventually turn black as it converts into its stable form: amorphous graphite. The stability of supercritical diamonds is unknown. Composed as they are of articulated supercritical diamond elements, the Sirens are hypersensitive to radiation.

3 RED GIANT. Sol will expand into a red giant 5 billion years from now. As it warms, Earth may become a copy of Venus, as its oceans boil away and the carbon locked up in limestones and other carbonates is released.

V11 - Diamonds 4 All (by Jon Manker and Paweł Garycki)

You struggle to develop rockets and journey to the corners of our solar system to build factories and colonies. However, on the way you stumble upon more riches than you expected, which can tilt the outcome of the game.

a. Number of Players. 1 or more, competitive/cooperative depending on other rules used.

b. Setup. As per Core rulebook **C**, with any Modules and/or any scenario, (or as per setup in *Race for Glory*), except as follows:

- **Deal 1 Sail & 1 Rocket Mission** to each player (interpret missions about spending water as spending Aqua).
- **Place Discovery Chits** either per (**iC2b**) to Sites in the 5 innermost Heliocentric Zones (including Ceres ?), or by adding chits to any zones in the following way:
  - **Mix** all discovery chits facedown (Spectral letter side up).
  - **Placement**. All players simultaneously place chits (without examining them) on any Site with icons (Astrobiology, Atmospheric, Push, Submarine). When these are filled, they load Sites without symbols.
  - **Single-Handed**. Players may only use 1 hand and grab chits one at a time. They must place a grabbed chit on a valid Site before grabbing another.
  - **Dark Sites.** After placement of all **D** chits, it is possible to place **M** or **S** chits on **D** Sites.

c. Interpretation of Specific Mission Cards:

- **Red Shirt Expendable:** You failed a Hazard Roll and thus Decommissioned a Sail.
- **Completionist:** Score 10VP for this mission if playing *Industrial Diamonds* **(V11f)**.
- **Emergency Eminence:** Instead, be the first to perform an Air-eater Refuel Op for 3 consecutive turns.
- **Double Messenger, Space Maze Ace:** Subtract 2 from each discovery roll on the required sites if playing **Industrial Diamonds (V11f)**.
- **Ring my Bell:** Be the first to have used both Saturn and Uranus flybys.
- **We Choose to do It because It is Hard:** If using Module 1, fulfilling an ad *astra future* **(1D1b)** at Sol-Jupiter Sol solar exit satisfies this mission's requirements.
- **Aegir in Space:** Have the most fuel steps onboard your rocket. If using Module 1, these are isotope fuel steps.

d. Gameplay. T.

- **Discovery Free Action.** To pick up a discovery chit your Colocated Humans need to perform a discovery *free action* **(G)** while on the Site. Roll a die and subtract:
  - 2 for each icon on the Site (Astrobiology, Atmospheric, Push, Submarine).
  - 1 if one or more operational buggies are present on the Site. On Submarine Sites, subtract 1 for each operational buggy.
  - 1 for each Colocated Colonist in the performing stack.

  Pick up the discovery chit if rolling 0 or less or discard it out of game if rolling otherwise.
- **Discovery Chits** are carried by stacks like FTs, with a Mass equal to the number of drops on them. Only the Stack carrying a chit may use their Ability.
- **Raygun Discovery** (Free Action). If you have an operational raygun Adjacent to a Site with a discovery chit, as a free action you may examine it in secret. This is not possible during movement.
- **Common Knowledge.** Everyone is able to examine any Site covered with a discovery chit without looking at its chit.

e. Game End. As per Core rulebook **M** + any scenario + any modules you prefer to use.

f. Diamonds 4 All Scoring as per Core rulebook **M** + any scenario + any modules you prefer to use, except do not score *token VP* **(M2a)** or *factory stock price VP* **(M2b)**, and glory chits are worth double.

g. Industrial Diamonds Scoring (Variant closer to the Core Game) as per Core rulebook **M** + any scenario + any modules used. Life, Gems and Industrial discovery chits score VP only at LEO or in your Anchored Bernal. All other discovery chits score if they are in any of your stacks.

STRATEGY NOTES:
This game is about winning glories and collecting discovery chits. Claims and Factories are merely a means to getting a Crew to ever more distant locations that provide glory chits, and returning them to LEO. Don't forget that ET production often can produce the technology essential to get your hands on those rewards. [V11]

STRATEGY NOTES FOR THE INDUSTRIAL DIAMONDS VARIANT: Because the discovery chits are a nice addition rather than the main theme, aim for exploration when you are well prepared, with good black or purple cards, a raygun and/or buggy, and Colonists. Prospects are best in Sites with many icons. During setup try to place chits on such Sites first. With proper placement (remember the Dark Sites rule), you will end up with 2 chits (M and/or S) to be placed on Sites without symbols, e.g. hermes or ariadne mentioned on mission cards. [V11]

V12. Panspermia Scenario (by Paweł Garycki)

Life has a single origin in the Solar System, yet has spread to various worlds. Some unknown goldilocks principle has caused several forms to develop consciousness simultaneously and emerge as space-farers.

a. Number of Players. 2 or 4 competitive. Select 2 species from the list below and use their home world and low orbit. Select a Crew Card/color for them as well. The game plays best if there are 2 players per species.

b. Earthlings Setup. See **V9b**.

c. Martians Setup. Treat as Earthlings above (**V9b**) but use **V8** for setup steps regarding starting location and special rules not contradicting **V9b**.

d. Venusians Setup. Same as Martians above.

e. Siren Setup. See **V9**.

f. Oceanian Setup.

- **Home World Europa.** Use its Radiation Belt as low orbit and L2/L1 jovian spaces for Bernals. Cycler allows safe passage through jovian Radiation Belts.
- **Oceanian Crew** is mass 2 (large swimmers) and may land on Sites adjacent to a geyser without a required net thrust.
- **Promotion Colony symbols** for the Oceanians are all Submarine and Aerostat, replacing the original dome icons. They only work in the Neptune Zone plus all Aerostats. For dirtside hydration count only Hydration on Submarine Sites, however add 2. Home Orbit Hydration remains at 6.

g. Tholian Setup.

- **Home World Titan.** Use LTO as low orbit and L1/L5 (except the innermost and outermost L1) saturnian spaces for Bernals. Cycler allows safe passage through all Radiation Belts in the Saturn system as well as rings. Use *moonlets treaty* (**V8c**) for Hyperion.

STRATEGY NOTES:
Perhaps the most difficult alien to play are the Nuclei, with 10 Burns to escape into the prograde solar system, and even more to land on the Synodic Comets they favor. The Tholians are able to bust large Sites that are "unbustable" according to the Core rules. Interpret this as contamination of the surface with tholin-based biochemistry. [V12]

- **Tholian Crew & Colonists.** When prospecting, Tholian's Crew and Colonists make a "hydration roll" instead of a Size Roll, which is successful if they roll less than or equal to the Site's Hydration.
- **Promotion Colonies** icons are Atmospheric, replacing the original dome icons. Triton and Pluto also count as having trace atmospheres. Saturn and Mars labs work only if their elevator is built first.

h. **Nuclei Setup.**
- **Home World Bee-Zed.** This asteroid is not a Synodic Comet in this variant. Use its red space as a low orbit and the first 6 burns as spaces for Bernals. Cycler works for Jovian flyby Radiation Belts. All boost costs are halved (rounded up).
- **Nuclei Crew and Colonists** are Mass 0. Size Rolls for the Nuclei Crew and Colonists are automatically successful for Synodic Comets. Due to low gravity, Nuclei can factory refuel 7 steps of water in Home Orbit as if a factory were there, however they cannot convert FT or fuel steps into Aqua.
- **Promotion Colonies** icons are Astrobiology, replacing the original dome icons.

i. **Special rules.** For this scenario, use the rules from *Sirens* (**V9**), plus the following:
- **Busted.** All Sites of a home world start Busted to indicate that they start inhabited. Glory chits cannot be picked up there by their inhabitants.
- **Earth.** If there are no Earthlings in the game, use the Earth overlay (**V8b**).

j. **Game End.** The game ends when the last Seniority Disk is removed.

k. **Victory Conditions.** Oceanians, Tholians and Nuclei count VP the same as for the *Sirens* (**V9e**).

W. Strategy Guide

W1. Core Game (by Chad Marlett & Eric Schiedler)

Concepts that should guide strategy that may not be clear from a quick read through the rulebook:

a. **Robonauts/ISRU.** Often, your first robonaut determines your strategy.
- **Missile Robonauts** are ISRU 2 or 3, and all act as inefficient thrusters. They are best at Size 3+ Sites with two or three water drops. Many crew thrusters can land on Luna, but don't have the necessary ISRU to *prospect* there. The 5•4 thrusters/robonauts have good targets at hertha, lutetia, eichsfeldia, and minerva.
- **Buggy Robonauts** are essential for the isolated Size 1 Sites and are useful for claiming multiple Sites on Mars or any of the Galilean Moons of Jupiter.
- **Raygun Robonauts** have the highest Mass, but they are the keys to the asteroid families and do not have to land to *prospect* (unless the Site has an atmosphere). One raygun robonaut has the only ISRU rating of 1 found on any of the white cards.

b. **Thrusters.** Get a thruster to match the supports of your robonaut, and remember you don't need a thruster if you have a decent missile robonaut. The 2•2 thruster is arguably the best one in the game. The 3•1 and 5•1 are even more useful but their supports (pulse generator & x reactor) are rare. Also beware the 0 rad-hardness on the 5•1. The 4•3 Dirt Rocket also needs a pulse generator, but if you can supply enough Fuel for the 2 Burn Spaces needed to refuel at deimos, it can refuel rapidly and go to almost any small world. The 0•0 Sails and the 3•4 solar thruster are useful for quick Claims and glory in the inner Sites (e.g. Mars), but have limited use in the later game. The 3•2 and 4•2 electric rockets are decent if their supports are not prohibitively heavy. The 4•3, 5•4 and 6•5 are fuel hogs but useful on the larger targets with a *lander burn*.

c. **Refineries.** Try to make use of your Black-Side refinery for your second mission, but note that there are no refineries of Spectral Type **C**.

d. **Crew.** A Crew with thrusters can go for glory or an early Claim on Mars - or Luna with an ISRU 1 robonaut. All of their ISRU ratings are poor, so only a few Sites could be claimed. You can Decommission a Crew at a Factory to form a Colony for Victory Points—the only one-way trip you can really plan with a Crew, other than the Taikonaut player. Note that the Taikonauts must be present to *Claim Jump* (**G4**), and other players' Crews can prevent this. The Crew thrusters can't land on or liftoff large Sites if they are carrying too much Mass because the Fuel cost of *lander burns* is prohibitive. Large Rocket Stacks have a *net thrust* penalty due to *weight class.*

e. **Aerobraking.** Don't forget that you don't have to meet the Site minimum thrust requirement to land after aerobraking. Of course, taking off again is another story.

f. **Failure Is Not an Option.** As in many games, a strategy with a slight degree of risk is more likely to win than a conservative strategy that takes no risks. Nevertheless, even if a roll of '1' seems quite unlikely, you should play it safe if you have a lot riding on a mission.

g. **Do Not Fly During Season Red** unless you can get to a Site or a planetary Radiation Belt.

h. **The Mag Sail** (not the other promoted Sails) receives +1 Bonus Burn if it flies through each radiation Hazard! This makes for a powerful Sail in the later stages of the game. It makes for a very nice Mercury trip with Crew, etc.

i. **Thrust Modifying Supports** are NOT applied if the thrust card does not need them as support. This includes Sails. The *powered landing* rules (**H6a**) allow you to cruise to a large destination such as Ceres or Callisto with your main thruster, then switch to a more powerful thruster (such as the Crew) to allow you to land.

j. **Radiation Belt Survival.** If you have low rad-hard Cargo, you will need to travel through the Van Allen Belts quickly with a high net thrust (which subtracts from the Belt Roll). One way to do this is using your Crew's thrusters. Halt in the Space just before the Radiation Belt, then on the next Turn activate the Crew's thrusters and enter the belt. Note that no fuel is expended as long as you do not enter a burn. This is because the engines are on only for the minutes necessary to zip safely through the belt.

k. **LEO to Asteroid Belt in 2 Burns.** Some NASA probes bound for the outermost parts of the solar system (e.g. Cassini), seemingly start in the wrong direction, headed inward towards Sol for a flyby of Venus, followed

DOM'S STRATEGY NOTES:

>Prospecting a size 1 site is more likely than you think, especially with a re-roll.

> Prospecting a size 3 site is less likely than you think.

> Jupiter and Saturn are more accessible than you think.

> Mars is a trap (except when it isn't. Consider building Phobos Space Elevator).

> Ceres is a trap (even if you think its not). Try Hygeia.

> C sites suck (except when they don't; value is relative).

>X reactors suck, and metastable helium is your ticket to dispersing helium throughout the Van Allen Belts.

>Luna belongs to China.

>The Venus Flyby is more powerful than you think, and can be worth the wait to Cycle Blue.

>Even "bad" combos have their 15 minutes of fame.

>Build to your extreme long term goal, not the cards you have right now.

>Be prepared to switch to a new extreme long term plan really quickly.

by a flyby of Earth. This can be opportunistically duplicated in the game: from LEO, fly through the cycler and GEO burns to reach the Venus flyby. From here on it is a game of interplanetary ping pong as you make flybys of Mercury, Earth, and Luna, using Bonus Burns to fly all the way to the asteroid belt using as many Burns as to land on Luna. This has limits: the Venus flyby is only available in season blue and one must survive many solar Belt Rolls.

W2. Reduce Mission Cycle Time (by Eric Schiedler)

I like to think of my mission cycle as the time between boost operations. I only want to boost once per mission, because I lose the opportunity of gaining an Aqua in income (or more) for each Turn that I boost. But, you likely have to boost for each mission, because you often Decommission cards from the previous mission that you will use in the next mission.

1. **Reduce Mission Cycle Time.** Complete missions (successfully or unsuccessfully) as quickly as possible. It almost doesn't matter what the missions are. You can't get anything useful to advance you on Victory Points or the later stages of the game until you complete a mission. You can only really have one mission going with only one Rocket Stack. Other players are doing the same process of trying to get their next mission off the launch pad. Your decisions should focus on getting this time between missions down to a minimum. One key way of doing this is ensuring you can *ET produce* (**I8**) your robonaut and refinery in relative proximity - either because they are the same Spectral Class or because they can be produced by two Sites on one moon or two asteroids in the same family.
2. **Find Income Sources.** *Researching* (**I2**) then selling cards is an efficient income source. Even more efficient is *researching* then letting other players win the auction, because then you don't bloat your hand and don't have to spend Operations clearing your hand of excess cards later. However, this is quite situational, as there is no cookbook way to make the most income. (Jeffrey Chamberlain)
3. **Get Free Operations.** If I buy at a *research auction* that another player has initiated, I saved having to use an Operation. If a player sells me a patent card, I saved having to use an Operation. If a player sells me a Stack of water at a Factory, I save several Operations of refueling. Look for free Operations, as they directly reduce the all-important mission cycle time.
4. **Have a Black-Side Plan.** If you start one or two Factories and you know which black card you will produce at them, and plan accordingly, you will crush your opponents. Black cards are powerful, but not if they just sit there—you need to have a plan to really make use of them. I want to point out that it's more important to have a crushing plan for your black cards, and to get that plan going, than to worry about how many victory points your Factories will be worth at the end of the game. The end Victory Point value depends too much on the actions of other players and random events. Turn your awesome black cards into solid Victory Points from space ventures that won't drop in value.
5. **Use Decommission to make missions feasible.** Since Decommission is a free action, not everything has to make the full trip (both one-way and round trips). Drop Mass when you can! Plan to drop Mass and Fuel! Use multiple thrusters to jigger the mass/fuel effects! You can even drop everything but a thruster and Crew card. As they limp back home, you can plan your next mission.
6. **Have a Small Mission running while planning the Big One.** A two-card Rocket Stack can do something, anything! An efficient thruster and a Crew card can try to claim ***glory*** points. This is not always an effective strategy if you are about to launch a mission, or are planning a medium-sized mission. But, if you are thinking of building a monster Rocket Stack to take over Saturn or Jupiter, for example, you'll have the time to have a small mission going.
7. **Learn to use the patents you have; don't fall in love with a card or a mission.** No card is perfect for every mission. No mission is always great; it depends on the stage of the game. No card is awesome unless combined with another complimentary card. No single purchase will get you through the whole game. Space ventures require multiple (or huge) missions, so work these in depending on the flow of the game.
8. **Don't be afraid to make deals.** How often have you desperately needed your ship to have one more thrust for the Turn? Make a deal with the ESA, and you've got it. Need a robonaut that is powered by exotics and masses exactly 1? Talk to Shimizu, they've likely got something stored away in their databases. Need money now for that software upload? NASA always seems to have extra cash lying around.

❶ VICTOR'S STRATEGIES:

>Don't wait for the perfect combo; time = Aquas.

>Don't forget to industrialize your best Black-Sides.

>C Sites are like training wheels: great for a few game-changing cards (e.g. ISRU 0 robonaut for Venus, ultracold neutrons for your metastable thruster). But you won't go far with only C.

>V Factories are tricky. If you have an ISRU 2 robonaut, fine, go to Vesta. If it is 3 or 4, the sites are <u>far</u> away (Uranus), or in deep gravity wells (Callisto, Ganymede, Mercury, Titan).

> S Factories require a high-powered thruster and enough fuel to reach Ganymede/Europa. Alternatively, try your luck in the Karin cluster, Saturnian Dione/Tethys Trojans, or (if you have an ISRU 1 robonaut) various dry asteroids like Flora or Kleopatra.

> D Factories are diffiult since few cards use them. But both Jovian Trojans have a few, as well as some Centaurs and Centaur Comets.

> Avoid Solar-Power supports, because in the long run many futures take you to Neptune or beyond where these are useless.

W3. Frequently Asked Questions (by Joe Schlimgen)

Q1: In order to build a Factory, do you have to Decommission cards with product letters that match the Site's letter?

A: No. The product letters of the refinery, robonaut, and support cards *Decommissioned* to *industrialize* (**I7**) are irrelevant. For example, in the basic game you could build a Factory at a type '**M**' world by *Decommissioning* a *basalt fiber spinning refinery* (type '**S**') and a *kuck mosquito robonaut* t (type '**V**'). However, the card you choose to be the Factory product must have a product letter that matches the Site's Spectral Type.

Q2: How do I perform an Apollo-style moon mission?

A: NASA has two mission objectives: to land a robonaut on Luna as a pedestal for a future Factory, and to return the astronauts for glory.

Year 1: Launch of Lunar Mission. After years of research, NASA pays 6 Aqua to boost a *Re solar moth thruster* (output 3•4, Mass = 0), a *free electron laser robonaut* (ISRU = 1, Mass = 2), a *marx capacitor bank generator* (Mass = 1), and a *radioisotope stirling generator* (Mass of 3). The 2 generators provide the pulsed support necessary for the robonaut. Once boosted, the equipment is joined by the astronaut crew (Mass = 1). He puts a Rocket Figure in LEO, and a blue Dry Mass Chit on the number "7" spot. He spends 10 Aqua to add 10 tanks of Fuel, moving the Wet Mass Chit to 17. It is now "tug class" (-2 *weight class modifier*).

Year 1 (continued): Cis-Lunar Move. With the moth activated, the net thrust is 1. The Rocket uses 4 steps of Fuel to enter the Earth cycler orbit. He is allowed to coast to the Van Allen radiation belt, but does not dare to since his net thrust is so low an unlucky roll could zap his generators, Crew and laser. Its Wet Mass is now 13, "transport class" (-1 *weight class modifier*).

Year 2: Lunar Landing. NASA activates the Crew's liquid fuel thrusters (output 14•8), and in its weight class the *net thrust* is 13, enough to safely transverse the radiation belt. It is also greater than the Size of Luna, permitting a *powered landing* (**H6a**) on the Shackleton polar rim (Hydration = 1). The lander burn costs 8 fuel steps to enter, leaving him with the Wet Mass Chit on his Dry Mass Chit, indicating it is out of fuel. During *prospecting* (**I6**) the NASA robonaut claims Luna (prospecting is automatically successful given the size of Luna and the laser robonaut is operational and has an IRSU of 1). Additionally, the astronauts nab the glory chit for the Earth zone.

Year 3: ISRU Refueling. As a cargo transfer free action, the stack is divided into 2 stacks: the Rocket Stack containing just the Crew, and Outpost Stack #1 containing the thruster, robonaut, and 2 generators. The Wet and Dry Mass chits are moved to 1, the Mass of the Crew. In order to obtain fuel for the return trip, the robonaut spends a year digging up regolith and squeezing out water drop by drop, moving the Wet Mass Chit one step (from 1 to 2).

Year 4: Ticker Tape Return. The Rocket has a Wet Mass of 2, which is "probe class" (+1 *weight class modifier*). The Crew's 14•8 thrusters are boosted to a net thrust of 15, more than enough to make a *powered liftoff* through the lander burn, and coast into the radiation belt safely. Eight steps of fuel are expended in the lander burn, leaving just 1/9th of a tank remaining. This is insufficient to enter the cycler Burn, so the Crew takes the aerobraking "shortcut" to LEO. Assuming their parachute opens properly, the Crew enters LEO. The fraction of a fuel is lost. The glory chit is flipped to its 2 VP side.

Year 5: The Next Mission. NASA plans its next mission, flying a refinery to Luna. Together with the operational robonaut already there, an *industrialize operation* creates an **S** Factory in Crater Shackleton.

Q3: How realistic is it to land without using fuel?
A: You will always need fuel for a powered landing, but for small worlds the amount is insignificant in the game's scale. The largest asteroid you can land on without a lander burn is size 5, for instance psyche with a surface gravity of 0.06 m/s^2 and an escape velocity of 0.13 km/sec. How much fuel is needed to land a Dry Mass = 5 with a 10•8 Rocket with exhaust velocity of 4.5 km/sec on psyche? Using the Rocket equation: Wet Mass = Dry Mass times e^(delta-v/exhaust velocity) = 5 * e^(0.13/4.5) = 5.15. Thus the amount of fuel needed is 5.15 – 5 = 0.15 tanks. Which is much less than one step of fuel.

Q4: What is the Solar Oberth?
A: The flyby rules approximate TWO effects: gravity slingshot and the Oberth effect. (You've got to love those crazy German scientists. Thanks to the email correspondence with Professor Nathan Strange of NASA for describing both effects).

The flyby effect describes the momentum transfer between a spacecraft and a planet (as the most useful example in game terms). For instance, by passing in front of an oncoming planet, the planet may speed up, and the spacecraft slows down, conserving momentum. This "gravitational slingshot" does not depend upon the Rocket engine, so it works for unpowered or ballistic vehicles. Also, notice that this slingshot does not help the spacecraft with respect to the gravity field of the planet used in the slingshot. An Earth flyby does not help you get captured by Earth. In general, using Sol for a slingshot is useful only for a solar system escape, e.g. using the *Jupiter-Sol-Jupiter Exit*.

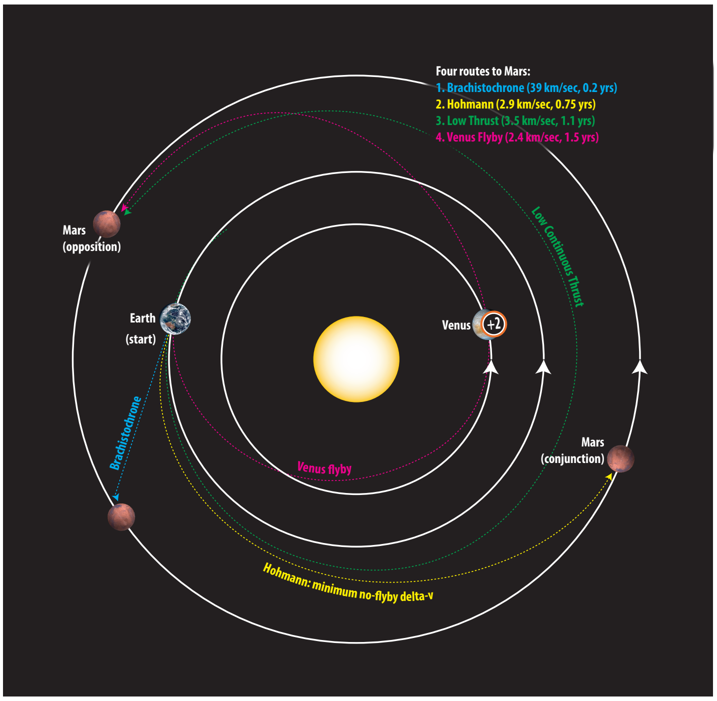
But the second effect, the Oberth effect, describes a multiplier if one thrusts close to a planet, as opposed to further away. This is because if you are discarding propellant by expelling it, you gain an energy advantage if you expel it at low altitudes rather than at high altitudes. To give a terrestrial analogy, suppose you are at the base of a mountain that you have to climb. You are carrying a liter of water. You should drink it all before your trip, at the lowest altitude, and sweat it off during the ascent, rather than haul it to the top and then drink it.

The Oberth multiplier does not violate conservation of energy. Remember that whenever your Rocket thrusts by expelling propellant, some of the energy goes into moving the Rocket and the rest into moving the propellant. (Swimmers have the same problem, wasting as much energy moving water backwards as moving the swimmer forward. Joggers have it easy, direct momentum transfer with the planet Earth.) If you thrust your Rocket at periapsis, more of the energy goes to moving your Rocket and less "wasted" into the propellant.

The Oberth delta-v multiplier is equal to the square root of one plus twice the escape velocity divided by the delta-v burn. Thus it is most effective for high thrusts at fast speeds, such as a periapsis close to a high gravity world with a chemical rocket. It is not so good for an electric Rocket, which can only expel a trickle of propellant at the interval when it is going the fastest. And, it is useless for Sails and ballistic spacecraft.

The Solar Oberth, as marked on the map, takes you through 5 burns and allows you a slingshot equal to your unmodified thrust (plus one if you afterburn). The solar escape velocity in this region is 68 km/sec, so the multiplier comes to 3.4 for a thrust 6 spacecraft able to execute these burns in a timely fashion. This is comparable to the net game value of 6 – 2 = 4 (two burns are lost exiting the Solar Oberth region).

Q5: Why are the planets static?
A: A partial answer is that for a map of potential energy from Sol, the alignments do not matter for nearly-circular orbits, only the distance from Sol. Only for highly-eccentric comets, like Halley's, do I bring synodic alignments (i.e. launch windows) into play.



Another reason is, for low fuel consumption rockets (most of the game designs fall in this class), the difference in energy between the worst and best synodic positions is less than 15%. Only for high fuel consumption rockets with miniscule delta-v (i.e. all NASA missions until Dawn) do such celestial billiards become significant.

But the biggest reason for not having moving planets is, if starting at LEO, and going to every destination except Mars, your wait for the perfect astrology (i.e. planetary alignment) is less than a year. If going to an inferior destination like Mercury, and the alignment of the planets happens to be the worst possible, just wait half a Mercurian year (44 days), and it's perfect. If going to a slow planet—like Saturn, which is practically "fixed" in position ("mercurial" means "fast," "saturnine" means "slow")—and again your astrology is the worst possible, wait one-half of an Earth year, and it will be perfect.

Four routes from Earth to Mars are illustrated to the right. The shortest (blue) is the **brachistochrone**, which is a straight line accomplished by pointing your nozzle at Sol, and thrusting just enough to balance your weight. With the solar gravity thus negated, you fly in a straight line for 2 months at 30 km/sec, the Earth's orbital velocity. This "levitation" requires a delta-v of 16 km/sec, plus another 23 km/sec impulse to attain a heliocentric circular orbit at the distance of Mars. The next fastest shown (yellow) is the Hohmann transfer, with high thrust impulses at the start and end of the 9 month voyage. This also is the lowest delta-v, if no gravity sources are considered except Sol. Note that, counter-intuitively, that lowest energy route is when the two worlds are the furthest apart. The green route shows a trip with a low thrust rocket or sail, that accelerates for the first half and decelerates for the second. The final trip first goes inward, for a gravity-assist at Venus, before flying to Mars.

Q6: I have a "factory loading only" Freighter and my Crew in LEO. What prevents the Crew from jumping aboard and flying to my outpost in space?
A: To simplify the game, freighters don't track water. Yet the "factory loading only" freighters are very low tech (e.g. one is just an inflated balloon), with a specific impulse of only 0.19 ks, and accordingly would need a lot of water propellant. If your outpost is 4 burn spaces away, then your balloon freighter would need 84 mass points of water. This is no problem at a factory, where water is cheap. It is prohibitive in LEO, where water is in extreme demand.

Q7: Why didn't you include Eris?
A: The Outer Solar System is a region of vast distances, far too large to recreate all of it. So I made a thin slice through the Kuiper Belt, and populated it with a few representative TNO dwarf planets. The scattered disk objects, of which Eris is the largest member, are at such a high inclination there was little chance for them to be within 50 AU of anything. Orcus was considered, but since the perihelions of Pluto and Orcus are opposite to each other, if one is on the map, the other would be far off it.

UPDATE, 2020. Even though the orbit of Eris is 44 degrees out of the ecliptic (the plane in which most of the planets orbit), the current position of Eris is only 10 degrees out of the ecliptic. Moreover, Eris orbits so lethargically it might as well be glued in place for the duration of the game (its orbital period is 557 years). Therefore, the delta-v to orbitally-match the inclination of Eris doesn't apply, since it is almost at a standstill. It is a long way to Eris, twice as far as it is to Pluto. But for the entire century of time the game is assumed to take place, Eris is close enough to the ecliptic that it is conceivable to reach it by gravity-assist from Uranus and Neptune, and seasonally Jupiter as well. The practicality of gravity-assist was the very reason that I excluded Eris to begin with. So I may include Eris in a future map edition.

Y. Essay (by Phil Eklund)

The fourth edition High Frontier is the culmination of 4 decades of design and development work! Here rogue designer Phil Eklund talks about some of the scientists, engineers, and entrepreneurs from its early days.

ATOMIC ORIGINS. My father, Melvin Eklund, was a rocketeer. While working for Los Alamos, he sent sounding rockets into "stabilized clouds" of atomic blasts in the Pacific, and witnessed from helicopters their effects. Maybe the radiation had something to do with the way I turned out.

L5 SOCIETY DAYS. Whether by nature or nurture, by 1978 I was a nerdy aerospace engineering student at the University of Arizona in Tucson. After reading ***High Frontier*** by visionary Gerard K. O'Neill, I joined the L5 society, a space activist group founded by fellow student Keith Henson. I wrote articles and illustrated the ***L5 News*** magazine, and campaigned against the Moon Treaty in 1980, on the grounds it would close space to private exploitation.

ROCKET FLIGHT, of which about a dozen copies were made in 1978, was my first "published" game design. It featured a 2-piece map covered with plastic. After each turn, you marked your rocket's location, altitude, and vector with a grease pencil. Each turn was 2 days; each hex a million kilometers. Combat was tricky, as interception required visualizing in 3 dimensions. And because changing vectors was so difficult, you generally only got one pass at the target. Decoys were common, so many missiles wasted on disguised chunks of rock. Each rocket relied on its "Forward Mass Detector" for IFF. I think this publication was the first appearance in any game of EMP and X-ray spalling as a damage mechanic.

FLEDGLING ROCKET SCIENTIST. The next year I landed my first big aerospace job with Hughes Aircraft, and worked on various Star Wars projects such as the exoatmospheric kill vehicle. Among the remarkable rocketeers I worked with at Hughes was Dr. Hans Mauer, one of the transplanted von Braun rocket team who collaborated with Howard Hughes himself to found the aerospace division. Dr Mauer distanced himself from my crazier projects, such as my 1982 paper on catalyzed fusion propulsion. This was instead sponsored at the Joint Propulsion Conference in Cleveland by Dr. Leik Myrabo, inventor of the Myrabo Lightcraft (see the cover art for ***Pax Transhumanity***), and tireless promoter of rockets and aircraft powered by laser beam. Leik gave me his book, gave advice for my game, and in general baselined the rules for remotely-powered rockets.

SIERRA MADRE IS BORN. Still innocent of customer preferences or marketing, I registered the boardgame company with the state of Arizona in 1992. My entrepreneurial mentor was Neal Sofge (aka Fat Messiah of ***Fat Messiah Games***). Neal and I had much in common, including both having had Dr. Myrabo as a mentor. Neal, now with NASA Goddard, volunteered as mission coordinator for ***High Frontier 4***.

GENIUS. Another Hughes rocketeer was Dr. Robert Forward, the free-thinking inventor of star wisp, space fountains, laser sails, antimatter propulsion, and the aforementioned mass detector. Robert rubbed elbows at Hughes Research Labs with Richard Feynman, another notorious genius. Robert explained how the ionosphere could be converted into a megawatt laser, and many other wonders. In a fever of productive excitement, all these elements were incorporated into the second edition of ***Rocket Flight***, which appeared in 1992. This edition featured the first "delta-v" map, a map of energy rather than space, and the first rules for heat rejection.

THE MAP. A conceptual leap converted the map from one of distance (each hex = million km) to one of energy (each space = 2.5 km/sec). The advantage: since each orbit is at a fixed potential energy from Sol, each space represents a stable orbit. No need to move markers around the sun or planets. This was opposed by fellow game designer (and Mars Society founder) Robert Zubrin, who advised for a more traditional map, with planets represented by marbles that revolved around Sol. But this leads to weirdnesses. Did you know that it is less energy to get to the surface of the moons of Mars than to get to the surface of our own moon? Have you ever tried to draw a map of the solar system where Mars is closer to us than Luna? Or how to represent that the lowest energy route occurs when the planets are furthest apart?

CANDYLAND. We tried all sorts of things to tame the monster. Working with my son Matt and fellow game designer Dr. John Douglass, spaces were discarded in favor of routes, with red diamonds along some routes to represent the delta-v requirements. As navigation aids, important routes were rainbow colored, and outfitted with signposts. This unfortunately made the map even more like ***Candyland***, but players came to appreciate them. The diamonds were dropped, instead coloring certain spaces pink to show they required energy to enter.

THE FLY-BY PROBLEM. For years I struggled with the transition between circumplanetary and heliocentric space. I learned about the Oberth effect from Dr. Nathan Strange of JPL, who said that if you make a planetary fly-by, you can gain a gravity boost, but this energy is specifically not useful for entering an orbit around the planet. The energy gained is only with respect to the sun. The solution was to have the paths to the fly-by space not intersect any of the circumplanetary spaces of that world. An entire page of rules were replaced by a geometric arrangement of the map. ***Candyland*** rules!

HOME ON LAGRANGE. Other than pockets of circumplanetary space, the entire Solar System is dominated by solar gravity. Yet there are null points here and there where gravity cancels out. These are the famed "Lagrange points" (The L5 society is named after Lagrange point 5). While taking astrophysics at U of A, I became acquainted with the LPL programmers for the Cassini mission. They showed me their programs and porkchops and explained how to shoot for these points during a mission. With solar gravity canceled, one could freely jump to a new orbit. The *Candyland* map accommodated Lagrange points easily, as natural intersections and jump-off points for many other trajectories.

TIME. The energy map handled fuel requirements accurately, but time was a different matter. After years of tinkering, I used a system of marker facing to put "lags" into the routes to make the mission require the correct number of years. Later, the concept was simplified to costing extra energy (and propellant) to change direction at intersections. At a Lagrange point a spacecraft can change direction without cost, in either time or energy.

HYDRATION. Water is the key to the solar system! Naturally water is essential for many biological activities, but this is a drop in the bucket to its usefulness as rocket propellant. Fortunately my camping buddy Dr. Jonathan Lunine (currently with Cornell) had just published an article about the accessibility of water everywhere in the solar system, the basis for the game's hydration system. Jonathan went on to write two textbooks (to which I contributed illustrations and editing): ***Earth, Evolution of a Habitable Planet*** and ***Xenobiology***.

THE OUTER WORLDS. Space is hazardous. Another camping buddy, Carolyn Porco, was the Mission Director of Cassini. Every time her team discovered a new moon or radiation current around Saturn, the game map got more complicated. Carolyn and Jonathan used to bicker around the campfire about which site (Jovian moons? Enceladus? Titan?) should get funding for the next outer planet mission. Naturally, they had opposite opinions about where I should locate my "high science" sites on the map. Carolyn favored Enceladus, which has a potential for subsurface oceans and life. Jonathan argued that his balloon observatory on Titan would give much more science results for the dollar.

RAD-HARDNESS. Both Carolyn and Jonathan agreed that the radiation of Jupiter (the highest in the solar system) argues against the exploration of Europa, another potential site with a subsurface ocean. I am familiar with radiation hardening of space vehicles I worked with at Raytheon I was and am involved in the radiation hardening of the exoatmospheric kill vehicle at Raytheon. Thus I know that shielding electronics from Jupiter's radiation belts would be heavy, costly, and risky. From this, radiation hardness evolved into the game's "defense factor".

A REGIME IN SPACE. I have extensively studied how politics influence the development of a frontier (see the designers notes in Pax Porfiriana for more on this). The key to any cutting-edge development is how much innovators are allowed the freedom to benefit from their own efforts. The political assembly in ***High Frontier*** is based on the Nolan Chart and expands the traditional left-right polarity to two dimensions.

WHERE FIRST? My game shows how and why man might first venture off Earth. But where to first? I met with two activists, Avery Davis of the Moon Society and Robert Zubrin of the Mars Society, with opposing views on this question. I eventually sided with Robert's position because of one key factor: water. There is water on asteroids and Luna, but the water on Mars is easier to attain. Water extraction technologies led to the breakthrough game concept of ISRU (in-situ resource utilization). ISRU, or "living off the land" is championed by Zubrin's "Mars Direct" proposals. Dr. Zubrin is also the inventor of two thrusters in the game: the Zubrin salt-water drive and the mini-magnetosphere drive.

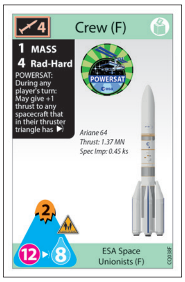
A THERMODYNAMIC ROCKET is a rocket with a fuel that releases thermal energy, and a nozzle to direct that energy into thrust. A new feature of HF4 is dividing a thermodynamic rocket into two parts: reactors (for generating power) and thrusters/nozzles (for collimating that power into a unidirectional beam). Earlier versions of the game had thrusters and reactors, but was not as rigorous in dividing them up into a power/geometry dichotomy. Unlike electric rockets, which might have propellant stagnation temperatures in the millions of degrees yet none of its components rise above room temperature, thermodynamic rockets run very hot for the best fuel economy. After all, temperature is nothing more than a measure of the speed of molecules as they fly around, and exiting these molecules as fast as possible conserves their mass.

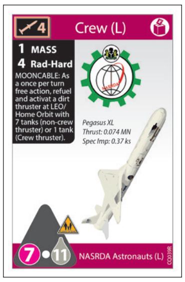
Phil Eklund, Sierra Madre Games, July 2015 (updated 2019).

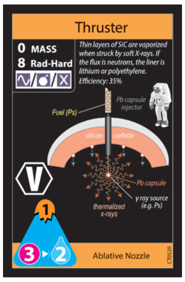
Z. Patent Card Descriptions (Phil Eklund & Noah Vale)

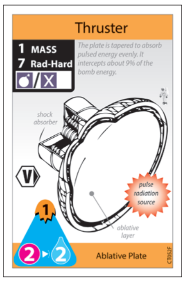
TEMPERATURES are listed in degrees Kelvin (K), (where 0 K is absolute zero, and water boils at 373 K). To convert degrees K into degrees C, subtract 273. Plasma temperatures are listed in kilo-electron volts (keV). To convert keV into degrees K, multiply by 11,604,000.

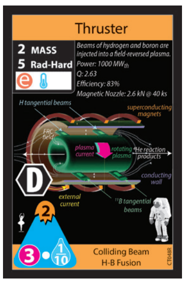
QUANTUM MECHANICS describe quite real and predictable laws of nature, that are commonly grossly misinterpreted due to widespread bad premises about the nature of physics, our means to describe the objective world. It is a myth that quantum mechanics "proves" that the universe operates under a different set of rules in the realm of the small, or that causality and objective reality are illusions. Every observation tells us something about either the phenomena being observed or the instrument doing the observing. If we stare at a star through a telescope, is the observed chromatic aberration a feature of the star, or the lens? If we observe a reproducible quantum effect, it undoubtedly tells us something about objective reality. But are we observing a property of the universe at large, or rather the way our minds work? Do we observe a feature of the quantum, or a feature of consciousness? I believe the latter. Is an observed photon a particle or a wave? Did it go through the top slit or the bottom slit? Is the cat alive or dead? Quantum entanglement, Heisenberg uncertainty, spooky action at a distance, these are all telling us relevant facts about our consciousness and its methodology of data compression. Why else would quantum effects only come into play if there is a human observer, and are strangely absent if nobody looks? Why do quantum devices such as q-computers, q-time machines, q-reactors, q-entanglement, q-transporters etc. never seem to make it to the prototype stage? For this reason, I have avoided quantum technology in the game.

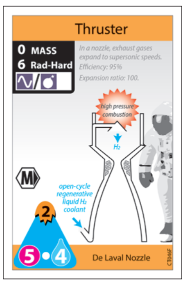












Z1. Crew Cards

Crew Card – Although not a patent card, your starting Crew represents the technology of consumables and life support as well as up to six astronauts. They are housed in 16 tonne inflatable Bigelow habitation modules (1760 m^3), made of Vectran (a "bulletproof" textile). Paired modules, 45 meters apart, are rotated at 5 RPM to provide 0.6 G of artificial gravity. Food and atmospheric conditioning is provided by crops that grow without soil but have their roots misted with nutrients daily. A plot 25 meters across provides all the foodstuffs for the year. Waste heat from plant evaporation requires low temperature radiators. A 10 tonne life support module requires 12 kW_e, and communications from Ka band antennas require another 0.2 MW_e. A charged plasma sustains a high electrical potential (10 GeV) about the hab unit for protection against most galactic cosmic rays. When a charged particle passes through this magnetic field, its path curves to avoid the occupants. If a solar storm erupts, the Crew must evacuate into a small (8m dia) storm shelter. The shelter is shielded by 100 kg/m^2 of polyethylene (12 cm thick), plus water propellant and graphite.

Chemical Thrusters – Most of the Crew cards include a chemical thruster, either liquid or solid fuel. The liquid fuel thrusters burn the cryogenic fuels hydrogen and oxygen for a vacuum specific impulse of 0.53 ks (equivalent to a fuel consumption of 8 in the game). The product is water, which is exhausted through a converging-diverging tube called a de laval nozzle. An example is the Space Shuttle main engine (SSME): specific impulse = 0.46 ks, 180:1 area ratio nozzle, regeneratively-cooled with liquid hydrogen, mixture ratio = 5.4, chamber temperature = 3500 K, chamber pressure = 2.8 MPa, thermal efficiency = 98%, frozen-flow efficiency = 55%, power = 2 GW_{th}, thrust = 440 kN (game value 10), initial thrust to weight ratio = one gravity. The solid fuel thrusters, simulated as dirt thrusters in the game, far lower specific impulses between 0.1 and 0.3 ks. –*Space Transportation Systems*, American Institute of Aeronautics and Astronautics, New York, 1978.

Z2. Thruster Cards

A rocket thruster is a device that accelerates in one direction by ejecting mass in the other direction. A sail thruster also uses the action-reaction principle to accelerate, but uses ambient mass rather than internal mass. Thrust is measured in kN (kilonewtons, about 100 kg). Thruster fuel economy is traditionally measured by specific impulse (I_{sp}), as measured in ks (kiloseconds). I won't bother to explain what specific impulse is, other than to say if you divide 4 by this value (in ks) you get the game's fuel economy number. Furthermore, if you multiply this value (in ks) by 10, you get its exit velocity (the speed of the propellant as it exits the nozzle) in kilometers per second. A rocket's exit velocity (Ve) in km/sec times its propellant flow in kg/sec is equal to its thrust in kN. Ve is also used in the rocket equation: delta-v (km/sec) = Ve * ln(wet mass/dry mass).

Ablative Nozzle Thruster – A hemispherical nozzle lined with a sacrificial material that is converted into reaction mass when vaporized by pulsed radiation. The reaction occurs externally, at the center of the hemisphere, such that half the reaction energy flies into space and is wasted. If the radiation is neutrons, then the liner is lithium or polyethylene (the latter absorbs 98% of neutrons in 4 cm). If the radiation is hard gammas, such as from an antimatter reaction, the radiation must first be thermalized (i.e. softened) by surrounding the fuel pellet with a layer of lead. Then the thermalized x-rays strike a thin film of silicon carbide (SiC) in the ablative nozzle for thrust.

Ablative Plate Thruster – A nozzle can be plate-shaped. External pulsed energy is intercepted, and a thin film of the plate is vaporized and expelled. This expellant is a type of collimated propellant. Project Orion uses a shock-absorbed plate, tapered so as to absorb nuclear energy evenly. Ablation requires more thermal management than other nozzles.

Colliding Beam H-B Fusion Thruster –Hydrogen and boron-11 can be brought to fusion by energetically colliding a tangential beam of H with ^{11}B in a FRC (field-reversed configuration) plasma. If in a magnetic mirror configuration, the helium-4 reaction products are exited for thrust. The Q is 2.63. With open-cycle cooling, a specific impulse of 40 ks is attained. The efficiency of 83% assumes that some means of controlling the bremsstrahlung radiation is found.

De Laval Nozzle Thruster – The familiar converging-diverging shape of the de laval nozzle is designed to accelerate a propellant flow to supersonic speeds. Its operation relies on the different properties of gases flowing at subsonic and supersonic speeds. As the nozzle constricts, the speed of a subsonic flow of gas will increase to maintain a constant flow rate. The gas flow through a de laval nozzle is isentropic (gas entropy is nearly constant). At subsonic flow the gas is compressible; sound, a small pressure wave will propagate through it. At the throat, the gas velocity locally becomes sonic (Mach number = 1.0), a condition called choked flow[4]. As the nozzle cross-sectional area increases the gas expands and the gas flow increases to supersonic velocities where a sound wave will not propagate backwards through the gas as viewed in the frame of reference of the nozzle (Mach number > 1.0). For high pressure chambers an expansion ratio (ratio of throat area to exit area) of 100:1 is used to capture enough heat for a nozzle efficiency of 90%. It is regeneratively-cooled by passing liquid hydrogen coolant through channels surrounding the nozzle wall. The heated hydrogen is then injected into the rocket as propellant.

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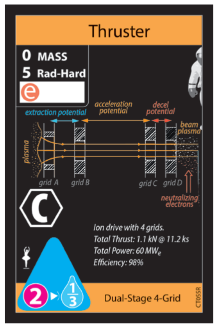
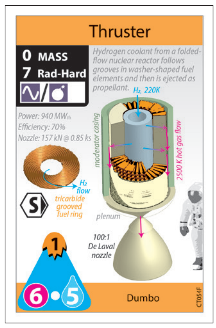
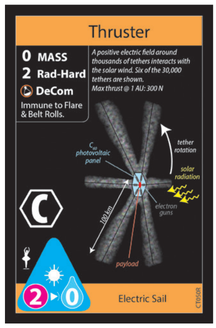
4 CHOKED FLOW. Every child with a balloon knows that rockets need nozzles, but some of the magic of nozzles is lost in dry explanations. To personify this a bit, imagine a nozzle as a 2-man team, with "Charlie" being the one responsible for delivering the propellant, while you travel in a bubble in the propellant itself. As you travel towards the narrow throat, the pressure rises but you yell at Charlie to increase his pressure to keep the fluid flow constant. A constant mass of fluid in an ever constricting chamber goes faster, as when you pinch a hose to squirt your sister. Soon you are traveling Mach 1, when suddenly the nozzle expands and the pressure plummets. You yell at Charlie, but now you are supersonic, and your words can't reach him. Because the flow is "choked", decreases in the downstream pressure won't increase the mass flow, because Charlie can't hear you. You now accelerate screaming to the supersonic speeds necessary for low fuel consumption.



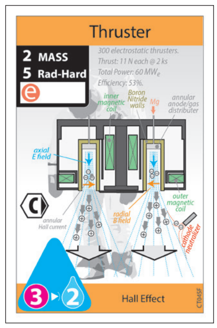
Dual-Stage 4-Grid Thruster – This type of ion thruster is derived from the ion accelerators in experimental fusion reactors. Unlike traditional ion thrusters which use 2 or 3 electrostatic grids to perform ion extraction and acceleration simultaneously, the DS4G uses two pairs of grids to decouple ion extraction from acceleration. This decoupling allows for a greater acceleration chamber length, and therefore higher exhaust velocity (11-14 ks). It also allows a higher potential (80kV) on the last grid pair, for decreased grid erosion and nozzle beam divergence (less than half a degree versus 15 degrees on conventional ion drives). –C. Bramanti, R. Walker, *et al., The innovative dual-stage 4-grid ion thruster concept – Theory and experimental result*s, 2006.



Dumbo Thruster –A "pachydermal" NTR (nuclear thermal rocket) maximizes the gas flow path through a heat exchanger, for greater efficiency and less mass at extracting coolant energy from a variety of nuclear reactions. Rather than have the gas flow from one end of the reactor to the other through straight pipes, the propellant in Dumbo would flow part of the way down the reactor core, then move radially (sideways) for a while, and then returns to flowing along the main axis of the reactor before exiting the nozzle. This change in flow path, called "folded flow", allowed less volume and mass for the same thrust (7500 MW/m^3). To increase the fuel element maximum temperature, advanced Dumbos use reflector geometry, hydride moderators, and "grooved-washer" fuel elements made of UC-ZrC carbide or tricarbides of uranium, zirconium, and tantalum. –Bill Kirk, *Dumbo, a Pachydermal Rocket Motor,* Los Alamos National Laboratory 1992. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920001882.pdf; Brian Taylor and Bill Emrich, *Investigation of a Tricarbide Grooved Ring Fuel Element for a Nuclear Thermal Rocket*, 2017.

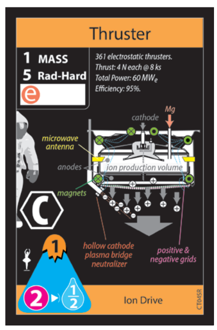


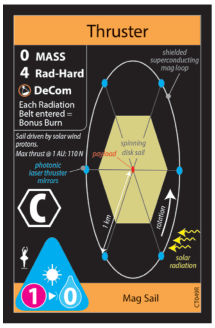
Electric Sail Thruster – The solar wind dynamic pressure varies but is on average about 2 nPa at one AU. An electric sail generates thrust from this stream of particles in a manner similar to a mag sail, except that electric rather than magnetic fields are used. The electric sail geometry employs hundreds of long (e.g., 100 km), thin (e.g., 20 microns) conducting tethers (wires). The entire sail rotates with a period of 20 minutes to keep its wires in positive tension. A solar-powered electron gun (typical power a few hundred watts) is employed to keep the spacecraft and the wires in a high (up to 20 kV) positive potential. The electric field surrounds each wire a few tens of meters into the surrounding solar wind plasma. Therefore the solar wind ions "see" the wires as rather thick obstacles. It is this multiplication factor that allows sails using the solar wind to outperform sails using photon pressure, which is 5000 times stronger. The positively-charged tethers repel solar wind protons, thus deflecting their paths. Each 100 km tether, massing but a kilogram, generates 0.01 N of thrust this way. Simultaneously it also attracts electrons from the solar wind plasma, which are neutralized by the electron gun. Potentiometers between each tether and the spacecraft control the attitude by fine-tuning the tether potentials. Additionally, the thrust may be turned on or off by simply switching on or off the electron gun. To make the design robust against meteoroids, each tether is composed of multiple wires with redundant interlinking. A variant of the electric sail is the dipole drive, which replaces the single positively-charged screen with two parallel screens, one positive and one negative. This allows the sail to maneuver by accelerating either ambient protons or electrons, permitting travel within magnetospheres and allowing the sail to travel faster than the solar wind. The dipole sail can achieve more than 6 mN/kW_e in interplanetary space and better than 20 mN/kW_e in Earth, Venus, Mars, or Jupiter orbit. – ***Electric Sail,*** AIAA Journal of Propulsion and Power, *Electric Sail,*2004; Janhunen, P. and A. Sandroos, *Simulation study of solar wind push on a charged wire: solar wind electric sail propulsion,* 2007; Robert Zubrin, 2018.



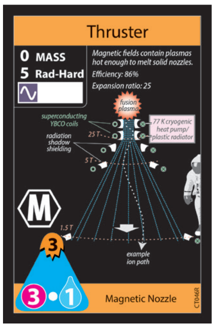
Hall Effect Thruster – This ion rocket accelerates ions using the electric potential maintained between a cylindrical anode and negatively charged plasma which forms the cathode. To start the engine, the anode on the upstream end of the thruster is charged to a high positive potential by the thruster's power supply. Simultaneously, a hollow cathode at the downstream end generates electrons. As the electrons move upstream toward the anode, they encounter a magnetic field produced by powerful electromagnets. This field traps the electrons, causing them to form into a circling ring at the downstream end of the thruster channel. The Hall thruster gets its name from this flow of electrons, called the Hall current. This gyrating current collides with a stream of magnesium propellant, creating ions. As the propellant ions are generated, they experience the electric field produced between the anode (positive) and the ring of electrons (negative) and exit as an accelerated ion beam. A significant portion of the energy required to run the Hall Effect thruster is used to ionize the propellant, creating frozen flow losses. This design also suffers from erosion of the discharge chamber. On the plus side, the electrons in the Hall current keeps the plasma substantially neutral, which allows much greater thrust densities than ion drives.

Ion Drive Thruster –An electrostatic particle accelerator in space is effectively an electric rocket. The illustrated design uses a combination of microwaves and spinning magnets to ionize the propellant, eliminating the need for electrodes, which are susceptible to erosion in the ion stream. The propellant is any metal that can be easily ionized and charge-separated. A suitable choice is magnesium, which is common in asteroids that were once part of the mantles of shattered parent bodies, and which volatizes out of regolith at the relatively low temperature of 1800 K. The ion drive accelerates magnesium ions using a negatively charged grid, and neutralizes them as they exit. To reduce grid erosion, C–C grids are used. Since the stream is composed of ions that are mutually repelling, the propellant flow is limited to low values proportional to the cross-sectional area of the acceleration region and the square root of the voltage gradient. Decoupling the acceleration from the extraction process into a two-stage system allows the voltage gradients to reach 30 kV without vacuum-arcing, corresponding to exit velocities of 80-210 km/sec. A 60 MW_e system with a thrust of 1.5 kN utilizes a hexagonal array, 25 meters across, containing 361 accelerators. Frozen flow efficiencies are high (96%). To boost the acceleration (corresponding to the "open-cycle cooling" game rule), colloids are accelerated instead of ions. Colloids (charged sub-micron droplets of a conducting non-metallic fluid) are more massive than ions, so a colloidal thruster boosts thrust at the expense of fuel economy.

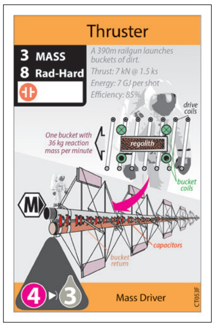




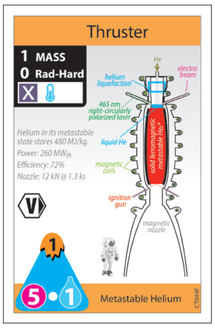
Mag Sail Thruster– A magnetic sail maneuvers by reaction with the protons of the solar wind. At 1 AU, this wind comprises several million protons per cubic meter, spiraling away from the sun at 400 to 600 km/sec (256 µwatts/m^2). When such charged particles move through a magnetic field formed by the mag sail, a tremendous loop of wire some 2 km across, they are deflected. An unloaded mag sail this size has a thrust of 100 newtons (at 1 AU) and a mass of 20 tonnes. The wire is superconducting whisker, at 10 kg/km, connected to a central bus and payload via shroud lines. The loop requires a simple multi-layer insulation and reflective coatings to maintain its superconducting temperature of 77 K. Because the sail area is a magnetic field, which has no mass, a mag sail has a superior thrust/weight ratio than photon sails. Just as with photon sails, lateral motion is possible by orienting the sail at an angle to the thrusting medium. A magnetic sail can also develop thrust from planetary and solar magnetospheres, which decrease as the fourth power of the distance from the magnetosphere source. Field strength is typically 10 µT (in Earth's magnetosphere) or less in the solar magnetosphere. The mag sail illustrated has its thrust augmented by a spinning disk photon sail attached to its staying lines. The sail is maneuvered using photonic laser thrusters (propellantless thrust derived from the bouncing of laser photons between two mirrors).



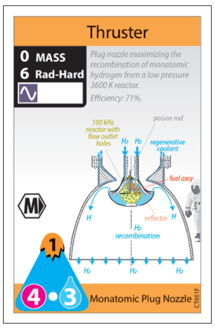
Magnetic Nozzle Thruster – High specific impulse thermodynamic rockets benefit from a nozzle that is not limited by the melting point of its material. Magnetic nozzles direct the exhausted flow of ions or a conductive plasma by use of magnetic fields instead of walls made of solid materials. The design illustrated operates at a throat magnetic field strength of 25 T and a nozzle efficiency of 86%. Its coils are made of a high temperature superconductor such as YBCO. Tungsten blades cover 1% of the nozzle's area to intercept 2% of the fusion radiation. The blades do not require cooling (they radiate their heat away) but use a layered Mylar/vacuum heat shield to prevent heat conduction to the coils. A cheaper alternative radiation shield is carbon, which at 1500 K radiates away 287 kW/m^2. A 12 cm thickness of carbon reduces the fraction of 14 MeV neutrons that get through to <0.001. Plastic radiators keep the YBCO operating at liquid nitrogen temperatures (77 K). The design illustrated operates at a throat magnetic field strength of 25 T and a nozzle efficiency of 86%.



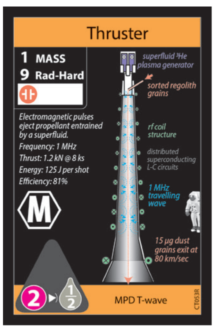
Mass Driver Thruster – An electrodynamic traveling-wave accelerator can be used as either a thruster or a payload launcher. Either system uses a lightweight bucket, banded by a pair of superconducting loops acting as armatures of a linear-electric guideway, loaded with of regolith (or anything else handy). The thruster illustrated accelerates the payload at 50,000 gravities, utilizing 3.8 GJ of electromagnetic energy stored inductively in superconducting coils. The trackway length is 390 meters. The 36 kg of payload is ejected at 11 km/sec every 30 seconds while the bucket is decelerated and recovered. Efficiency is 85%, although cryogenic 77 K radiators are needed to cool the superconductors. A mass-driver optimized for materials transport rather than for propulsion uses a higher ratio of payload mass to bucket mass. With a 54% duty cycle, this system can launch 10 kt/yr. of factory products or stones. Coupled with a pointing accuracy in the tens of microradians, the latter can launch payloads or threaten enemy bases at destinations millions of kilometers away. The ejected mass velocity is equal to the Earth escape velocity (11 km/sec), making it feasible for a terrestrial mass driver to launch payloads up the side of a convenient equatorial mountain. Imparted with a launch energy of 76 GJ, a one tonne payload the size and shape of a telephone pole with a carbon cap would burn up only 3% of its mass and lose only 20% of its energy on its way to solar or Earth orbit. –Gerard K. O'Neill, *The High Frontier: Human Colonies in Space*, 1977.



Metastable Helium Thruster – Metastable helium is the electronically excited state of the helium atom, easily formed by a 24 keV electron beam in liquid helium. If the spin-orbit decay could be suppressed by a coherent laser pump, its theoretical lifetime would be eight years (as ferromagnetic solid He*2 with a melting temperature of 600 K). Spin-aligned solid metastable helium is a useful, if touchy, high thrust chemical fuel with a theoretical specific impulse of 3.2 ks. –J.S. Zmuidzinas, *Stabilization of He2(a ^{3}Sigma$_u$+) in Liquid Helium by Optical Pumping*, unpublished (1976).

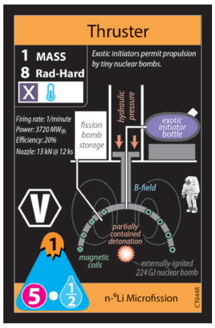


Monatomic Plug Nozzle Thruster – Monatomic hydrogen has half the molecular weight of molecular hydrogen so it has a much higher performance in a thermodynamic rocket (specific impulse >1.32 ks). However, temperatures hot enough to disassociate hydrogen (>3000 K) would destroy a solid core reactor unless the pressure was low enough so that the heat actually delivered is low. Most NTRs run at 31 bar, but a monatomic reactor runs at only 1 bar, for 50X less heat flux and no need for turbopumps. The core is spherical, with propellant introduced into the center and exiting through outlets on the surface at a temperature of 3600 K. The fission fuel elements can be any geometry: pebbles, washers, twisted ribbons, whatever. The plug nozzle is much shorter than standard NTRs, due to the low pressure and heat flux. The plug design is to maximize recombination at an efficiency of 71%. Use of hydrogen to control the reaction eliminates the need of control drums. –J.H. Ramsthaler, *Low Pressure Nuclear Thermal Rocket Concept (LPNTR)*, 1991.

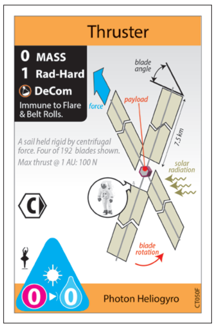


MPD T-wave Thruster – Impulsive electric rockets can accelerate propellant using magnetoplasmadynamic traveling waves (MPD T-waves). In the design shown, superfluid magnetic helium-3 is accelerated using a megahertz pulsed system, in which a few hundred kiloamps of currents briefly develop extremely high electromagnetic forces. The accelerator sequentially trips a column of distributed superconducting L-C circuits that shoves out the fluid with a magnetic piston. The propellant is micrograms of regolith dust entrained by the superfluid helium. The dust and helium are kept from the walls by the inward radial Lorentz force, with an efficiency of 81%. Each 125 J pulse requires a millifarad of total capacitance at a few hundred volts. Compared to ion drives, MPDs have good thrust densities and have no need for charge neutralization. However, they run hot and have electrodes that will erode over time. Moreover, small amounts of an expensive superfluid medium are continually required.

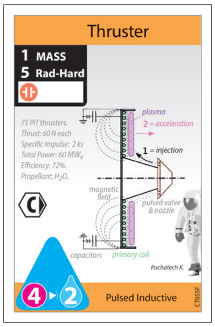
n-^{6}Li Microfission Thruster – Rockets that fly by using atomic explosions, such as Project Orion, require huge shock absorbers, due to the fact that the minimum explosive yield for fission bombs is about a quarter kiloton. The pulse size can be brought down to microfission levels by the use of exotic particles. The isotope of lithium ^{6}Li can be brought to a spontaneous nuclear reaction (I am unsure if this would be fission or fusion) by interaction with particles with very large reaction cross-sections such as ***ultracold neutrons***. No "critical mass" is required. This is a clean reaction, with charged particles (T and He) as products, each at about 2 MeV. The system illustrated uses a 5 meter magnetic nozzle to transfer the microexplosion energy to the vehicle. This maintains the advantage of magnetic impulse transfer indicated by the MagOrion concept (combination of Orion and the magnetic sail). A fuel reaction rate of 30 mg/sec produces 2000 MW_{th}. At a pulse repetition rate of one 224 GJ detonation every 2 minutes, the thrust is 5 kN at a 16 ksec specific impulse. A hydraulic fixture oscillates at a tuned frequency to provide a constant acceleration to the spacecraft. The combined frozen-flow and nozzle efficiencies are 25%, and the thermal efficiency is 80%. –Ralph Ewig, *Mini-mag Orion Concept*, modified for n-Li^{6} fission.



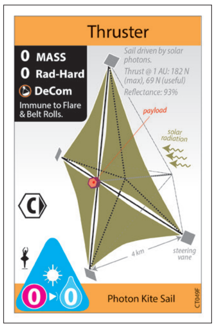
Photon Heliogyro Sail – A photon sail consisting of multiple spinning blades is called a heliogyro. Its blades are rigidized by centrifugal force and pitched to provide attitude control, much like a helicopter. Although a spinning design does not need the struts of a kite sail, the centrifugal loads generated must be carried by edge members in the blades. Moreover oscillations are created when the sail's attitude changes, which need to be restrained by transverse battens. Small sail panels prevent wrinkling from the curvature in edge members between the battens. For these reasons, the heliogyro has no mass advantage over a kite sail, but it has the advantage of easier deployment in space. The reference design at 1 AU generates 100 newtons (maximum) from 4 banks of 48 blades each. Each blade has a dimension of 8 x 7500 m. The sail film is 1 µm thick with reflective and emissive coatings. Each bank is fixed to a hub so the members co-rotate. The combined film masses 7 tonnes alone, and with the supporting cables mass 20 tonnes. –Jerome Wright, *Space Sailing*, pp. 82-88, 1992 (scaled up).



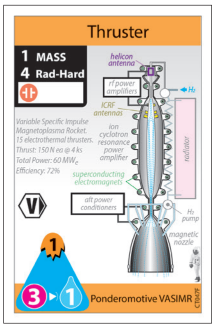
Pulsed Inductive Thruster – PIT is a type of magnetoplasmadynamic (MPD) thruster with many advantages over other electric thrusters. It handles a huge range of propellants, from water to ammonia to hydrazine, allowing a "live off the land" ISRU approach to solar system exploration. A PIT thruster doesn't need an electrode, which is a major causes of wear in most thrusters. Finally, its non-steady state operation allows it to maintain a specific impulse over a wide range of power levels. The pulse is in two stages: first gaseous propellant is sprayed in brief jets onto a flat induction coil, which is then discharged for a very brief period from a bank of capacitors (usually in the nanosecond range), causing the gas to become ionized and then accelerated through the Lorentz force. The frequency of pulses and thus the thrust is dependent on the time it takes to charge the capacitors. –Frisbee, 2005.



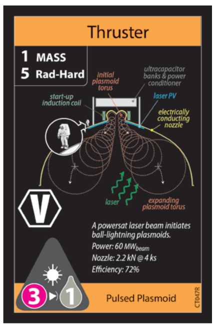
Photon Kite Sail – The simplest way to hold a sail out to catch sunlight is to use a rigid structure, much like a kite. The columns and beams of such a structure form a three-axis stabilization, so-named because all three dimensions are rigidly supported. Kite sails are easier to maneuver than sails that support themselves by spinning. By tilting the sail so that the light pressure slows the vessel down in its solar orbit will cause an inward spiral towards the sun. Tilting the opposite way will cause an outward spiral. The kite sail shown has a mast, 4 booms, and stays supporting a square sail 4 km to a side. At 93% reflectance, it develops a maximum thrust of 100 newtons at 1 AU. Control is provided by 4 steering vanes at the ends of the booms of 20,000 m^{2} area each. It has an unloaded mass of 16,000 kg and 1 g/m^{2} unloaded sail loading. A sail this light must be quite thin (300 nm aluminum film) and perforated with holes the size of the wavelength of visible light. (It is not necessary to have a full surface to reflect light). The perforated microstructure is formed by DNA scaffolding, which is then coated with aluminum and the DNA baked off. The kite sail is thermally limited to 600 K, and cannot operate in an Earth orbit lower than 1000 km due to air drag. Its thrust can be increased tenfold by the illumination of the 60 MW laser beam which is standard in this game. Operating at 50 Hz, this beam boils off water coolant replenished through capillary action in the perforated film. Tiny piezoelectric robot sailmakers repair ablated portions of the sail using vapor-deposited aluminum. –J. M. Garvey, *Space station options for constructing advanced solar sails capable of multiple mars missions*, AIAA Paper 87-1902, AIAA/SAE/ASME 23rd Joint Propulsion Conference, San Diego, California, 1987 (Twice the size of Garvey's Large Square Rigged Clipper Sail).

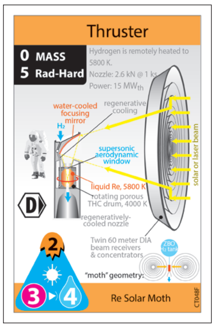


Ponderomotive VASIMR Thruster – VASIMR stands for variable-specific-impulse magnetoplasma rocket. This electric rocket has two unique features, the removal of the anode and cathode electrodes (which greatly increases its lifetime compared to other electric rockets) and the ability to throttle the engine, exchanging thrust for specific impulse. A VASIMR spacecraft would use low gear to climb out of planetary orbit, and high gear for interplanetary cruise. Other advantages include efficient resonance heating (80%), and relatively low current and high voltage power conditioning, which saves mass. Propellant (typically hydrogen, although many other volatiles can be used) is first ionized by helicon waves and then transferred to a second magnetic chamber where it is accelerated to ten million degrees K by an oscillating electric and magnetic fields, also known as the ***ponderomotive force***. A hybrid two-stage magnetic nozzle converts the spiraling motion into axial thrust at 97% efficiency.
– Franklin Chang-Diaz, ***et al.***, *The Physics and Engineering of the VASIMR Engine, 2000.*



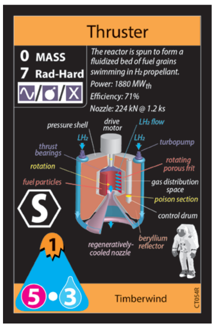
Pulsed Plasmoid Thruster – A plasmoid is a coherent torus-shaped structure of plasma and magnetic fields. "***Kugelblitz***" (ball lightning) is a terrestrial example of a plasmoid (one of my mentors, Dr. Roger C. Jones of the University of Arizona, has demonstrated the physics of this). A plasmoid rocket creates a torus of ball lightning by directing a mega-amp of current onto the propellant. Almost any sort of propellant will work. The plasmoid is expanded down a diverging electrically conducting nozzle. Magnetic and thermal energies are converted to directed kinetic energy by the interaction of the plasmoid with the image currents it generates in the nozzle. Ionization losses are a small fraction of the total energy; the frozen flow efficiency is 90%. Unlike other electric rockets, a plasmoid thruster requires no electrodes (which are susceptible to erosion) and its power can be scaled up simply by increasing the pulse rate. The design illustrated has a 50 m diameter structure that does quadruple



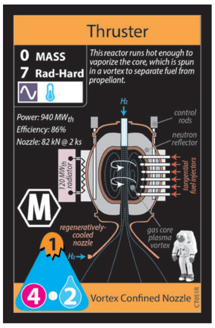


duty as a nozzle, laser focuser, high gain antenna, and radiator. Laser power (60 MW) is directed onto gap photovoltaics to charge the ultracapacitor bank used to generate the drive pulses. –R. Bourque, *General Atomics, 1990.*

Re Solar Moth Thruster – Solar thermal rockets collect sunlight and focus it on propellant headed for the nozzle. The "moth" geometry uses two 60m diameter mirrored-Mylar "wings" (7g/m^2) to concentrate the light. Unfortunately, hydrogen propellant is essentially transparent to sunlight, so a high-temperature heat exchanger is necessary. This heat exchanger is a rotating porous drum made of Tantalum-Hafnium Carbide (THC), which is regeneratively-cooled to remain solid at 4000 K. The propellant/coolant is then pumped at high pressure through pores in the drum, emerging as plasma bubbles into the next heat exchange stage: a bed of liquid rhenium. Rhenium (Re) melts at 3459 K but remains liquid up to 5903 K. Rotation of the drum creates artificial gravity by which the hydrogen bubbles rise through the denser rhenium and get centrally exhausted through a de laval nozzle. The propellant temperature is 5800 K, the same as the solar surface, which corresponds to a specific impulse of 1.2 ks (for hydrogen) or 0.5 ks (for water). –F.G. Etheridge, *Solar Rocket System Concept Analysis, Rockwell Space Systems Group* (resized for 3 kN thrust), Malik K. (Matterbeam), 2017.



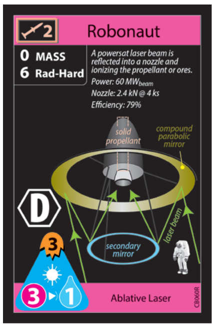
Timberwind Thruster – In this type of NTR reactor, the fluid propellant/coolant is pumped through a fluidized bed of solid fuel pellets with enough velocity to suspend the pellets and cause them to behave as a fluid. The reactor spins at 3000 rpm, enough to hold the fuel pellets in place with centripetal force as the hydrogen propellant flows through them. Since the pellets are not held in a static rod, they can move through the reactor as it heats and cools. This reduces the fuel strength requirements, permitting a higher temperature and specific impulse (1.2 ks) than solid-core NTR's. – El-Genk *et al.*, 1990; Ludewig, 1990; Horman *et al.*, 1991; ISNPS, 2003.



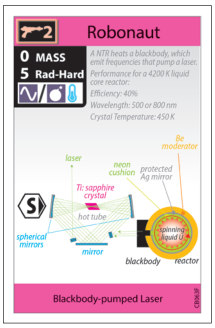
Vortex Confined Nozzle Thruster – The hotter the core of a thermodynamic rocket, the better its fuel economy. If it gets hot enough, the solid core vaporizes. A vapor core rocket mixes vaporous propellant and fuel together, and then separates the propellant out so it can be expelled for thrust. Energy is efficiently transferred from fuel to propellant by direct molecular collision, radiative heat, and direct reaction fragment deposition. The open-cycle arrangement illustrated accomplishes this by spinning the plasma mixture in a vortex maintained by tangential injection of preheated propellant from the reactor walls. The denser material is held to the outside of the cylindrical reactor vessel by centrifugal force. The fuel is subsequently cooled in a heat exchanger and recirculated for re-injection at the forward end of the reactor, while the propellant is exhausted at high velocity. For fission reactions, the outer annulus of the vortex is high-density liquid uranium fuel, and the low-density propellant is bubbled through to the center attaining temperatures of up to 18500 K. A BeO moderator returns many reaction neutrons to the vortex. Maintaining a critical fuel mass given the turbulent flow of water or hydrogen propellant requires advanced prompt feedback actuators. Since the core has attained meltdown, reaction rates must be maintained by fuel density variation rather than with control rods or drums. For antimatter reactions, swirling liquid tungsten (about 4 cm thick) is used instead of uranium, for absorbing hard x-rays. For fusion reactions, it is the propellant that is cooler and higher in density, and thus it is the reacting fuel ball that resides at the center of the vortex.

Z3. Robonaut Cards

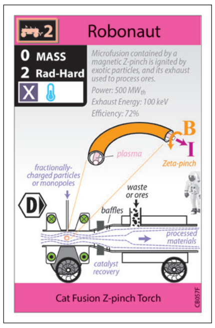
Rather than being robots, which rely on their own programmed intelligence for decision-making, "robonauts" are mechanical avatars, remotely piloted by a human. This term was created for the game. The motivation is simple: spacesuit hours are expensive, hazardous, and uncomfortable. Rather to place the human in a shirtsleeeve environment in a nearby space station, with time for pizza breaks and recreational sex, while a robonaut does the prospecting, radiator maintenance, heavy lifting, mining, and building/servicing of the refinery. The Bernal space station must be rather close by, since each AU of distance adds over 16 minutes of lag time, time for the signal to travel to the human and back again at the speed of light.



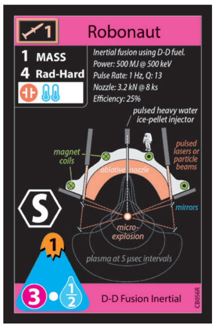
Ablative Laser Robonaut – A rocket can be driven by high-energy, short-duration (<10^{-10} sec) laser pulses, focused on a solid propellant. A double-pulse system is used, in which one laser pulse ablates material and a second laser pulse further heats the ablated gas. A low Z propellant such as graphite obtains the best fuel economies (4 ksec). (Unfortunately, ice is not a suitable medium due to melting and "dribbling" losses.) Primary and secondary mirrors focus the laser pulses at irradiances of 3×10^{13} W/cm^2. The mass-removal rate is 3.0 µg per laser pulse. Powered with a 60 MW laser beam, an ablative laser thruster has a thrust of 2.4 kN and, with a fuel tuned to the firing sequences and an efficient double-pulsed shape, an overall efficiency of 79%.
– Dr. Andrew V. Pakhomov, UAH, *Specific Impulse and other Characteristics of Elementary Propellants for Ablative Laser Propulsion*, 2002.



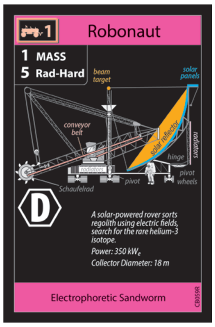
Blackbody-pumped Laser Robonaut – This uses a reactor heat source to heat up a blackbody emitter, which radiates strongly in certain wavelengths that lasing materials can be pumped with. Lasing materials that overlap with blackbody emissions at 2000 to 3000 K include crystals such as Nd:YAG (1060 nm), gases such as iodine, or fibers such as erbium-doped lithium-lanthanide-fluorine (1530 nm). These materials sit inside a "hot tube" in order to recycle heat. Some designs use a diffraction grating to extract the desired wavelengths from the blackbody spectrum. A liquid core reactor using molten uranium can elevate the blackbody temperature to 4200 K. A good fit to this spectrum is a titanium-sapphire laser, operating at 450 K with 40% efficiency. A gas core reactor elevates the blackbody to 19,000 K, suitable for a xenon-fluoride gas laser (350nm) operating at 800 K with 39% efficiency. Blackbody laser have rather long wavelengths, so frequency doubling is used to avoid the huge optics that would otherwise be needed to traverse the vast distances in space.
– Malik K. (Matterbeam), *Nuclear Reactor Lasers: from Fission to Photon, 2019.*



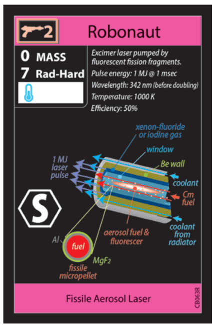
Cat Fusion Z-pinch Torch Robonaut – A plasma torch driven by catalyzed fusion may be used in the refining of ores or the recycling of waste materials. Fusion occurs in a zeta-pinch, a high-density fast-pulsed plasma focusing device, using a vanadium-gallium (V3Ga) superconductors and aluminum stabilizers. The confining force of the zeta-pinch is a "self-generated" magnetic field (a field set up by electric currents in the plasma itself). The megamp electric current (I) is in the zeta direction, and the resulting magnetic field (B) is in the theta direction. A variety of hypothetical exotic particles catalyze the D-T and D-D fusions. Catalyst escape is minimized by the Z-pinch configuration, but is enhanced downstream by high temperature staged cascades of modulated sorting nanorotors, which are themselves continually destroyed and rebuilt.



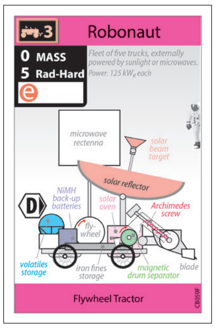
D-D Inertial Fusion Robonaut – A "target" of fusion fuel can be brought to ignition by "inertial confinement": the process of compressing and heating the fuel with beamed energy arriving from all sides. A snowflake of deuterium, the "heavy" isotope of hydrogen, can be imploded and fused with a combination of lasers and deuterium particle beams. The illustrated design uses combined input beam energy of 38 megajoules, arrayed in a ring surrounding the ejected iceball target. This energy operates at 1 Hz to blast a 2 gram ice pellet ejected each second. The outside 99% of the pellet is ablated away within 10 ns, super-compressing the deuterium fuel at the core to a density of a kilogram per cubic centimeter. The T and ^{3}He products are catalyzed to undergo further fusion until all that remains is hydrogen, helium and some neutrons. (Neutrons comprise 36% of the reaction energy.) Fractional burn-up of the fuel (30%) is twice that of magnetic confinement systems, which implies a 40% higher fuel economy. The energy gain factor (Q) is 13. For a 500 MW_{th} reactor, 320 MW of charged particles are produced, which can be used directly for thrust or metals refining. About 105 MW of fast neutrons escape to space, but another 75 MW of them are intercepted by the structure. About two thirds of this energy must be rejected as waste heat, but the remainder is thermally used to generate electricity or to breed tritium to be added to the fuel to facilitate the cat D-D pellet ignition. When used as a rocket, an ablative nozzle, made of nested layers of whisker graphite whose mass counts as propellant and shadow shield, is employed. –R. Hyde, *A Laser Fusion Rocket for Interplanetary Propulsion*, 34th International Astronautical Conf., AIF Paper 83-396, Budapest, Hungary, 1983. (To keep radiator mass under control, I reduced the pellet repetition rate from 100 Hz to 1 Hz).



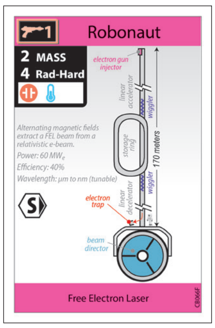
Electrophoretic Sandworm Robonaut – The mining vehicle depicted, called a ***sandworm***, is designed for regolith devolatilization. It consists of a ***Schaufelrad*** (shovel-wheel) and conveyor belts to transport material to a central hopper, which holds a soil pressurizer, grinding mill and heater, solid - vapor separator, volatiles collector bag, tailings disposal, and gas cleaner / reheater / repressurizer. A solar concentrator is pivoted to concentrate sunlight onto a heat engine target. The term "sandworm" is inspired by the huge worms that appear in the novels of Frank Herbert, which filter huge amounts of sand for tiny amounts of valuable "spice". Here, the "spice" is helium-3, a substance not found on Earth, but present in tiny amounts in asteroidal and lunar regolith. Helium-3 is necessary for the clean ^{3}He-D fusion reaction, and thus in the future may become more valuable than oil. After the irons are magnetically removed, the remaining regolith is processed in a high-voltage zone electrophoretic tank. (Electrophoresis beneficiates charged particles in an electric field according to the magnitude and sign of the electrophoretic mobility.) A 30 tonne sandworm of the size depicted operates with 350 kW_e derived from beamed power (using a 12 MW beam). It would process 9 million tones of regolith a year, yielding 110 tonnes of water (propellant), 200 tonnes of hydrogen (propellant), and 33 kg of helium-3 (fuel). –Based on Gajda NASA academy model Mark 2 and 3 sandworms.



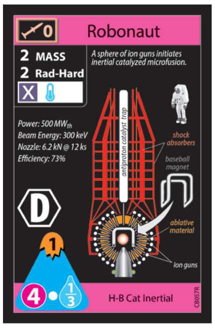
Fissile Aerosol Laser Robonaut – This is an excimer laser pumped by fission fragments instead of electron beams. The micrometer-sized fissile particles are held at high temperatures and surrounded by a moderator. Their output strikes an iodine gas mixtures to create I2* excimers. These return to their stable state by releasing photons of specific wavelength through fluorescence. Pulses of 1 MJ energy and 1 millisecond duration are produced at a wavelength of 342 nm. Conversion efficiency is 50%. Waste heat is reduced by use of polished aluminum acting as a UV mirror. The overall high temperature operation allows heat rejection at 1000 K. – Prelas, Boody, Zediker, *An Aerosol Core Nuclear Reactor for Space-Based High Energy/Power Nuclear-pumped Lasers, 1985.*



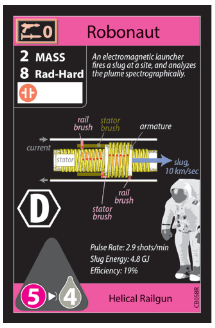
Flywheel Tractor Robonaut – A fleet of a half dozen wheeled mining haulers. Each is capable of scooping and hauling 120 tonnes of iron fines or volatiles per year over rugged terrain, using a 6 MW (8500 horsepower) flywheel motor. The flywheel is recharged via a microwave rectenna. Acting as a long-range rover, its dynamic active neutron spectrometer homes in on hydrogen signals indicating ice deposits or crystals. An auger digs through the regolith, which uses an impact grinder and screens to break up the agglutinates. Starting with a 7 tonnes/hr throughput of regolith, a one Tesla magnetic separator can pick-out 11 kg/hr of free iron, titanium ilmenite grains, and magnetic oxides of iron, cobalt, and nickel. If volatiles are required, a large solar concentrator will be needed to roast the ice crystals out of the regolith. –Dave Dietzler *www.moonminer.com.*



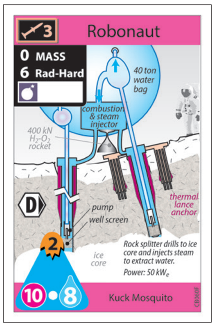
Free Electron Laser Robonaut – An intense and rapidly alternating set of static magnetic fields, called a "wiggler", can efficiently convert the energy in a relativistic electron beam into coherent photons. This is the basis of the free electron laser (FEL). Shown is a 125 MW_e FEL with an 80m electron accelerator. The acceleration may either be continuous, using resonant electrical cavities powered by high frequency electrical power, or it may be pulsed with a set of microwave "transformers" that use the electron beam as the effective secondary winding. The wavelength is tunable in the 300 nm repetitively pulsed range. The electrons are decelerated, and recirculated. The FEL's conversion of electrical energy to light energy is remarkably efficient (40% overall).



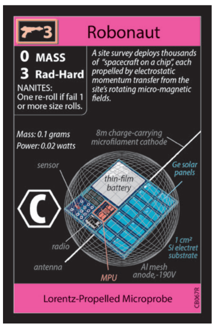
H-B Cat Inertial Robonaut – The fusion of hydrogen and boron-11 is a clean reaction, releasing only 300 keV alpha particles, which can be magnetically directed. However, the H-^{11}B fusion will not proceed at temperatures less than 300 keV unless catalyzed using exotic particles. One possibility: replace the electrons in H-^{11}B atoms with stable massive leptons such as magnetic monopoles or fractionally-charged particles (the existence of these is hypothetical). The resulting exotic atoms can fuse at "cold" temperatures, allowing the exotic catalysts to be recycled. A second possibility is to use antiproton-catalyzed microfission to initiate the H-^{11}B fusion. If a hundred billion antiprotons at 1.2 MeV in a 2 nsec pulse are shot at a target of three grams of H-^{11}B: ^{235}U in a 9:1 molar ratio, the uranium microfission initiates H-^{11}B and releases 20 GJ of energy. Operating at a fifth of a hertz, hydrogen and boron 11 reacting at a rate of 145 mg/shot produces 2000 MW$_{th}$. A shell of 200g of lead about the target thermalizes the plasma from 35 keV average to 1 keV, low enough that this radiation can be optimally transferred to thrust using a magnetic or ablative nozzle at 80% efficiency. The ejected mass per shot is 2.4 kg. The exotic catalysts are recycled. Catalyzed fusion enjoys an excellent thermal efficiency (86%) and thus a good thrust/weight ratio (34 milli-g), making it one of the best engines in the game. The specific impulse ranges between 8 and 16 ksec, depending whether spin-polarized free radicals are used as the hydrogen fuel. –G. Gaidos, ***et al.***, *Antiproton-Catalyzed Microfission/Fusion Propulsion Systems for Exploration of the Outer Solar System and Beyond,* Pennsylvania State University, 1998. (I used the ICAN-II spacecraft design, modified from cat D-T to cat H-B fuel, and scaled way down from 1 Hz to 0.2 Hz, and 302 GW to 2 GW.)



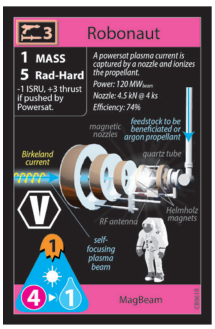
Helical Railgun Robonaut – The traditional railgun is a single turn, contact, linear motor limited by the inductance of the rails. In high acceleration, the necessary high current and brush contact heats the rails greatly limiting their life. By twisting the rails in a helical fashion (with matching turns on the armature and projectile) higher accelerations can be achieved at a tiny fraction of the current. In its prospecting mode, the helical railgun fires a 1 ton metal projectile at a potential mineral deposit. By placing it in a highly elliptical suborbital trajectory, the projectile collides at 10 - 70 km/sec from a fraction of the launch velocity. The resulting plume is analyzed spectrographically to determine the contents. The small crater can then be used as the start of any open pit mining operation. In its thruster mode, its capacitor banks charge for days before firing a single, high impulse, dirt projectile along with the armature, which is not recovered. –Engel, Nunnally, & Neri, *Research Progress in the Development of a High-Efficiency, Medium-Caliber Helical Coil Electromagnetic Launcher*, 2004. Inspired by the LCROSS mission.



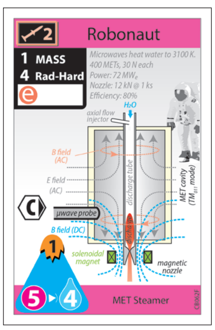
Kuck Mosquito Robonaut - As icy dormant comets or **D**-type asteroids are warmed by the sun, they accumulate an outer anhydrous lag layer. An in-situ mining robonaut called the Kuck mosquito is designed to drill through this layer, inject steam, and pump out the water in the core. Some of the water is electrolyzed for fuel for a small H_2-O_2 chemical engine. Thermal lances are used to melt into the substrate and gain a secure foothold. The targeted bodies must have ice in a cometary matrix of not less than 30%. There is a danger of catastrophic fracture, if the subsurface mantle layer is too weak to resist the tensile forces generated by the pressurization. –Dave Kuck, *The Exploitation of Space Oases*, Princeton Conference on Space Manufacturing, Space Studies Institute, 1995.



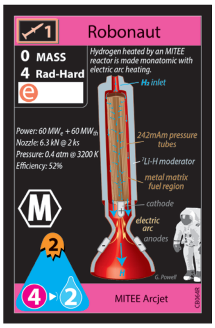
Lorenz-Propelled Microprobe Robonaut –A swarm of tiny probes can be sent to distant sites by exploiting the force that results from a charged particle moving perpendicular to a magnetic field line (in this case the Earth's). Each probe would consist of a long electrically charged (+10V) microfilament (10μm radius), essentially acting as part of a magnetic sail, which slowly accelerates it for years towards the target site. Two simple low-powered electrostatic micro-thrusters provide small course corrections. The anode is a faraday cage charged to -190V to protect the probe's electronics. The cage is shed upon arrival. Integrated into the probe's chip are a solar panel, sensor, and microprocessor. Each sensor in the swarm would fulfill a different purpose (e.g. detect hydration, temperature, chemical tests) and transmit its results. The probes are sturdy enough to survive a direct impact on the target body, allowing surface sampling to take place. Even if up to 90% of probes are lost or malfunction, enough will be available to provide a detailed analysis of the site. –Atchison & Peck, *A millimeter-Scale Lorentz-Propelled Spacecraft*, 2007; http://www.popsci.com/military-aviation-space/article/2007-08/mmmm-space-chips.



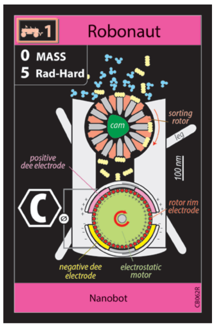
MagBeam Robonaut – A current can be propagated through space in a self-focusing plasma beam called a Birkeland "MagBeam" current. Differential motion between the ions and electrons in the MagBeam produce currents and magnetic fields such that the magnetic field in which the plasma is born stays with the plasma, making its own transmission line. The magnetic field continuously expands, keeping the ion stream focused. If produced by a helicon plasma source on a power station, it can be intercepted for mineral processing or thrust by a spacecraft equipped with a small amount of gas for propellant such as argon or xenon, a power source and a set of electromagnets to produce a mini-magnetosphere magnetic sail. The intercepted beam ionizes the argon in the sail, which is accelerated for thrust. Parameters to achieve a delta-v of 20 km/sec: beam of density of 2 X10^{13} /cm^3, a speed of 30 km/sec, robonaut mass of 10 tonnes, propellant mass of 7 tonnes, a 300 mW thruster with a specific impulse of 4 ks, and an interaction time of 4 hours. The disadvantages of the system as a thruster is that the power station must have kilotonnes of capacitors to store the required energy, the beam is of limited range permitting only hours of acceleration time, and there must be another such station at the destination to decelerate the rocket. –G. A. Landis, *Interstellar Flight by Particle Beam*, 2004.



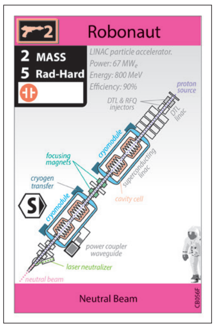
MET Steamer Robonaut - This device works by generating microwaves in a cylindrical resonant, propellant-filled cavity, thereby inducing a plasma discharge through electromagnetic coupling. The discharge performs either mining or thrusting functions. In its mining capacity, the head brings to bear focused energy, tuned at close quarters by the local microwave guides, to a variety of frequencies designed to resonate and shatter particular minerals or ice. In its electrothermal thruster (MET) capacity, the microwave-sustained plasma superheats water, which is then thermodynamically expanded through a magnetic nozzle to create thrust. The MET needs no electrodes to produce the microwaves, which allows the use of water propellant (the oxygen atoms in a steam discharge would quickly dissolve electrodes). MET steamers can reach 0.9 ks of specific impulse due to the high (8000 K) discharge source temperatures, augmented by rapid hydrogen-oxygen recombination in the nozzle. Vortex stabilization produces a well-defined axisymmetric flow. However, the specific impulse is ultimately limited by the maximum temperature (~ 2000 K) that can be sustained by the thruster walls. The illustration shows a microwave plasma discharge created by tuning the TM(011) mode for impedance-matched operation. This concentrates the most intense electric fields along the cavity axis, placing 95% of the energy into the propellant, with less than 5% lost into the discharge tube walls. Regenerative water cooling is used throughout. For pressures of 45 atm, each unit can produce 30 newtons of thrust. The thrust array contains 400 such units, at 50 kg each. –John L. Power and Randall A. Chapman, *Development of a High Power Microwave Thruster, with a Magnetic Nozzle, for Space Applications,* Lewis Research Center, 1989.



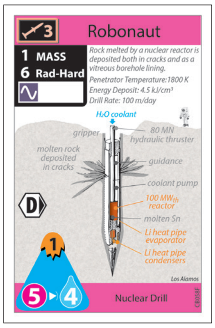
MITEE Arcjet Robonaut – A working fluid such as hydrogen can be heated to 12,000 K by an electric arc. Since the temperatures imparted are not limited by the melting point of tungsten, as they are in a solid core electrothermal engine such as a resistojet, the arcjet can burn four times as hot. However, the thoriated tungsten electrodes must be periodically replaced. When used as an electrothermal thruster, the arcjet operates at low pressures allowing the propellant to disassociate to monoatomic hydrogen, increasing specific impulse to 2 ks with frozen-flow efficiencies of 52%. The thrust is boosted by hybridization with a MITEE reactor, an assembly of 37 individual beryllium pressure tubes each containing an inner ^{242}Am core surrounded by an outer ^{7}Li hydride moderator. Cold hydrogen propellant flows radially inwards through a 1cm thick fuel region where it is preheated to over 3200 K before entering the arcjet. When used for mining beneficiation, regolith or ore is initially processed with a 1T magnetic separator and impact grinder (3.5 tonnes), before being vaporized or arc welded by the MITEE arcjet. –J. Powell & J. Paniagua, *Lightweight, High Specific Impulse (1000 Sec) Space Propulsion System, The MITEE Family of Compact Ultra Lightweight Nuclear Thermal Propulsion Engines for Planetary Space Exploration*, 1999.



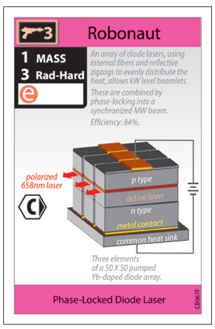
Nanobot Robonaut – An army of nano regolith and ore scavenging machines can be used for ore beneficiation. Molecular assemblers will use nano-structures much like enzymes to work with reactive molecules. Mechanical nanobots based on biomimetic soft nanotechnology might actually incorporate biological protein molecules (enzymes and ribosomes) to do some of their work. The nanobot illustrated uses legs driven by a harmonic drive. Harmonic drives use a pair of dislocations driven by a wave generator moving along the inner interface of a nanotube to deform a flexspine. Each rotation of the wave generator turns the flexspine by a two-tooth increment relative to the surrounding drill spline. A sorting rotor selects for a desired atomic shape, such as helium-3. These features are driven by a nano-electrostatic motor, that operates on the principle of a Van der Graaff generator worked backwards. – K. Eric Drexler, *Nanosystems, 1992.*



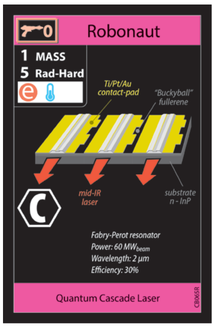
Neutral Beam Robonaut – Beams of ions are easy to accelerate, but they must be neutralized in space, otherwise their mutual electric repulsion would quickly diffuse the beam. (Also arcing would destroy the robonaut.) The ions accelerated are negatively charged, which obtains higher neutralization efficiency than positive ones. Neutral beams of hydrogen or deuterium, operating in a pulsed mode up to 800 MeV, pack more punch than lasers, which makes them useful in mining or combat. They can also be injected into fusion reactors both to heat the plasma and replenish the burned fuel. If a plasma vortex is needed, the neutral beam is introduced into the chamber off-axis. The design illustrated uses a Dudnikov high-brightness H- source with a radiofrequency quadrupole (RFQ) injector. A stage of resonance-coupled Alvarez drift-tube linacs (DTLs) boosts the beam to 85 MeV. A stage of superconducting linacs increases the energy of the ions to 600 MeV without unduly increasing the emittance of the beam (10^{-8} m·rad). The beam is very precisely focused on a target by a magnetic beam-steering optics, and then passed through a laser photodetachment neutralizing cell in order to remove the extra electron. –Martin Reiser, *Theory and Design of Charged Particle Beams*, 1994.



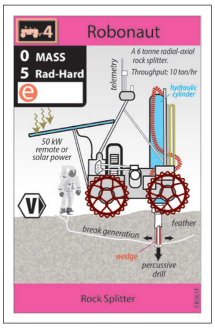
Nuclear Drill Robonaut – Shaft mining and boreholes are cornerstones to any effective ISRU operation. However, the power and mass requirements increase rapidly as the mine extends to greater depths and to harder rocks. Given a melting point of basalt on the order of 1500 K, 4.3kJ/cm^3 of energy can be used to melt the rock (compared to 2-3 kJ/cm^3 required for a rotary drilling). Using a heat-pipe, thermal energy from a nuclear reactor to the drill head, keeping it above the melting temperature of the rock. The heat pipe cavity is lined with a capillary structure which transports the working liquid continuously from the cool end to the heat source end. A closed evaporative/condensation cycle allows considerable heat transfer even though the difference in temperature between the hot and cold end is minimal. Venting the hot liquid can allow the drill to operate as a thruster. Under the thermal stress the rock face walls rock would crack, but by applying mechanical pressure through the tunneling device, the melted rock at the drill head is then forced into the cracks, reinforcing the tunnel walls (lateral extrusion). The pressure is provided by 6 hydraulic pusher pipes capable of exerting 80,000 kN of force. –D. Armstrong, B. McInteer, *et al. Method and Apparatus for Tunneling by Melting*, United States Patent, 1972.



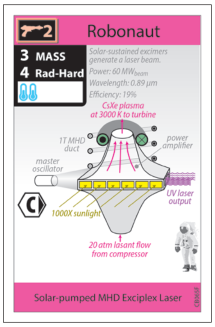
Phase-Locked Diode Laser Robonaut – Using a solid state chip, results in $^1/_3$ the heat per watt of output power by matching the heat emission spectrum with the absorption lines of the diode. Diode lasers however are typically limited in power to the 100 mW range or must accept a wide beam divergence (>10°) that comes with a large aperture. With internal fibres and reflective zigzag slabs heat can be more evenly distributed across the chip allowing higher powers (10s of kW) per beamlet. To reach the megawatt range multiple beamlets must be combined. Active phase-locked coherent beam combination uses the constructive interference of numerous polarized beamlet elements. With this careful synchronisation of each element seed as it is pumped to high power, beam quality stays constant even as elements scale into the hundreds. These lasers are electronically steerable requiring no mechanical components. –G. Goodno, C. Asman, *et al, Brightness-Scaling Potential of Actively Phase-Locked Solid-State Laser Arrays*, 2007.



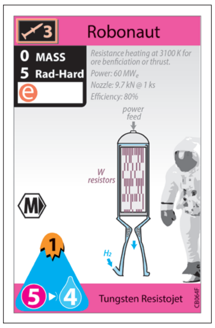
Quantum Cascade Laser Robonaut – Mineral grains blasted from the substrate can be photoelectrically charged with solid-state IR lasers such as quantum cascade lasers. Once photoelectrically separated, it is possible to process them electrically, thermally and with chemicals to extract metals and oxygen. The quantum cascade laser shown uses carbon buckytubes as the gain medium in a Fabry-Perot resonator. The layers of buckytubes form a series of quantum wells, down which electrons cascade. Each quantum-cascade laser electron tumbles down thousands of wells, producing a photon at each step. This electronic waterfall significantly boosts wall plug efficiency (30%), enabling quantum cascade lasers to emit gigawatts of peak power in pulsed operation and tens of megawatts in a continuous wave. The wavelength is altered by modifying the buckytube temperature. For long range work, a set of laser expanders are used for precise beam pointing and to decrease the spot size.



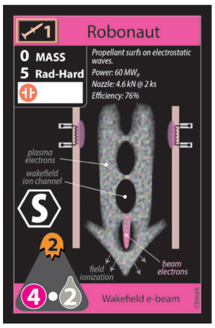
Rock Splitter Robonaut –The Bureau of Mines has developed a crawler-mounted excavation machine combining a percussive drill, drill feed, radial-axial rock splitter, and loader on a single boom. The system weighs 6 tonnes with a power requirement of 50 kW and a production rate of 10 tonnes/hour.



Solar-pumped MHD Exciplex Laser Robonaut – A UV laser can be pumped by short-lived pseudo-molecules called ***excimers***, which are stable only in the excited state. The excimers are formed in a cesium-xenon solar-sustained plasma, heated to 3000 K by sunlight amplified a thousand times, that acquires supersonic speeds at 20 atm in a nozzle. The nozzle is part of a short-circuited Faraday MHD duct, which decouples the electron and gas temperatures in its 1 T magnetic field. The system illustrated is a pulsed, solar-pumped, high-pressure CsXe excimer laser with a lasing volume of 40 liters. Each laser pulse is 15 KJ of 0.8944 µm UV light. A frequency of 4 kHz and a solar collector 540 meters in diameter is needed to produce a 60 MW cw beam. The efficiency is 19%, requiring tons per second of gas flow to remove heat from the lasant. This system does not need the economies of scale that a photovoltaic/microwave solar power satellite would entail. The receiving antenna can be small. It could beam its modest power to spacecraft, or to remote areas on Earth that need energy.
-Young *et al., Comparison of Electrically Driven Lasers for Space Power Transmission*, 1988.



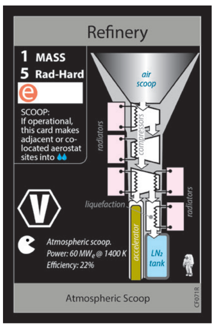
Tungsten Resistojet Robonaut – Tungsten, the metal with the highest melting point (3694 K), may be used to electric-resistance heat ore for smelting or propellant for thrusting. In the latter mode, the resistojet is an electro-thermal rocket that has a specific impulse of 1 ksec using hydrogen heated to 3500 K. The frozen flow efficiency (without hydrogen recombination) is 85%. Internal pressures are 0.1 MPa (1 atm). To reduce ohmic losses, the heat exchanger uses a high voltage (10 kV) low current (12.5 kiloamp) design. The specific power of the thruster is 260 kg/MW and the thrust to weight ratio is 8 milli-g. Once arrived at a mining site, the tungsten elements, together with a wall of ceramic lego-blocks (produced in-situ from regolith by magma electrolysis) are used to build an electric furnace. Tungsten resistance-heated furnaces are essential in steel-making. They are used to sand cast slabs of iron from fines (magnetically separated from regolith), refine iron into steel (using carbon imported from Type **C** asteroids), and remove silicon and sulfur impurities (using $CaAl_2O_4$ flux roasted from lunar highland regolith).



Wakefield e-beam Robonaut – An electron beam has many uses. It can bore holes in solid rock (mining), impart velocity to reaction mass for thrust (rocketry), remove material in a computer numerical control cutter (finished part fabrication), or act as a laser initiator (free electron laser). A wakefield accelerator accelerates the electrons by using a brief (femtosecond) laser pulse to strip them from gas atoms and to shove them ahead. Other electrons entering the electron-depleted zone create a repulsive electrostatic force. The initial tight grouping of electrons effectively surf on the electrostatic wave. Wakefield accelerators a few meters long exhibit the same acceleration as a conventional rf accelerator many kilometers in length. In a million-volt-plus electron beam the electrons are pushing lightspeed, so the term relativistic electron beam is used. When used as an electrothermal rocket, it is similar in principle to the arcjet, but far less discriminating in its choice of propellant. Dr Bussard (of interstellar ramjet fame) calls relativistic e-beam-heated systems "QED" (Quiet Electric Discharge) engines.

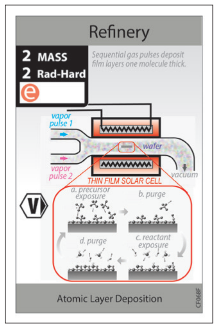
Z4. Refinery Cards

The tyranny of the rocket equation ensures that every kilogram of payload is precious. Accordingly, the material brought back from a mining mission must be highly refined, so that any useless waste is left behind. This means that most mineral beneficiation must occur in an in-situ refinery, and not, for example, at some central refinery near Earth. As an example, say you want to mine an asteroid that is 4 burn spaces (delta-v = 10 km/sec) from LEO. Your thruster is a MET, basically a microwave oven that turns water into steam for thrust, expelling the steam out the nozzle at 10 km/sec. How much water do you need to bring your ore back? According to the rocket equation: Wet Mass = Dry Mass * e^(delta-v/exit velocity) = 2.71 Dry Mass. In other words, every kilogram of material brought back will expend 2.7 kilograms of water. If the site is incredibly rich, say 1% platinum metals, then if you collect rocks without refining, 99% of what you bring back will be waste tailings. And you will have expended 271 kilograms of water for every kilogram of useful ore returned.

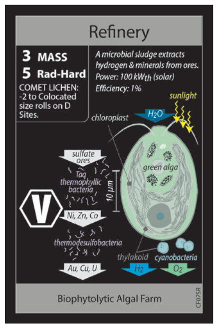


Atmospheric Scoop Refinery – A gas scoop rammed through an upper atmosphere can liquify the gases it collects to be used as propellant. The scoop must compensate for the momentum lost by drag by expending some of the collected gas for rocket power. Assume the scoop is propelled by a VASIMR electric rocket and orbits the Earth at 200 km altitude. It is ramming a scoop through immobile air and accelerating it to orbital velocity. Accordingly, the rocket's exhaust velocity (40 km/sec) must be greater than the orbital velocity (7.8 km/sec) in order to collect more propellant than expelled. Here the retention is (40 - 7.8)/40 = 80%. A 30m diameter scoop could collect 47 tonnes of liquid nitrogen plus 76 tonnes of liquid oxygen per year. The drag force is only 27 N. A 52 kW$_e$ Stirling cryocooler provides the power necessary to liquify and store the propellant.
–Reichel, Smith, and Hanford, *Electric Propulsion Development*, 1962.

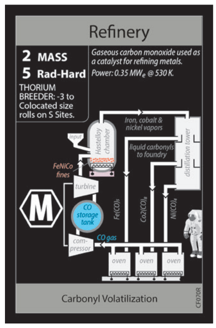
Atomic Layer Deposition Refinery – Two or more gas phase chemicals (precursors) react with a surface in a one-at a time sequential manner (essentially CVD at an atomic scale by breaking it into two steps). Each cycle can deposit a layer as thin as 10pm (10^{-12} m). A pulse of an inert purging gas after each precursor pulse removes any excess from the chamber preventing the CVD deposition. The final film thickness is dependent only on the number of cycles. Because layers are deposited atom by atom, the process is slow for manufacturing anything substantial in size. ALD is used primarily to manufacture the microchips required for Robonauts and ET Factories. Thin film solar cells can also be produced using local amorphous silicon. While these solar cells are of lower efficiency than their thicker cousins, they have a higher power density. They also are more sensitive to radiation damage, rapidly degrading in the presence of ionizing radiation. The circular solar cell sail produced by this refinery takes two years to manufacture and masses 80 tonnes (including structural supports). Specifications include a 290m radius and 10.25µm thickness (too thick to provide thrust). At 1AU it provides 34 MW_e with 9.5% efficiency (output increases to 70 MW_e at the 0.7AU orbit of Venus). –G. Levitin, D. Hess, *Surface Reactions in Microelectronics Process Technology*, 2011; N. Wyrsh, D. Domie, *et al., Ultra-light amorphous silicon cell for space applications*, 2006.



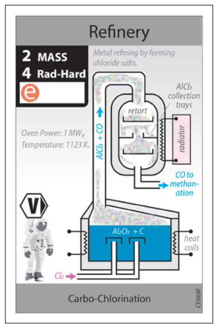
Biophytolytic Algal Farm Refinery – *Biophytolysis* is the use of microorganisms to break down and refine low grade ores and volatiles. Thermophillic bacteria are used to extract nickel, zinc, and cobalt. Sulfur-metabolizing bacteria obtain gold, copper, and uranium. In either case, weak solutions of acids are dripped through the ore and a bacterial liquor forms that is then electrolytically or chemically processed. Cyanobacteria and green algae, bioengineered for radiation and O_2 tolerance, will oxidize water at room temperatures, producing hydrogen and oxygen. This process is carried out by photosynthetic enzymes, which split water to obtain electrons, excite these electrons with photons, and eventually use these electrons to reduce 2H+ to H_2. Molecular complexes involved in mediating electron flow from water to carbon-fixing or hydrogen-production reactions make up the photosynthetic electron-transport chain found in the ***thylakoid*** membranes of cyanobacteria and green algae. Chaff from the algae farm is used as an organic substrate. Biophytolytic processes do not require much energy, and have a theoretical efficiency of 40%, but they are slow. –G. Jeffrey Taylor and Linda Martel, Hawaii Institute of Geophysics and Planetology, University of Hawaii, *Prospecting for Lunar & Martian Resources*, 2001.



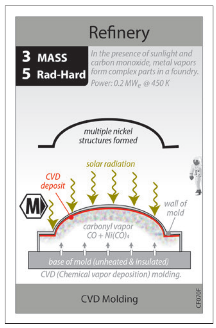
Carbonyl Volatilization Refinery – Gaseous carbon monoxide (CO) is the catalyst for carbonyl volatilization, by far the easiest way to refine metals in space. Solar-heated ores of nickel, iron, cobalt, and other metals react with CO to form gaseous carbonyls, which are then vapor-deposited via the ***CVD molding*** or ***CVI foam stereolith*** processes to form finished materials. The foamed metal composites exhibit tremendous directional strength and stiffness, and can produce shape-welded vessels many tons in mass. The CO can be recovered by another heating cycle or replenished by heating (to 1300 K) almost any known type of asteroidal material. The temperatures and pressures involved are particularly mild for nickel refinement via the Mond process: $Ni(CO)_4$ carbonyls form at just 530 K. The residue from carbonyl extraction of native ferrous metal alloys in **M** type asteroids is very rich in cobalt and platinum group metals, which are far more valuable than gold. The cobalt may in turn be separated from the platinum-group metals by very high-pressure extraction with CO, by extraction with CO-H_2O mixtures as the carbonyl hydride, or by wet chemical techniques. –John S. Lewis and Melinda L. Hutson, University of Arizona, *Asteroidal Resource Opportunities suggested by Meteorite Data*, 1993.

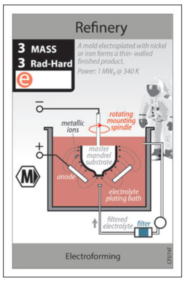


Carbochlorination Refinery – Metal sulfates may be refined by exposing a mixture of the crushed ore and carbon dust to streams of chlorine gas. Under moderate resistojet heating (1123 K) in titanium chambers (Ti resists attack by Cl), the material is converted to chloride salts such as found in seawater, which can be extracted by electrolysis. The example shown is the carbochlorination of Al_2Cl_3 to form aluminum. Al is valuable in space for making wires and cables (copper is rare in space). The electrolysis of Al_2Cl_3 does not consume the electrodes nor does it require cyrolite. However, due to the low boiling point of Al_2Cl_3, the reaction must proceed under pressure and low temperatures. Other elements produced by carbochlorination include titanium, potassium, manganese, chromium, sodium, magnesium, silicon and also (with the use of plastic filters) the nuclear fuels uranium 235 and thorium 232. Both C and Cl must be carefully recycled (the recycling equipment dominates the system mass) and replenished by regolith scavenging. –Dave Dietzler.

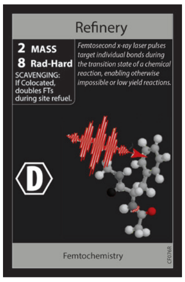


CVD Molding Refinery – Metal-walled structures and complex metal parts are readily produced through chemical vapor deposition (CVD). The beauty of CVD molding is that no machining is required for the final product. In particular, nickel is the easiest ferrous metal obtained from ***carbonyl volatilization***, and is strong, ductile, corrosion-resistant, versatile, and common in space The CVD process distributes nickel carbonyl vapors over a mildly solar-heated surface, where they decompose and deposit structurally-sound nickel on a mandrel. Deposition occurs with mild temperatures (450 K) and high purity (less than .02% carbon impurities). A vapor stream of 90% $Ni(CO)_4$ carbonyl and 10% CO creates forms and shapes with phenomenal leveling and corner-filling. If the fines are mixed nickel and iron, as from a type M asteroid, the carbonyls formed will be mixed, and a Fe-Ni alloy will be deposited. Synthesis of iron carbonyls is not as simple as for nickel, requiring higher pressures and a carbon dioxide-water vapor mix. The unreacted gases must be recycled, so as not to waste the iron carbonyl. However, due to the near instant disassociation of escaped carbonyl in a vacuum, some replacement of CO is needed. –William C. Jenkin

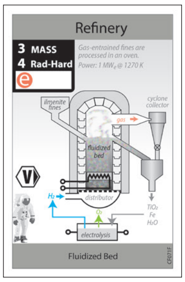




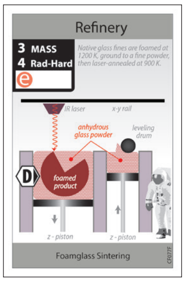
Electroforming Refinery – Metal thin-walled structures can be manufactured in a bath of electrolyte-plating solution by depositing metal onto a mandrel having the inverse contour. A robonaut monitors the electrical current densities as a function of metal deposition rate. Extraterrestrial metals most commonly deposited by this electroforming technique include nickel and iron. Mandrels are prepared from aluminum-coated cast or spun basalt. The need for an electrolyte-plating solution requires the electroforming unit to be pressurized and operated only in an accelerated frame. The anode plate is consumed during the forming process, but lunar or asteroidal iron and titanium are widely available for this purpose. The electrolyte is recycled.
–Robert Freitas Jr. of Space Initiative/XRI, *Proceedings of the 1980 NASA/ASEE Summer Study.*



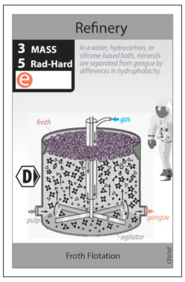
Femtochemistry Refinery – During a chemical reaction, bonds within a molecule pass through an unstable transition state lasting on the order of a picosecond (10^{-12}). By utilizing femtosecond (10^{-15}) laser pulses it is possible to monitor molecules as they undergo the transition state and even influence the pathway they take. Using femtosecond pulses with sub-angstrom (0.1nm) lasers, individual bonds can be targeted. The result is that otherwise unfavorable or even impossible reactions can become possible and high yield. Types of catalysts for certain reactions become more variable and easier to produce. Furthermore, catalysts are more likely to be recovered and exotic catalysts (which are ordinarily consumed) can often be re-used for hundreds of reactions. Antimatter transmutation alchemy uses antimatter and other exotic catalysts to convert one element to another. The easiest reaction occurs when a heavy metal is bombarded with anti-protons, yielding a small amount of radioactive higher order elements. Through careful control of this reaction, a small chain reaction can be initiated resulting in substantial yields. Light isotope production using antiprotons is currently being investigated.
–Zewail Ahmed, *Femtochemistry, Past, Present and Future*, 2000.



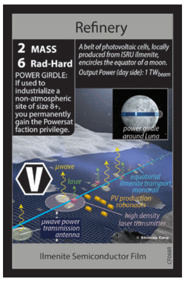
Fluidized Bed Refinery – In a fluidized bed refiner, a fluid (gas or liquid) is passed through a granular solid ore (such as regolith) at high enough velocities to suspend the particles and cause them to behave as though they were also a fluid. The heat and agitation increases the reaction rate. ***Ilmenite*** fines (grains of $FeTiO_3$ electrostatically separable from lunar regolith) may be reduced in a fluidized bed, using either hot hydrogen (1270 K), or carbon monoxide, to obtain iron fines and titanium dioxide particles. In either case, titanium is obtained from the reactants by acid leaching, carbonyl CVD, or vacuum high temperature heating, followed by electrolysis to Ti metal in FFC Cambridge cells. A variety of machine tools are used to finish the Ti part, including a grinder, e-beam welder, drill press, small lathe, and small rolling mill.



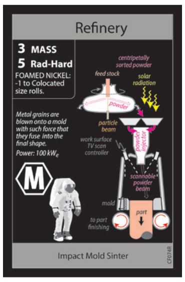
Foamglass Sintering Refinery – Natural glass formed in the heat of asteroid impacts can be easily separated with electrostatic beneficiation. Formed in the absence of water vapor, this anhydrous glass is less brittle and has compressive tensile strength. Foamglass (or cellular glass) is a lightweight yet strong extremely finely pored glass that can be used in place of metal and ceramics for structural components (such as long booms to separate crew from a reactor). Complex structural components and prototypes can be sintered. Sintering is a process whereby fine powder is heated below its melting point causing them to adhere to each other. A point heat source builds the product layer by layer. Given high purity starting materials, the resulting product is of extremely high and uniform quality with absolute control of the porosity. Nearly any ceramic, plastic or metal can be sintered.



Froth Flotation Refinery – This highly versatile method uses air bubbles to selectively adhere to specific mineral surfaces within a mineral/water slurry. The particles with air-bubbles then float to the surface and can be skimmed off. Sulfites, silicates and metallic ores (including zinc, iron, nickel and tungsten) can all be separated and concentrated and recovered at over 95% efficiency per run. The hydrophobicity which selectively attracts the air-bubbles can be natural or induced through chemical treatments with non-polar oils. Through variations in pH, surfactants, wetting agents, activators, depressants and various other reagents, one can selectively float a wide variety of compounds and minerals. The limiting factor in a space-based froth flotation operation is the vast amounts of water required, even with wastewater recycling. While non-water based solutions are possible (e.g. ammonia, hydrocarbons), they are not as well studied.

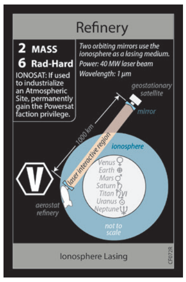


Ilmenite Semiconductor Film Refinery – The common lunar mineral ***ilmenite*** ($FeTiO_3$), could produce 10% efficient PV cells (compare to 25% efficient cells from silicon). Although actual efficiencies are much lower, the Shimizu Corp is studying how to ISRU-produce a girdle of photovoltaic cells completely around the lunar equator. The day side of Luna produces TW of power, which is beamed to Earth from the near side.
–Franklin Hadley Cocks, *Energy Demand and Climate Change: Issues and Resolutions*, 2009.

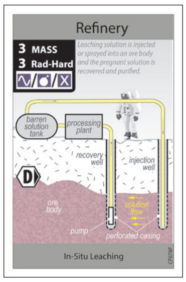


Impact Mold Sinter Refinery – Sintering is a method for making objects by heating powdered material below its melting point until the particles adhere to each other. Metal grains, produced perhaps by CVI or CVD space vacuum processes which suffer no surface contamination, are sequentially blown into an impact die made of sintered regolith ceramics. As these grains accumulate on the developing workpiece, they are sintered by the energy of impact and coalesce by cooling. Insertable shields are used to create voids and internal patterns. As it is made, the part is actively inspected by scanning electron microscopes or optical sensors which guide the beam to areas where the surface is rough, appears too porous, or has not adequately been filled. The parts then move to an inspection station for trimming by a high-energy laser, and assembly using an e-beam welder. Such an assembly line can produce at 180 kg/hr, with a specific power of 0.5 MW/(ton/hr of product), and 5 ton machinery/(ton/hr of product). The parts will typically be made of a nickel/carbon fiber system sintered with minor amounts of aluminum. The reaction creating nickel aluminide is highly exothermic, so much of the heat of reaction supplies the sintering energy required. A part made of nickel aluminide has a stiffness and a strength to weight ratio far superior to titanium, for temperatures well over 770 K. Iron-nickel fines can also be impact mold sintered.
–George Hansen, Metal Matrix Composites Company.

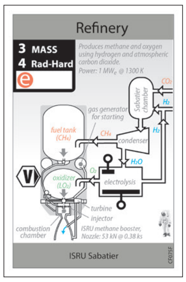
Ionosphere Lasing Refinery – Sunlight maintains population inversions in the ionospheres of Venus, Mars, and (possibly) Saturn. If two orbiting mirrors are arranged so the path between them intersects this portion of the atmosphere, the atmosphere itself can lase. A two satellite system sized as shown, 1000 km apart, orbiting at 8 km/sec and interacting with a grams worth of excited molecules, can achieve about 5 kJ per pulse at 8 kHz (average power 40 MW). This is a significant power level, for propulsion, refining, and weapons purposes. –D. Deming and M. Mumma, *Modeling of the 10 micrometer natural laser emission from the mesospheres of Mars and Venus*, NASA TM-85045, NASA/Goddard, 1983.



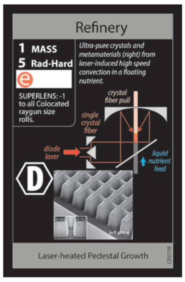
In-Situ Leaching Refinery – This process is an extension of the Kuck Mosquito Robonaut applied to mineral beneficiation. After identifying a potentially rich mine, boreholes are drilled into the site or explosives are used to fractionate the mine so that strong acids can be injected. The acid (or alkali in the case of aluminum recovery) dissolves the minerals (including uranium) such that the pregnant solution is then pumped to the surface for easy de-volatilization recovery. By varying the leaching solution, different minerals and precious metals can be selectively recovered. Considerable mass savings are realized by this method as mining, transportation, crushing, grinding, separation and tailing disposal steps are skipped. On sites with low Hydration, heap and dump leaching techniques are employed, applying the leaching solution to crushed ore over an acid resistant leaching pad. The downside is lower efficiencies and risks to site contamination in the event of an accident.
–S. Ross, *Near-Earth Asteroid Mining*, 2001.



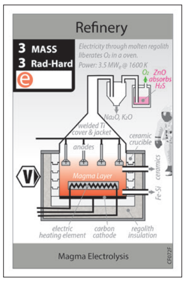
ISRU Sabatier Refinery - The Sabatier reactor is a small lightweight steel cylinder that has a mixing chamber and a chamber filled with a nickel catalyst. When charged with hydrogen and atmospheric carbon dioxide, it produces water and methane. (The similar Bosch reactor using an iron catalyst produces elemental carbon and water.) A condenser removes the water vapor from the products of the Sabatier reaction. The condenser is a simple pipe with outlets on the bottom to collect water; natural convection on the surface of the pipe is enough to carry out the necessary heat exchange. Electrolysis of the water recovers the hydrogen for reuse. These ISRU (In-Situ Resource Utilization) reactors create closed hydrogen and oxygen cycles for life support on bases with access to CO_2 atmospheres such as Mars bases or Venus aeroxities. The methane and oxygen produced can be used to power chemical rockets for the ascent stages. The CH_4/O_2 fuel, with a specific impulse of 380 sec, is the highest-performing space-storable chemical propellant that can be easily manufactured in space. In the absence of an atmosphere, ISRU units can produce H_2O, H_2, and CO by steam-heating crushed carbonaceous asteroidal material to 1300 K in a closed vessel. In either case, the elemental carbon produced is used to make nanotubes through electrophoretic techniques (the migration in solution of charged colloids). Nanotubes have higher electrophoretic mobilities than do particles, and move toward the negative electrode aligned along the electric field. –C.R. Nichols, Bose Corporation,Carbonaceous asteroids, 1993.



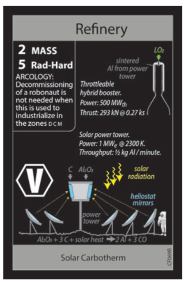
Laser-heated Pedestal Growth Refinery – This crystal growth technique uses a 10-100 kW CO_2 or YAG diode laser as a heat source with the nutrient suspended in a floating zone. The liquid phase undergoes high speed convection resulting in a high yield crystal fiber. These very pure crystals can exhibit unique properties such as very high melting points when doped with rare-earth metals. Of particular interest is the growth of organic-inorganic gold-based composite materials for batch production of ***metamaterials*** - engineered materials which exhibit properties impossible in nature. By employing periodic features smaller than the wavelength of light passing through them the electromagnetic response can be controlled resulting in a zero or negative refractive index. Metamaterial "super-lenses" can focus beyond the diffraction limit of light for sub-wavelength antennas, microwave cloaking, and inductive power transmission over longer distances (decaying on the 3rd instead of 6th power of distance used in induction coils).

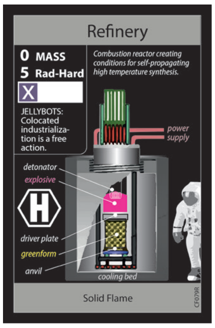


Magma Electrolysis Refinery – This refining unit melts regolith with solar energy, and passes electricity through the melt. This liberates oxygen at one electrode, and reduces the material to a lower oxidation state at the other. A flux material is used to reduce the melting temperature of the regolith to around 1600 K. A 80 tonne magma electrolysis unit with a throughput of 5000 tonnes of regolith per year and a 3.5 MW_e power source could produce 2000 tonnes of ceramic and silicon blocks or heatshields, 1000 tonnes of oxygen, and hundreds of tonnes of iron, magnesium, and silicon. The silicon can be zone-refined to high purity for solar panels. Zone-refining does not require chemicals that must be "upported" from Earth and will be done more easily in the low gravity and vacuum of space than on Earth (where it must be done in inert gas-filled chambers and rods can't be too massive lest they fall apart at the molten zone). –David Dietzler www.moonminer.com

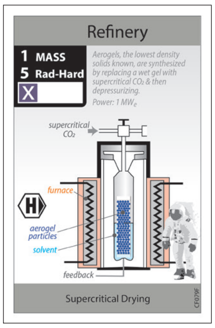


Solar Carbothermal Refinery – An ISRU (In-Situ Resource Utilization) alternative to carbochlorination for the refining of aluminum and oxygen is solar carbothermal, the solar heating of alumina ores in the presence of carbon. This process needs no chlorine, which is rare in space, and also uses solar heat instead of electricity, which uses less energy than electrolysis since the energy comes directly from solar radiation without the inefficiencies of conversion to electricity and power conditioning. The aluminum and oxygen produced can be used to fuel $Al\text{-}O_2$ chemical boosters and suborbital hoppers, which burn fine sintered aluminum dust in the presence of liquid oxygen (LO_2). Unlike pure solid rockets, hybrid rockets (using a solid fuel and liquid oxidizer) can be throttled and restarted. The combustion of aluminum obtains 3.6 million joules per kilogram. At 77% propulsion efficiency, the thrust is 290 kN with a specific impulse of 0.27 ks. The mass ratio for boosting off or onto Luna using an $Al\text{-}O_2$ rocket is 2.3. In other words, over twice as much fuel as payload is needed.

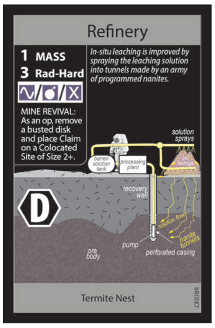




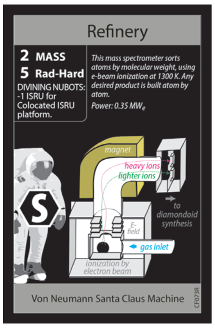
Solid Flame Refinery – Combustion is typically thought of in the context of organic compounds, but an exothermic combustion known as ***self-propagating high-temperature synthesis*** can be sustained with combinations of metals and other inorganics under very high temperatures and pressures (10s of MPa). If the reactants, intermediates, and products are all solids, it is known as a solid flame. Two finely-powdered reactants, one an oxidizer, are point-ignited, causing a slow-moving combustion wave leaving a chemically altered "ash" in its wake. Varying the material ratios, gravity, and wave propagation velocity creates materials such as superstrong nanocomposite alloy coatings, Fe/Al/AL$_2$O$_3$-Cr alloy for lightweight structural materials, TiB$_2$-Cu for highly conductive wires, and NiZn-Fe$_2$O$_4$ in electromagnets. These materials can perform some "self-healing" processes, sealing micro-fissures and cracks.



Supercritical Drying Refinery – A liquid brought beyond its critical point by high pressures (MPa) and moderate temperatures (~300 K) behaves like a gas, useful in the manufacture of barely-there solids called aerogels. If a supercritical liquid (often CO$_2$) replaces a wet gel and then is depressurized, the gel's surface-tension structure is preserved. The resulting aerogels are the lowest density solids. Silica aerogels have extremely low thermal conductivity (~4mW/m·K). Carbon aerogels can be used for radiation shielding due to their extreme internal scattering capacity. Their strong electrical conductance makes them ideal supercapacitors with specific power and energy of 20 kw/kg and 325 kJ/kg respectively. Alumina aerogels are easily doped and used as high temperature, high surface area catalyst supports. Their high thermal capacity can allow for improved high temperature alloy melt processing.
–Poco, Satcher, Hrubesh, *Synthesis of high porosity, monolithic alumina aerogels*, 2001.



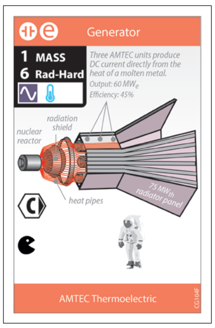
Termite Nest Refinery – This employs an army of nanites to locate and bore holes into stopes so that in-situ leaching can proceed more efficiently. The nanites employ simple cellular automaton algorithms using input based on material sampling and flow rate to optimize beneficiation. These nanites are adept at extracting useful ore from tailings discarded by previous mining operations as uneconomical, an example of how improved technology can revive an uneconomical mine.



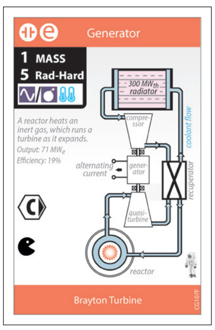
Von Neumann Santa Claus Machine Refinery – The great mathematician John Von Neumann (pronounced von noi-man) visualized a set of nanomechanical assemblers, operating on local energy sources and material inputs, which use sensors integrated by a central processing unit to perform a wide range of mechanosynthetic operations including mining. Assemblers are molecular machines capable of being programmed to build stuff from raw materials such as those readily gleaned from carbonaceous regolith. Electrophoresis and magnetoplasmadynamic systems separate this regolith into its basic elements. The basic building blocks of Von Neumann machines are rods of interlocked diamondoid fibers. (Diamondoid structures comprise a wide range of polycyclic organic molecules consisting of fused, conformationally rigid cages.) The system includes internal radio communications, fuzzy logic design data storage, and a robot that can disassemble faulty engines and drills, test them, and replace them with new diamondoid components made on site. This device is called a Santa Claus machine, because of its capacity to make anything you want, including copies of itself. However, in practice self-reproduction (of disassembled parts) is vastly easier than self-assembly of parts. The machine illustrated (like the 2009 RepRap open-source project) can self-reproduce, but relies on humans to assemble itself.
–John Von Neumann, *Theory of Self-Reproducing Automata,* 1966.

Z5. Generator Cards

Many of the game's thrusters use electrical power to accelerate their water propellant. For this they need a generator, either solar or nuclear powered. To make the generators modular, they are standardized at 60 MW$_e$ (megawatts of electrical power). Of course, life support, mining robonauts, refineries, etc. also need electricity, but these are usually less than a megawatt, contrasted to the game's electric rockets that need 60 MW$_e$. GW rockets need generators as well, but for reaction ignition rather than for propulsion. The 60 megawatts of electricity supplied for ignition is insignificant compared to gigawatts of fission or fusion power, once the reactor fires up. A few generators are **pulsed**, these use capacitors or flywheels to store electricity and release it rapidly.

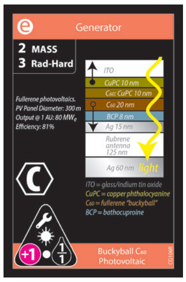


AMTEC Thermoelectric Generator – The alkali metal thermoelectric converter (AMTEC) is a thermally regenerative electrochemical device for the direct conversion of heat to electrical energy using high-voltage multitube modules. These modules accept a heat input (solar or nuclear) at 900–1300 K and reject it at 400-700 K, producing direct current with an efficiency of 45% and no moving parts. The molten alkali metal (sodium or potassium) is driven around a closed thermodynamic cycle between the heat source and the heat sink, in a similar fashion to the Rankine MHD heat engine. However, instead of the MHD unit, the AMTEC cycle expands the alkali metal vapor through a solid electrolyte (sodium beta-alumina) which causes it to ionize. The isothermal expansion of the alkali vapor is thus converted directly into electricity, with power densities of 100 kW/m^2 and 2 ton/MW$_e$. –M. A. Ryan and J. P. Fleurial, *Direct Thermal-to-Electric Energy Conversion for Outer Planet Spacecraft*, Jet Propulsion Laboratory, 2002.

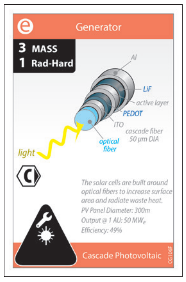


Brayton Turbogenerator – A solar or nuclear heat source can be used to generate electricity via a closed-loop Brayton cycle. Unlike the Rankine cycle, in which the working fluid changes phase, the Brayton cycle uses an inert gas such as helium which is expanded through a power-producing turbine, after which it is circulated through a radiator for cooling and reuse. Typically, heated helium enters the turbine at 1700 K and 24.5 atm. A mass breakdown: 3600 rpm turbine with a diameter or 2.6 meters: 4.5 tonnes, alternator-generator: 12 tonnes, recuperator: 12 tonnes, compressor: 10 tonnes, transformers: 20 tonnes. The liquid fluids used in the Brayton cycle have heat-transfer coefficients approximately 50 times lower than the gaseous fluids used in the Rankine cycle. As a result, the closed Brayton cycle has an inherently lower thermal efficiency (19% vs. 22%).

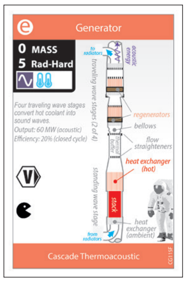
Buckyball C60 Photovoltaic Generator – The C60 "Buckyball" molecule is a fullerene carbon allotrope, about a nanometer across, composed of 60 carbon atoms arranged in a hollow sphere. It has semiconducting and magnetic properties, up to its Curie temperature around 500 K. In its amorphous form, Buckyball C60 is a semiconductor with a bandgap of 2.5 eV. By intercalating dopants between the Buckyballs, the conductivity can be increased. The organic photovoltaic device illustrated uses charge-generating layers of copper phthalocyanine (CuPc)/fullerene (C60) over a light-absorbing rubrene antenna. Radiation absorbed by the antenna is transferred into the charge generating layers via surface plasmon polaritons. The antenna tunes the cavity to absorb light strongly, improving the quantum efficiency to 85%. Membrane photovoltaic C60 films, centrifugally-tensioned and supported by wires, have a specific area of 1.5 kg/m^2 and power/mass ratios similar to today's best thin film substrates: 4 kW/kg.
–Heidel, Mapel, Celebi, Singh, & Baldo, *Analysis of surface plasmon polariton mediated energy transfer in organic photovoltaic devices*, Proc. of SPIE, 6656, 2007.



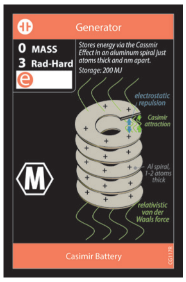
Cascade Photovoltaic Generator – A photovoltaic device is one that generates a voltage when radiant energy falls on the boundary between dissimilar substances. A high efficiency example is the multijunction cascade cell, made from combinations of elements from the third and fifth columns of the periodic table. Three junction cells arranged in tandem atop one another achieve 50-percent conversion efficiency at 100 times solar concentration and at 350 K. For space use, radiation resistance has been improved by technologies such as introducing of an electric field in the base layer of the lowest-resistance middle cell, and EOL current matching of sub-cells to the highest-resistance top cell. If light is waveguide-directed down woven optical fibers (50 µm diameter) coated with indium-tin oxide, the absorption range is greatly increased. The fiber bundles act as their own radiator. Other nano-technology enhancements include double-hetero wide band-gap tunnel junctions, precise lattice-matching to Ge substrates, and 1.96 eV AlInGaP top cells. Cascade photovoltaics so enhanced attain a power density of almost 1kW/kg and 1.4 kg/m^2. –Tatsuya Takamoto, Minoru Kaneiwa, Mitsuru Imaizumi, Masafumi Yamaguchi, *InGaP/GaAs-based multijunction solar cells*, Progress in Photovoltaics, Vol. 13, 2005.



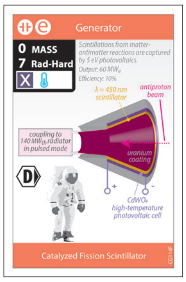
Cascading Thermoacoustic Generator - Two pairs of traveling wave stages in a linear topology can create acoustic power from thermal power with high efficiency (20%). In a closed-cycle, hot coolant from a radiator enters a standing wave stage, which supplies power to a traveling-wave stage, which produces 60 MW of acoustic power.
–D.L. Gardner & G.W. Swift, 2003.



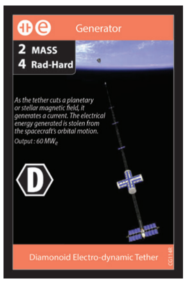
Casimir Battery Generator - The Casimir-Polder force is the relativistic retarded van der Waals force between two metal plates. The force per unit area between the plates goes to zero as alpha, the fine structure constant, goes to zero. In the nanotech battery application shown, energy is stored in an aluminum spiral just 1 or 2 atoms thick and a few nm apart. The coil is positively charged, so that the electrostatic repulsion between each coil loop balances the vacuum fluctuation attraction. The Casimir force is an example of the de-reification of quantum effects; what was once described in terms of zero-point energy and vacuum fluctuations has been shown to be nothing more than the relativistic van der Waals forces between two plates.
–Robert Jaffe of MIT, 2005.



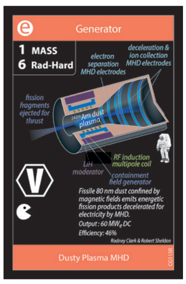
Catalyzed Fission Scintillator Generator - The output of a matter-antimatter reaction is a horrible mess of pions and gammas almost impossible to convert into electricity. One possibility is to direct a stream of antiprotons onto a conical receptor consisting of a uranium-coated scintillator. The collisional fissions emit light, captured by high temperature $CdWO_4$ photovoltaic cells in the next layer down. These PVs operate in the 350nm (5-eV) range, converting 10% of the antiproton beam into electricity. Radiators, coupled to the scintillator in a pulsed mode, reject 21% of the energy. Howe estimates the specific weight at 6.6-tonnes/MW_e, although the game uses a more optimistic value of 2 tonnes/MW_e.
–Steven Howe, 2012.

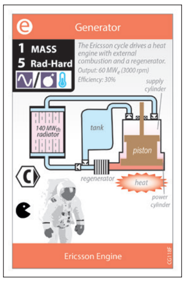


Diamonoid Electrodynamic Tether Generator - When a conductive tether is deployed from a spacecraft and cuts a planet's magnetic field, it generates a current, and thereby converts some of the spacecraft's kinetic energy to electrical energy. As a result of this process, an electrodynamic force acts on the tether and attached object, slowing their orbital motion. The tether's far end can be left bare, making electrical contact with the ionosphere. Functionally, electrons flow from the space plasma into the conductive tether, are passed through a resistive load in a control unit and are emitted into the space plasma by an electron emitter as free electrons. Megawatts of high-current tether power are attainable. The energy is stored in a magnetically insulated spacecraft acting in the ultrahigh vacuum of space as a gigavolt capacitor.
–Winterberg, 2008.

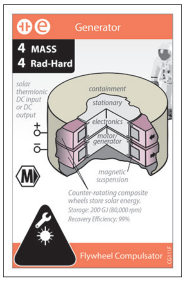


Dusty Plasma MHD Generator –This generator produces electricity by decelerating an ion beam of fission products. This bypasses the Carnot cycle and thus achieves twice the efficiencies of heat engines. The ions are emitted by fissile 80nm dust particles suspended by magnetic fields. Dust increases the surface area enough to allow for effective radiative cooling. As the particles naturally ionize as fission occurs, electrostatic suspension is a simple process. Deceleration is accomplished by a series of MHD electrodes, generating 60 MW_e DC power at 46% efficiency.
–Rodney A. Clark and Robert B. Sheldon, 2005.

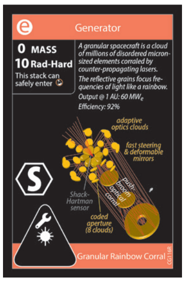




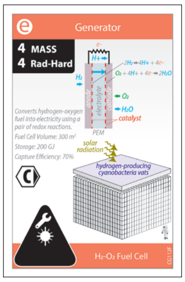
Ericsson Engine Generator–The Ericsson thermodynamic cycle is similar to the Stirling cycle in that both generate electricity efficiently using external combustion with regenerators. Both cycles can run off either a solar or nuclear heat source. The game design uses the latter, generating 60 MW_e at 3000 rpm and 30% efficiency.



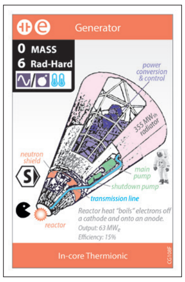
Flywheel Compulsator Generator – A low-density disk spun in a vacuum to up to 80000 rpm can store considerable energy in its angular momentum. There are two 2.5 tonne wheels, each 1.5m in diameter and 1.2m thick and made of graphite stiffened with carbon whiskers. They spin on a single axle suspended by superconducting YBCO magnetic bearings. The system includes rectification, filtering, and inversion electronics, as well as fuzzy logic dampening of shaft vibration. A compulsator (short for compensated pulsed alternator) provides the power supply. The maximum energy stored is 200 GJ, with a peak load of 600 MW_e. The specific power and energy are 7.6 kW/kg and 2.5 MJ/kg.



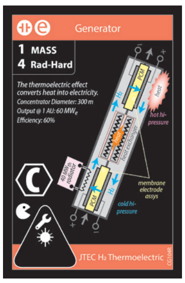
Granular Rainbow Corral Generator– A cloud of micron-sized reflective particles are shaped into a specific surface by light pressure, allowing it to form a very large and lightweight aperture of an optical system. Flying in a formation as part of a so-called "granular spacecraft", it reflects sunlight like a rainbow. The rod-like particles are corralled in three dimensions by use of a strongly focused Gaussian laser beam. The opto-mechanical interactions are at the grain level, trapping the low index particles within an optical vortex.
–Marco Quadrelli, 2013.



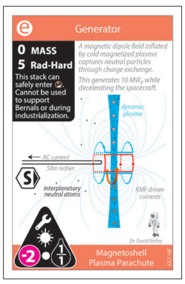
H_2-O_2 Fuel Cell Generator – Regenerative alkaline fuel cells convert the chemical energy of fuels directly into electricity, using hydrogen as the fuel and oxygen as the oxidant. At the anode, hydrogen gas combines with hydroxide ions to produce water vapor plus free electrons. The specific energy of the fuel alone is 13.5 MJ/kg. At the cathode, oxygen and water plus returning electrons from the circuit form hydroxide ions that are recycled back to the anode. Either proton exchange membranes (PEM), or microbes that transfer electrons to the electrode as they metabolize, are used to produce the current. Titanium-crusted carbon nanotubes meet the two key requirements for efficient hydrogen storage: the abilities to latch on to hydrogen molecules in adequate numbers and to relinquish the hydrogen readily when heated. A 200 GJ fuel cell stack has a peak load of 600 MW_e, and a volume of 300 m^3. The specific power and energy are 15 kW/kg and 5 MJ/kg. Operating temperatures are 400 K with a thermal efficiency of 70%.



In-core Thermionic Generator - Thermionic conversion systems may be conceived as an "electron boiler" in which electrons are thermally boiled off a heated emitter cathode, and collected on an anode surface, delivering DC electrical power to an external load. Solid state SiC transistors, operating at 520 K and 98% efficiency at a power density of 6 kW/kg, convert DC current to AC. In-core thermionic systems are composed of converters which are directly attached to individual fuel elements within the reactor core (fast fission or fusion). Anode cooling is by a loop which circulates a liquid metal coolant to an external radiator. The baseline system uses single-layer BaCs converters and collector anodes coated with SiC. Thermoelectric-electromagnetic (TEM) pumps are used to pump the sodium to the radiators and back. When operating at an emitter temperature of 13000 K, the cycle conversion efficiencies are 15%, and the output is 125 MW_e. Specific power including the sodium heat pipes is 2200 kg/MW_e.

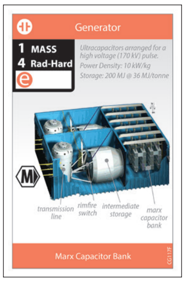


JTEC H_2 Thermoelectric Generator – Most heat engines use a Stirling, Brayton, or Rankine cycle operating between a hot source and a cold source. These are mechanical devices which use circulating fluids and pistons or turbines to express their energy, typically with about 30% efficiency. In contrast, the JTEC (Johnson Thermo-Electrochemical Converter) is all solid-state, generating electricity without moving parts at efficiencies of about 60%. The JTEC generator utilizes the electrochemical potential of hydrogen pressure applied across a proton conductive membrane (PCM). On the high-pressure side of the PCM, hydrogen gas is oxidized resulting in the creation of protons and electrons. The pressure differential forces protons through the membrane causing the electrodes to conduct electrons through an external load. On the low-pressure side, the protons are reduced with the electrons to reform hydrogen gas. The PCM and a pair of electrodes form a membrane electrode assembly similar to those used in fuel cells. The JTEC uses two such assemblies, one coupled to a high temperature (up to 1400 K) heat source and the other to a low temperature radiator. Hydrogen circulates within the engine between the two MEA stacks via a counter flow regenerative heat exchanger.
–Lonnie Johnson, *www.johnsonems.com*

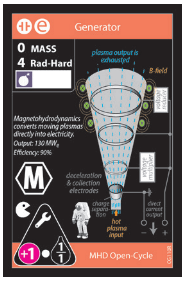


Magnetoshell Plasma Parachute Generator–The magnetoshell parachute, deployed on a 50m tether during an aerobrake maneuver, forms a 500 Gauss magnetic dipole field. A low temperature magnetized plasma is injected into that field. Instead of deflecting gas like an aeroshell, or plasma like a magnetic decelerator, it captures hypersonic neutral gas through collisional processes. The momentum of the charge-exchanged gas is absorbed by the magnetic structure, while the ionized gas fuels and heats the plasma. Assuming a Neptune aerobrake at 2000km altitude, and a maximum atmospheric density of 3.5×10^{18} molecules/m^3 at an incoming velocity of 26.7 km/s, the neutral molecular weight is 2.5 amu and the directed neutral energy is 9.4 eV. This generates 10 MW_e while decelerating the spacecraft.
–David Kirtley, NASA, 2013.

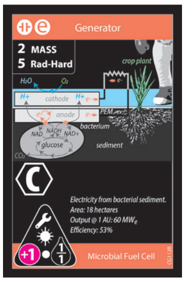
Marx Capacitor Bank Generator - Many impulsive drives (Z-pinch, fusion focus) require a large bank of capacitors to be charged over several microseconds and discharged much more quickly with very little loss. The circuit known as a Marx Generator generates a high voltage pulse by charging capacitors in parallel to a given voltage, then discharging them in series by spark gap or plasma switches. Diodes prevent ringing between the capacitive and inductive portions of the circuit. A bank of Marx capacitors has 0.53 Amps/m and stores 54 kJ/kg at a few hundred kilovolts.



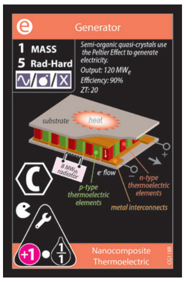
MHD Open-Cycle Generator – Magnetohydrodynamics (abbreviated MHD) is the control of plasmas using magnetic fields. A MHD electric generator has the advantages of high direct energy conversion efficiencies (90%), no moving parts, and instant turn-on. Installed on the output of a rocket nozzle or vapor core reactor, it magnetically expands and cools the exhausted plasma, extracting electrons with a large grounded collector plate. MHD can also convert laser energy into electricity. For the open-cycle design shown, an expander spreads out into a fan shape with a radius of many meters. The positive ions (at energies in the region of 400 kilovolts for fusion end loss plasmas) are collected on a series of high voltage electrodes, resulting in the direct transfer of kinetic energy to a direct current. The electrodes must be cleaned to prevent build-up of conductive deposits that can cause shorts. The process is reversible, with an input of electricity the fuel economy of the rocket exhaust (such as for chemical rockets or arcjets) can be doubled. Room-temperature superconducting magnets with a high current density create a crossed field region (4 T) that accelerates the plasma with Lorentz forces. Because of material limits, the duct temperature is limited to 2500 K. The plasma is usually seeded with an alkali metal (e.g. magnesium) for conductivity, which must be recovered and recycled from the effluent stream. The net power density is 350 kg/MW_e. –Samim Anghaie, *Development of Liquid-Vapor Core Reactors with MHD Generator for Space Power and Propulsion Applications*, University of Florida, 2002.



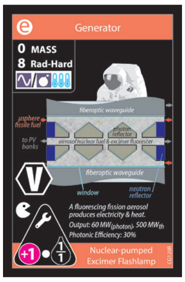
Microbial Fuel Cell Generator – Bioengineered "organic-electronic" crops grown in space transfer organic material through their roots into the sediment, a process called ***rhizodeposition***. A microbial fuel cell (MFC) uses bacteria as a catalyst to convert the chemical energy of this sediment directly into electricity. The bacteria in the anaerobic sediment will use the MFC anode as an insoluble electron acceptor. Using nano-wires, the anode collects 95% of the electrons originating from the microbial metabolism. The protons flow through a proton or cation exchange membrane to the cathode, where they are reduced with oxygen into water. For rhizodeposition feeding rates of 0.3 kg/liter/day, MFCs achieve powers of a kW/m^2 of electrode surface. This power is stored in "living capacitors", which utilize entrained nanotubes for high surface area, enabling near instantaneous charging and no degradation. The dielectric is whisker nMOS, and the leads are vapor deposited gold. Up to 4 GJ of solar energy are stored in 20,000 cells, each at 390 K and 30V. A plot 470m across (18 hectares) at 1 AU can generate 60 MW_e.



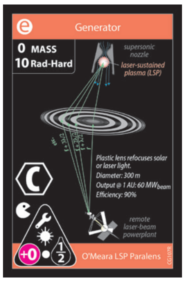
Nanocomposite Thermoelectric Generator–When current flows between a junction of two different metals, heat is generated at the upper junction and absorbed at the lower one, known as the Peltier effect. A unit-less figure of merit known as the ZT score reflects the overall efficiency, with 1 the standard for most compounds and 4 performing similar to mechanical devices. Nanocomposites, particularly Ytterbium, Perovskite-type oxides, Si-Ge-doped buckyballs and Copper Aluminate compounds have shown promise of ZT > 5 at temperatures approaching 1400 K. Complex semi-organic quasi-crystals may achieve ZT scores on the order of 20, allowing efficiencies > 90%. The thermoelectric effect can also be used in reverse to convert waste heat to electricity. Specific area is 34 kg/m^2 at 1275 K. –L. Su, Y. Gan, *Advances in Thermoelectric Energy Conversion Nanocomposites*, 2011.



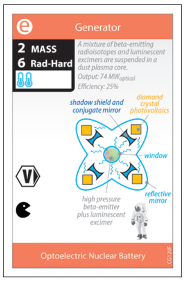
Nuclear-pumped Excimer Flashlamp Generator – A fission or fusion reactor using fissile microspheres mixed with an excimer fluorescer gas as an aerosol. This aerosol is driven to an excited state by nuclear radiation, and then emits incoherent narrow band photons. Conical waveguides transport the photon energy out of the cylindrical generator to fiberoptic bundles, and then to banks of PV cells, which convert it to electricity at 30% efficiency. This two-step method enables non-Carnot-limited electric power generation from fission fragments, whose transport length (microns) is far too short for direct energy conversion such as MHD. The narrow band enables a high photovoltaic efficiency of 90%, and the excimer fluorescence efficiency is 35%. Radiation damage to the crystalline PV is alleviated by periodic thermal annealing. Alternately the VUV photons can be transmitted to a gaseous laser medium in close proximity to the core. Critical dimensions for the aerosol generator: 2.45m core length and diameter, 9cm fuel cell radius, ^{235}U fuel density of 1 mg/cm^3, or 2.5 X10^{18} atoms/cm^3, Be Moderator/reflector radius is 12.5cm and reflector thickness is 20cm (keff = 1.11). –M.A. Prelas, 1990.



O'Meara LSP Paralens Generator – A laser can project a beam only so far before it starts to spread. If a lens is inserted into the beam before the spreading starts, then the energy in the beam is captured and refocused to form a completely new beam. A lens is a gossamer structure that has the ability to focus electromagnetic radiation, typically optical, infrared or microwave radiation. Illustrated is a 55m diameter O'Meara para-lens, consisting of alternating layers of nothing and Kapton plastic with a thickness chosen to add a half-wave of phase to the laser light. Its parameter is 9 kg/m^2. Injecting the beam into a specially-shaped rocket nozzle that focuses the beam with a laser absorption efficiency of 90%, the rocket fuel efficiency can be doubled. –Robert L. Forward, *Advanced Propulsion Concepts Study-Comparative Study of Solar Electric Propulsion and Laser Electric Propulsion*, 1975.

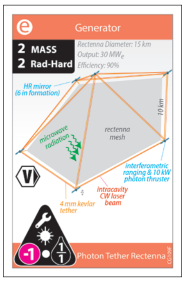


Optoelectric Nuclear Battery Generator – This lightweight, low-pressure, high-efficiency battery converts nuclear energy into light, which it then uses to generate electrical energy. A beta-emitter such as technetium-99 or strontium-90 is suspended in a gas or liquid containing luminescent gas molecules of the excimer type, constituting a "dust plasma." This permits a nearly lossless emission of beta electrons from the emitting dust particles. The electrons then excite the gases whose excimer line is selected for the conversion of the radioactivity into a surrounding photovoltaic layer. The surrounding weakly ionized plasma consists of gases or gas mixtures (such as krypton, argon, and xenon) with excimer lines such that a considerable amount of the energy of the beta electrons

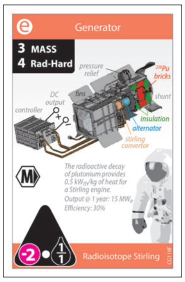


is converted into this light. The surrounding walls contain photovoltaic layers with wide forbidden zones such as diamond. This converts the optical energy into electrical energy. –German Patent DE19833648, 2000.

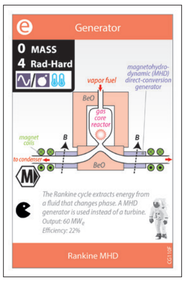
Palmer LSP Aerosol Lens Generator – The lightest possible lens is formed from a cloud of glass beads or aerosol droplets forming a 3-D pseudo-holographic Fresnel lens. If these droplets have a highly nonlinear index of refraction, they can be "organized" by a structured laser beam that interacts with the nonlinear optical index of the beads to put forces on the beads that "trap" the beads into fresnel-zone-like three-dimensional holographic-grating lens structures. A typical droplet field is 80 meters across, with a parameter of 0.1 kg/m^2 and a transmission efficiency of 96%. The aerosol (vacu-sol?) lens can improve the fuel efficiency of a rocket by focusing the laser light into its supersonic exhaust stream in the nozzle. This creates a laser sustained plasma (LSP), a 15,000 K stationary region which transfers energy to the propellant via the reverse bremsstrahlung process. –J. Palmer, Aerosol Lens, J. Optical Society of America, Vol. 73, p. 1568 ff, 1983; A. Mertogul and H. Krier; *Two-temperature modeling of laser sustained hydrogen plasmas,* Journal of Thermophysics and Heat Transfer, 8:781–790, 1994.



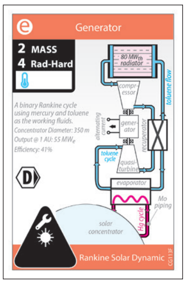
Photon Tether Rectenna Generator – Microwaves beamed from a remote satellite are efficiently converted into DC power by using a special antenna called a ***rectenna***. This is an assemblage of little dipole antennas connected to a network of semiconductor diodes and filter circuits that rectify AC into DC power. Using nanotube Schottky barrier diodes as the rectifier allows high conversion efficiencies (90%). The thin film rectenna illustrated installs these diodes on an etched layer of Kapton film, and operates at 30 GHz at a specific power of 700 kg/MW. However, the range is quite limited for receiving and transmitting antennas of reasonable size. For instance, a transmitter in LEO would need to be 10 km in size to send 30 GHz power to a 100 m rectenna in GEO.



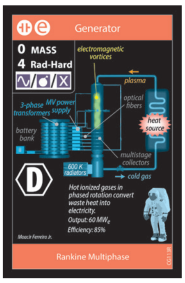
Radioisotope Stirling Generator– The radioactive decay of plutonium provides 0.5 kW$_{th}$/kg. A hundred tonnes of plutonium produces 15 MW$_e$ using a Stirling engine operating at 30% efficiency.



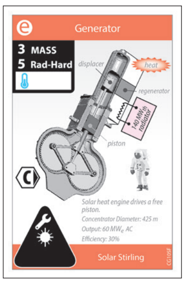
Rankine MHD Generator - As contrasted to the Brayton cycle, the Rankine heat engine cycle uses a working fluid that changes phase. This gives it lower cycle temperature ratios, and thus lower masses and higher efficiencies (22%). Rankine MHD is a closed-cycle version of the MHD generator. Magnetohydrodynamic (MHD) conversion systems produce electrical power the same way as conventional turbine generators, except that the rotating magnet is replaced by a conductive ionized plasma, which passes through a channel surrounded by a magnetic field. The power generated is proportionate to the channel volume, plasma velocity, and the field strength of the surrounding magnets. The ultrahigh temperature system shown uses a disk MHD generator (Hall type with 4T magnetic field) surrounding the output stream of a reactor. For a vapor-core fission reactor, the working fluid might be uranium tetrafluoride (UF_4) plus KF at 4000 K and 40 atm. After being expanded to 0.08 atm in the MHD diffuser, the UF_4 /KF is condensed and separated in radiators operating at 2100 K, and recycled, with losses proportionate to channel area. The steady state parameters are: a neutron flux of 10^{15} n/cm^2-sec, a nuclear-enhanced electric conductivity of 60 mho/m, a magnetic field of 4 Tesla, and a specific power of 1.5 ton/MW$_e$. This generator can operate in a burst mode when powering pulsed lasers or electric engines. When pulsed power is not needed, the nuclear core remains at a subcritical fuel density. Then when a pulse of power is needed, the active volume of the core is decreased to criticality, using pulsed MHD magneto-induction. –Samim Anghaie, University of Florida, *Development of Liquid-Vapor Core Reactors with MHD Generator for Space Power and Propulsion Applications*, 2002.



Rankine Multiphase Generator - This thermal-to-electric closed-cycle heat engine is designed to convert "waste heat" bremsstrahlung radiation into electricity. The unwanted radiation is absorbed by and ionizes a high-temperature working fluid. Two twisting electromagnetic forces out of phase with each other form vortices that axially and radially expand the ionized gas. The F= q (v Å~ B) force longitudinally expands and cools the gas and the F= i (L Å~ B) magnetic force transfers its energy to a multiphase electrical system where electricity is harvested by rectifiers. Thus the vortex acts as an MHD "turbine" extracting heat energy in a cycle similar to the Rankine MHD generator. The claimed almost-Carnot efficiency of 85%, unheard of in a closed-cycle, has not been demonstrated. The 15% low quality heat passes to a heatsink and ultimately to a medium temperature radiator. An inlet temperature of 4000 K generates 60 MW$_e$ and requires a 600 K radiator of 1.5m^2 area. -Moacir Ferreira Jr.

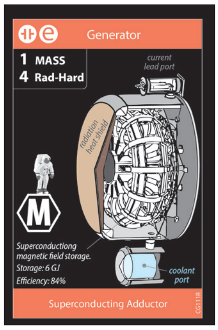


Rankine Solar Dynamic Generator - This version of the Rankine heat engine cycle uses dual working fluids: mercury (high temperature) and toluene (intermediate temperature). A solar concentrator heats the mercury, which transfers its energy to the toluene in an evaporator. Overall efficiency (solar energy to AC electricity) is 41%.

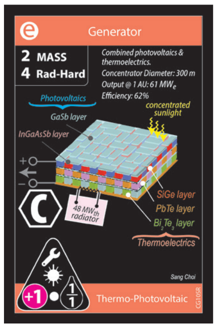


Solar Stirling Generator - The Stirling cycle uses a closed-cycle reciprocating engine and a high-pressure single-phase gaseous working fluid, often hydrogen or helium. The fluid may be heated by solar or nuclear energy. The engine is designed to compress the working fluid in the colder side of the engine and expand it in the hot side, resulting in a net conversion of heat into rotary motion. The free piston Stirling converter illustrated is optimal for space applications due to the absence of wear mechanisms. A Stirling engine heated by a solar mirror 425 m in diameter at 1 AU, can drive a generator with an output of 60 MW$_e$ of alternating current. If carbon-carbon composites are used, the hot side of the Stirling cycle can reach temperatures of 2000 K, with a thermodynamic efficiency of 30%. This efficiency is superior to all other heat engines.

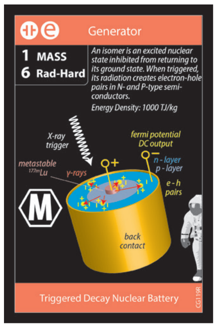
Superconducting Adductor Generator – Energy can be stored inductively in the magnetic field of coils chilled to superconducting temperatures. A toroidal geometry lessens the external magnetic forces and reduces the size of the mechanical support needed. A 25 tonne adductor with a volume of 150 cubic meters stores 6 GJ in a magnetic field of 10 T. Its parameter is 40 MJ/m^3 at 60 MW_e. –Kamiyama, 1994.



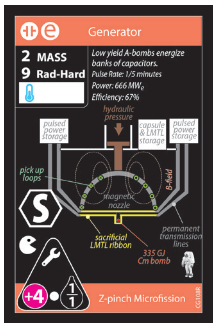
Thermo-Photovoltaic Generator – A solar thermophotovoltaic (TPV) system includes both a photon element and a heat element, so it can run off of both light and heat. The photon element includes a filtered blackbody-based converter, bandpass/infrared (IR) reflector filters, and monolithic two-junction two-terminal TPV converters: GaSb (top cell)/InGaAsSb (bottom cell). The heat element has three diamond nanofactured layers: silicon germanium (SiGe), lead tellurium (PbTe), and bismuth telluride (Bi^2Te^3). When equipped at 1 AU with a lightweight solar concentrator 300 meters in diameter, solar TPV generates 60 MW_e of DC power. With an 1800 K heat source, both high cascade efficiency (62%) and high output power density (about 2 W/cm^2) are realized. Other parameters are 1 kg/m^2 specific area, and 1400 kg/MW_e specific power. –Sang Choi, Nano-BEAMS Lab, NASA Langley Research Center, 2003.



Triggered Decay Nuclear Battery Generator–The nucleus of an isomer—a long-lived excited state of an atom's nucleus—holds an enormous amount of energy. If this energy is suddenly released by a trigger, rather than a slow decay over time, it would be the basis for a powerful nuclear battery. This design uses the radioactive isomer ^{177m}Lu, triggered into fission by x-rays. 1000 TJ/kg are released. The radioactive material sits atop a device with adjacent layers of P-type and N-type silicon, so that ionizing radiation directly penetrates the junction and creates electron-hole pairs for the generation of electricity. –*http://phys.org/news/2013-03-revolutionary-nuclear-battery-closer.html#jCp*, 2013.



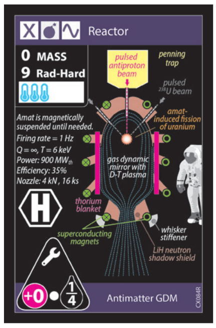
Z-pinch Microfission Generator – Electrodynamic zeta-pinch compression can be used to generate critical mass atomic bombs at very low yields. These detonations can be used to generate impulsive power or thrust. Exotic fission material (^{245}Cm) is utilized to reduce the required compression ratio. The explosion of each low yield (335 GJ) atomic bomb energizes and vaporizes a set of low mass transmission lines, used to pump either another high current Z-pinch, or a bank of nanotube-enhanced ultracapacitors. Each bomb uses 40 g of Cm fissile material and 60g of Be reflector material, with an aspect ratio of 5. A DT diode is used as a neutron emitter. The mylar transmission lines have a mass of 15 kg, and are replaced after each shot. The design illustrated is rated for a shot every 5.5 minutes, equivalent to an output of 1000 MW_{th}. If utilized for thrust, this provides 7.7 kN at a specific impulse of 17 ksec. –Ralph Ewig & Dana Andrews, *Mini-MagOrion Micro Fission Powered Orion Rocket*, Andrews Space & Technology, 2002.



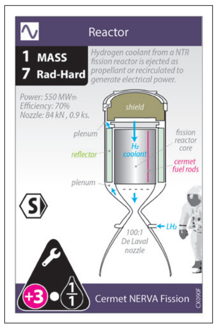
Z6. Reactor Cards

Reactors obtain thermal energy from fuel, usually fission or fusion nuclear fuel. This energy can be used for propulsion, refining, or electricity generation. Reactor design is often dominated by the need to minimize waste heat. There are three strategies for this: **stationary**, **bomb**, and **exotic**. Stationary reactors are basically chambers containing the cleanest steady-state reactions, either aneutronic fusion whose products can be channeled by magnetic fields, or fission whose dirtier products can be mitigated by open-cycle cooling. Bomb reactors ignite the fuel external to the rocket, and channel the charged reaction products for energy or thrust with a magnetic or ablative nozzle. The idea here is that an external reaction allows all the nasty neutrons and gammas to fly into space without intercepting rocket parts and causing waste heat. The exotic reactors store catalysts which serve as ignitors for fission or fusion reactions.

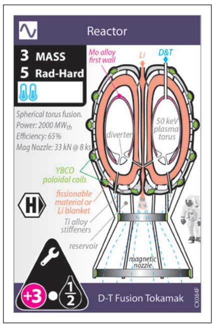
Antimatter GDM Reactor – If a way to produce antimatter fuel cheaply is found, it can be stored as levitated antihydrogen ice. A few micrograms can be removed from storage by first using UV to drive off the positrons, and then accelerating the antiprotons out with electric fields. A pulse of 5 μg of fuel (3 X10^{18} antiprotons) is then collided with 60 g of heavy metal propellant (9 X 10^{24} atoms of lead or depleted uranium) in a magnetic bottle. Each antiproton annihilates a proton or neutron in the nucleus of a heavy atom. The use of heavy metals helps to suppress neutral pion and gamma ray production by reabsorption within the fissioning nucleus. If regolith is used instead of a heavy metal, the gamma flux is trebled requiring much more cooling. Each pulse contains 900 MJ of energy, and at a repetition rate of 1 Hz, a power level of 900 MW_{th} is attained. Compared to fusion, antimatter rockets need higher magnetic field strengths to ensure adequate containment: 16 T in the bottle and 50 T in the throat. After 7 ms, when the plasma reaches 6 keV in temperature and 350 atm in pressure, this field is relaxed to allow the plasma to escape. Compared to fusion, more power is lost to bremsstrahlung X-rays due to the higher temperatures and pressures. Furthermore, the short-lived charged products of the antiproton reactions (charged pions and muons) must be exhausted quickly to prevent an increasing amount of reaction power lost to unrecoverable neutrinos. About a third of the reaction energy is X-rays and neutrons stopped as heat in the shields (some of which is recoverable in a Brayton cycle), another third escapes as neutrinos, and the final third is charged fragments directly converted to thrust or electricity in a MHD nozzle. If ^{238}U is used for the high Z material, the reaction is enhanced by uranium fission. If the chamber is a gas dynamic mirror (GDM) filled with D-T plasma, the reaction is further enhanced by fusion power generated by the annihilation muons. If the GDM is surrounded by a thorium blanket, neutrons from the D-T fusion breed fissionable uranium to further enhance the reaction.– D.L. Morgan, *Concepts for the Design of an Antimatter Annihilation Rocket*, J. British Interplanetary Soc. 35, 1982. (For use in this game, to keep the radiator mass within reasonable bounds, I reduced the pulse rate from 60 Hz to 2 Hz.); Robert L. Forward, *Antiproton Annihilation Propulsion*, University of Dayton, 1985.



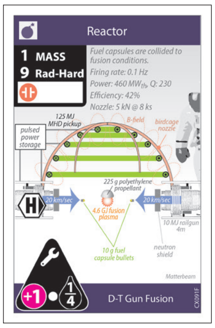
Cermet NERVA Reactor – A fission reactor designed to be cooled by hydrogen, which is then either expelled out a nozzle for open-cycle cooled propulsion or recirculated in a thermodynamic cycle to generate electricity. The coolant pipes pass from one end of the reactor to another, surrounded by the fuel rods and a beryllium oxide neutron reflector. The fuel rods are made of high temperature cermets (ceramic metals) which remain safely solid for extended operational life at a chamber temperature of 3100 K. Assuming hydrogen propellant, 550 MW_{th} matrix at 96% thermal efficiency, 76% frozen-flow efficiency (mainly H_2 dissociation, including recombination in the nozzle), and 96% nozzle efficiency yields a power density of 340 MW/m^3, a thrust of 84 kN, and a specific impulse of 0.9 ks. –Altseimer et al. *Operating Characteristics and Requirements for the NERVA Flight Engine*, AIAA Paper 70-676, June 1970.



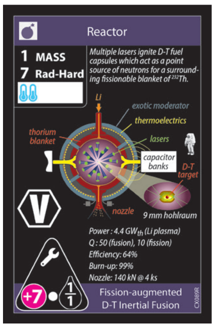
D-D Fusion Magneto-inertial Reactor –In theory, deuterium fuel can be compressed to fusion conditions by an imploding metal liner if the implosion is uniform, intense, and accomplished with great precision. If a large magnetic field in the target suppresses thermal transport, the imploding power becomes low enough to use magnetic implosion. The metal shell could subsequently be used as a propellant. An oscillating compression coil magnetically implodes a plasma liner used to bring a target FRC plasmoid to fusion conditions. The reciprocating nature of this engine also provides efficient direct electrical power needed for target plasmoid formation and heating. By using sprayed on Lithium liners, a repetition rate of 0.1 Hz and a power of 510 MW_{th} is attained, at a Q of 200. Uses a 350 kW solar-powered initiator. –John Slough, MSNW, 2012.



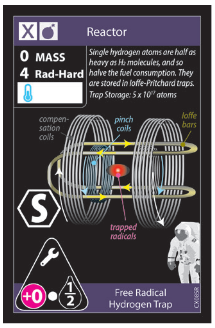
D-T Fusion Tokamak Reactor – Of all the fusion reactions, the easiest to attain is a mixture of the isotopes of hydrogen called deuterium and tritium (D-T). This reaction is "dirty", only 20% of the reaction power is charged particles (alphas) that can be magnetically extracted with a diverter for power or thrust. The remaining energy (neutrons plus bremsstrahlung and cyclotron radiation) must be captured in a surrounding jacket of cold dense lithium plasma. The heated lithium is either injected into the nozzle as an open-cycle coolant, or recirculated through a heat engine (to generate the power needed for the microwave plasma heater). The fusion reactor shown uses magnetic confinement. The donut-shaped tokamak uses eight poloidal superconducting coils, weighing 22 tonnes with stiffeners and neutron shielding, to produce a 30T magnetic field. The pulsed D-T plasma, containing a current of tens of megamps, is superheated by 50 MW of microwaves or colliding beams to 20 keV. The Q (gain factor) is 40. Closed field line devices such as tokamaks can ignite and burn, in which case the Q goes to infinity and microwave heating is no longer needed. However, since ignition is inherently unstable (once ignited, the plasma rapidly heats away from the ignition point), the reactor is kept at slightly below ignition. Fuel is replenished at 24 mg/sec by gas puffing to maintain a plasma ion density of 5 X $10^{20}/m^3$ and a pressure of 26 atm. At a power density of 250 MW_{th}/m^3, the lithium-cooled first wall has a neutron loading of 1 MW/m^2 and a radiation loading of 5 MW/m^2. More advanced vortex designs, which do away with the first wall, separate the hot fusion fuel from the cool lithium plasma by swirling the mixture. The thermal efficiency is 50% in open-cycle mode. –Borowski, Dudzinski, and Juhasz, *A Spherical Torus Nuclear Fusion Reactor Space Propulsion Vehicle Concept for Fast Interplanetary Travel*, Williams, Lewis Research Center, 1998. (The tokamak used in *High Frontier* is a smaller lower tech version of the Lewis design. Because it uses D-T instead of ^{3}He -D fuel, it requires far more open-cycle and radiator cooling.)



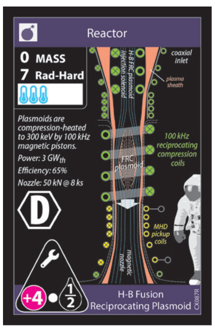
D-T Gun Fusion Reactor – This geometry of fusion uses two railguns, each accelerating a 10 g bullet of fusion fuel to speeds of 20 km/sec, enough so if enhanced by staged compression creates fusion conditions upon collision. The bullets contain three elements: a thin (100nm) faceplate of gold, a chamber containing a gas mixture of deuterium, tritium and hydrogen, and a solid 'tail'. Upon impact, the gold faceplates vaporize as kinetic energy is converted into thermal energy (10% efficiency). The heat radiated by the impact raises the temperature of the gas mixture (1% of bullet mass) to 3.125 million K. This lowers pressure requirements for ignition by a factor of 10^5. The momentum of the solid tails compress the mixture to D-T fusion ignition at 80 million atmospheres. With a fuel burn-up of 6.6%, each shot generates 4.5 GJ of fusion energy. Although the fusion of deuterium and tritium (D-T) is the easiest to attain, it is also one of the messiest - about 80% of the reaction power is in the form of 14 MeV neutrons, a type of power that tends to end up as waste heat. The impact is capped by a hemisphere of polyethylene, with a 5cm depth to absorb over 98% of the neutrons. Absorbing half the fusion power (2.3 GJ), its 225 gram mass can either be captured via MHD for energy or expelled as propellant. Since the collision is external, the other half of the energy escapes into space. Polyethylene turned into a plasma has a heat capacity of 4.67 J/g/K, so it rises to a temperature of 2 million K. In a magnetic nozzle with 85% efficiency, it turns into an exhaust with a velocity of 80 km/s and 5.5 kN of thrust. The 16% efficient railguns require 10 MJ per shot, for a Q of 230. This power is tapped from the propellant using MHD, and stored in supercapacitors. –Malik K. (Matterbeam), 2016.



Fission-augmented D-T Inertial Fusion Reactor – A hypothetical hybrid fission-fusion reactor may use D-T fuel pellets surrounded by a fissionable blanket Th-232 to produce energy sufficiently greater than the input (laser) energy for electrical power generation. The principle involved is to induce inertial confinement fusion (ICF) in the fuel pellet which acts as a highly concentrated point source of neutrons which in turn converts and fissions the outer fissionable blanket. –LLNL, 2008. http://nextbigfuture.com/2008/12/proposed-laser-ignition-fusionfission.html

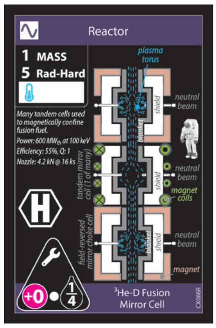


Free Radical Hydrogen Reactor – Free radicals are single atoms of elements that normally form molecules. Free radical hydrogen has half the molecular weight of H_2 and, if used as propellant, doubles the specific impulse of thermodynamic rockets. Alternatively, if recombined, its specific energy (218 MJ/kg) produces a theoretical specific impulse of 2.13 ksec. Monatomic H is produced in situ in a solid H_2 matrix by particle bombardment, cooled by VUV laser chirping, and finally trapped in a hybrid laser-magnet as a Bose-Einstein gas at ultracold temperatures. Free radical hydrogen is confined in a Pritchard-Ioffe trap to keep its mobile spin aligned. Confinement is provided by the interaction of the atomic magnetic moment with the inhomogeneous magnetic field. The trapping density is >10^{14} atoms/cm^3 (much higher than Penning traps). Spin-vector polarization increases the fusion reactivity cross-sectional area of heavy hydrogen by 50%, increasing its utility as a fusion fuel, and neither ionization nor atomic collisions will depolarize the free radicals.

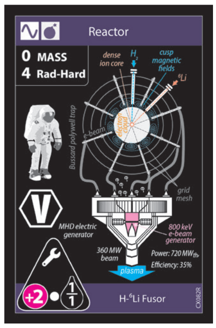


H-B Fusion Reciprocating Plasmoid Reactor – The operation of this fusion engine is comparable to that of an internal combustion engine. The fuel to be combusted is a 25 mg pellet of decaborane ($H_{14}B_{10}$), a solid at room temperature. This is magnetically converted into a hydrogen-boron plasmoid in a field-reversed configuration (FRC), and injected into a compression/burn chamber. The compression stroke is driven by a piston sheath coupled to a 100 kHz axial magnetic field. This stroke ignites the plasmoid at 300 keV. The sheath plasma forming the piston is lithium, water, or scooped atmosphere propellant. After being superheated, both the fusion products and the sheath propellant are expanded for thrust or energy in a magnetic nozzle. Electrical energy for the compression is picked up via MHD coils in the exhaust. The high energy density, direct propellant coupling, magnetic insulation, and low fusion gain allow for a vastly lighter engine than other magnetically-confined fusion systems such as spherical Tokamaks. With open-cycle cooling and an air scoop, the thrust to weight ratio can be above unity, allowing a ramjet version to enter orbit from the Earth's surface. Although the H-^{11}B reaction is aneutronic, collisions between the ions and electrons lose half the energy to bremsstrahlung X-rays. The sheath, acting as open-cycle coolant, intercepts many of these X-rays, allowing a thermal efficiency of 85%. At 100 kHz and 2.5 kg/sec, 3 GW$_{th}$ is generated with an overall efficiency of 65%. –John Slough, *"Earth to Orbit based on a Reciprocating Plasma Liner, Compression of Fusion Plasmoids,"* University of Washington, 2007.

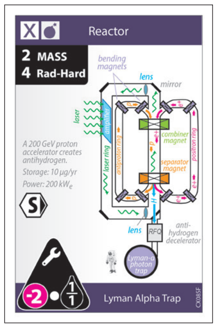
^{3}He-D Fusion Mirror Cell Reactor – Helium-3 is an isotope of helium, and deuterium (abbreviated D) is an isotope of hydrogen. The ^{3}He-D fusion cycle is superior to the D-T cycle since almost all the fusion energy, rather than just 20%, is deposited in the plasma as fast charged particles. Magnetic containers with a linear rather than toroidal geometry, such as steady-state mirrors, have superior ratios of plasma pressure to magnet pressure (ß >30%) and higher power densities necessary for reaching the high (50 keV) ^{3}He-D operating temperatures. The mirror design shown is a tube of 11 T superconducting magnetic coils, with choke coils for reflection at the ends. The magnets weigh 12 tonnes, plus another 24 tonnes for 60cm of magnet radiation shielding and refrigeration. A mirror has low radiation losses (20% bremsstrahlung, 3% neutrons) compared to its end losses (77% fast charged particles). These losses limit the Q to about unity and prevent ignition. (This is not a problem for propulsion, since reaching break-even is not required to achieve thrust. The plasma is held in stable energy equilibrium by the constant injection of auxiliary microwave heating.) The Q can be improved by a tandem arrangement: stacking identical mirror cells end to end so that one's loss is another's gain. The exhaust exiting one end can be converted to power by direct conversion (MHD), and the other end's exhaust can be expanded in a magnetic flux tube for thrust. Mirrors improved by vortex technology, called field-reversed mirrors, introduce an azimuthal electron current which creates a poloidal magnetic field component strong enough to reverse the polarity of the magnetic induction along the cylindrical axis. This creates a hot compact toroid that both plugs end losses and raises the temperature of the scrape-off plasma layer fourfold (to 2.5 keV), corresponding to a specific impulse of 32 ksec. Mirrors, like all magnetic fusion devices, can readily augment their thrust by open-cycle cooling. – M.J. Schaffer, *Considerations for Steady-State FRC-Based Fusion Space Propulsion*, General Atomics Project 4437, Dec 2000.



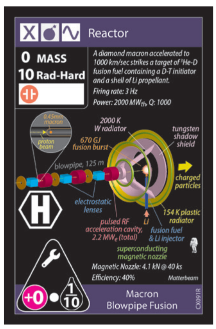
H-^{6}Li Fusor Reactor – A Farnsworth-Bussard fusor is little more than two charged concentric spheres dangling in a vacuum chamber, producing fusion through inertial electrostatic confinement. Electrons are emitted from an outer shell (the cathode), and directed towards a central anode called the grid. The grid is a hollow sphere of wire mesh, with the elements magnetically-shielded so that the electrons do not strike them. Instead, they zip right on through, oscillating back and forth about the center, creating a deep electrostatic well to trap the ions of lithium 6 and hydrogen that form the fusion fuel. With a one meter diameter grid and a fuel consumption rate of 7 mg/sec, the fusion power produced is 360 MW$_{th}$. Half of this energy is bremsstrahlung X-rays, which must be captured in a lithium heat engine. The other half are isotopes of helium (^{3}He and ^{4}He), each at about 8 MeV. (Overall efficiency is 36%). Since both products are doubly charged, a 4 MeV electric field will decelerate them and produce two electrons from each, producing an 18 amp current at extremely high voltage. An electron gun using this 4 million volt energy would emit electrons at relativistic speeds. This beam dissipates quickly in space, unless neutralized by positrons or converted into a free electron laser beam. –R W. Bussard and L. W. Jameson, *Inertial-Electrostatic-Fusion Propulsion Spectrum: Air-Breathing to Interstellar Flight*, Journal of Propulsion and Power, v. 11, no. 2, pp. 365-372. (Philo Farnsworth, the farm boy who invented the television, spent his last years in a lonely quest to attain break-even fusion in his ultra-cheap fusor devices. His ideas are enjoying a renaissance, thanks to Dr. Bussard, and working fusion reactors are making an appearance in high school science fairs. On the theory that the fusor is power-limited, I have scaled down Bussard's 10 GW design to 720 MW.)

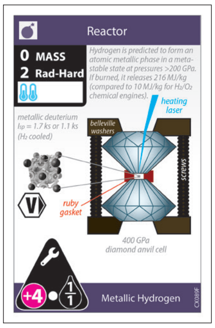


Lyman Alpha Trap Reactor – This antimatter factory uses a 200 GeV proton accelerator to smash a stack of multiple thin targets surrounded by wide angular arrays of multiple lenses with different velocity acceptances. At a beam power of 0.2 MW and a current of 3.2 µamps, one in ten incident protons becomes an antiproton. The shower of antiprotons is entrained with positrons to form first atomic, then molecular, antihydrogen. This formation process is enhanced 100-fold by an optical laser traveling opposite to the beams of antiprotons and positrons, as shown in the illustration. This antimatter beam is cooled by a radio frequency quadrupole (RFQ) decelerator, trapped with Lyman alpha laser beams, and tickled into forming an iceball in a Lyman-α light trap. The iceball is grown into a charged microcrystal levitated by electrostatic forces. The temperature is kept below 1 K by lasers to keep sublimation pressure low. The energy of the unused exiting proton stream is recovered via MHD or uranium enrichment. Solar energy is obtained through solar-pumped iodine gas dynamic lasers. 10 µg/year of antimatter is produced.

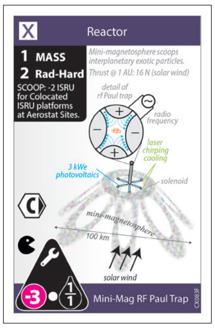


Macron Blowpipe Fusion Reactor –A "blowpipe" particle accelerator consists of a proton beam generator and a series of electrostatic lenses spaced by negatively charged rings. Hundreds of RF magnetron cavities in the beam generator, each imparting 2.68 µJ at 1 GHz, produce a 134 kA proton current. The low beam energy (10 keV) means that the lenses are needed to keep focus. The resultant beam current density of 74.5 kA/m^{2} sits well below the Child-Languir limit. This current acts as a pushrod to accelerate a diamond macron, grown through chemical vapor deposition to a diameter of half a millimeter. By charging it by microneedle electrodes up to an internal voltage gradient of 1000 MV/m, it gains an effective electrostatic repulsion area of 35.7 mm^{2}. An accelerator 250 meters long accelerates the macron to 1000 km/sec in half a millisecond. The macron impacts a target of D-T ice embedded in a larger amount of ^{3}He-D fuel and serves as the 'fast ignition' system for the latter. The impact shockwave is far more efficient than laser ablation to bring D-T to ignition; 0.67 MJ is required (which means a projectile mass of 1.34 milligrams). A mass of 0.5 milligrams of DT is ignited, which in turn brings a 10 milligram mass of ^{3}He-D to fuse.

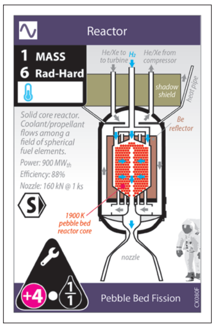




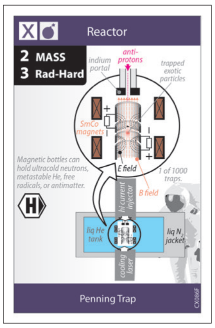
The result is a 667 MJ explosion, for a Q of 1000. This energy is 80% charged particles, half of which is intercepted by a hemispherical magnetic nozzle. All but 0.2% of the remaining products (10% neutrons, 10% x-rays) fly into space. As the exit velocity (11,000 km/sec) is excessive for interplanetary travel, a 3 gram shell of lithium propellant, 8.4 mm thick, surrounds the fusion fuels, with a gap for the macron to enter. It absorbs 5% of the neutron energy and all of the charged particle energy. It decreases the useful energy density of the fusion reaction from 44.8 TJ/kg to 178 GJ/kg while raising the average molar mass of the resulting plasma from 2.5 g/mol to 7 g/mol. Exhaust velocity drops by a factor (44.8/0.178)^0.5 * (7/2.5)^0.5 = 26.5. At a firing rate of 3 Hz, two gigawatts of thermal power is generated. MHD pickup in the nozzle is used to generate the 2.3 MW_e to run the magnetrons. The accelerator tube masses 13 tonnes, plus another 3 tonnes for the proton generator and 2 tonnes in the nozzle.
–Y. Nakao, *Ignition and Burn Properties of DT/D ^{3}He Fuel for Fast-Ignition Inertial Confinement Fusion*, 2009; Malik K. (Matterbeam), 2019.



Metallic Hydrogen Reactor –The 25 GPa pressure required for metallic hydrogen can be greatly reduced both by lithium doping and by entrapping it within cryogenically frozen solid hydrogen. SiH_4, even at moderate pressures forms a sub-lattice of metallic hydrogen. Deuterium is easier to metallize than hydrogen, requiring less than a third the pressure and solid D_2 has been achieved at room temperatures. When the metastable metallic hydrogen lattice is heated above 1000 K at 40 bar pressure, the metastability breaks down and the hydrogen lattice recombines into hydrogen gas, releasing 216 MJ/kg in the process (LOX-H_2 has an energy density of 10 MJ/kg). Pure metallic hydrogen could yield a specific impulse of 1.7 ks but would result in reaction chamber temperatures above 6000 K. The design cools the reactor with hydrogen for a more modest specific impulse of 1.1 ks. –I. Silvera, J. Cole, *Metallic hydrogen: the most powerful rocket fuel yet to exist*. 2010; Ranga Dias, Isaac Silvera, *Observation of the Wigner-Huntington transition to metallic hydrogen*, 2017.

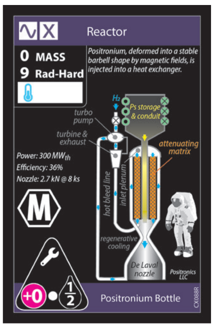


Mini-Mag RF Paul Trap Reactor – The natural environment of space can be used as a low energy accumulator to store a variety of exotic particles, including antimatter. This device turns a spacecraft into a Bussard ramjet, (albeit one that scoops its fuel rather than its propellant, a much simpler task). The "scoop", a huge (100 km) magnetic bubble called a "mini-magnetosphere", is inflated with conductive ionized gas or plasma. Field lines are generated by onboard solenoids, powered by 3 kW_e photovoltaics. A reservoir of helium replenishes ions that leak from the plasma. The field lines of the mini-magnetosphere direct solar wind onto a heavy metal target. The resulting spray of photons and particle-antiparticle pairs contain a small fraction (<5%) of proton-antiproton pairs, as well as other exotics. These are magnetically focused, debunched and cooled using laser chirping and radio frequency (rf) fields, and stored along with positrons in a low energy antiproton Paul trap (see illustration). Neutral antimatter hydrogen and other exotics are condensed as electrostatically-suspended ice pellets. A few micrograms per year of antimatter ice condensates are produced, at densities approaching 10^{23} atoms/cm^3. The mini-magnetosphere can also act as a sail, deriving thrust from the solar winds. –Robert M. Zubrin, *The use of magnetic sails to escape from low earth orbit,* Journal of the British Interplanetary Society, Vol. 46, pp. 3-10, 1993.



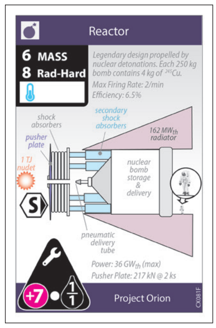
Pebble Bed Fission Reactor – This is a graphite-moderated, gas-cooled, nuclear reactor that uses spherical fuel elements called "pebbles". These tennis ball-sized pebbles are made of pyrolytic graphite (which acts as the moderator), interspersed with thousands of microparticles of a fissile fuel (such as ^{235}U). In the reactor illustrated, 2.7 million pebbles are placed together to create a 900 MW_{th} reactor. The spaces between the pebbles form the "piping" in the core for the coolant, either propellant or inert He/Xe gas. The design illustrated is dual mode. It can operate either as a generator for 240 MW_e of electricity, or act as a solid-core thruster using hydrogen propellant/coolant expelled at a specific impulse of 1 ksec. When used as a thruster, it offers a slight increase in specific impulse but significant acceleration benefits over traditional fission reactors. Moreover, the high temperatures (2400 K) allow higher thermal efficiencies (up to 50%).

Penning Trap Reactor – Exotic fuel, produced in a superconducting supercollider, can be cooled by a radio frequency quadrupole (RFQ) and stored and transported into space in liter-sized Penning trap thermos bottles. For instance, a thousand such traps, each weighing 80 kg, would hold 10^{17} antiprotons (140 ng), enough fuel for a delta-v of 100 km/sec. Other fuels include metastable helium, ultracold neutrons, and free radical hydrogen. A Penning trap uses a combination of laser cooling and electromagnetic fields to store particles. Each is able to store more particles (10^{14}) then rf Paul traps, and also does not use dynamic rf fields which can heat the trapped fuel. The Brillouin limiting factor for Penning traps is 10^{11} antiprotons/cm^3.

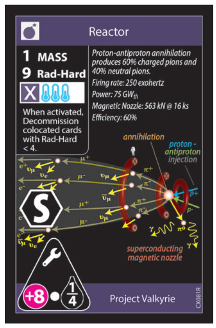


Positronium Bottle Reactor – Positronium (Ps), comprised of an electron and a positron, is the smallest possible "atom" as both components are structureless point-like leptons (massing 1.82× 10^{-30} kg compared to 1.67 × 10^{-27} kg for hydrogen) . Depending on the spin state, para-Ps has a lifetime of 0.125 ns while ortho-Ps has a lifetime of 142 ns before decaying into two or three gamma-rays respectively. Ps can be stabilized by pinning the electron and positron in a magnetic field while a crossed electric field stretches the atom apart by up to 400 nm. This increases the potential barrier that the leptons must tunnel through to annihilate one another, extending their lifetimes to over a year. A Ps beam is created by impacting a beam of positrons onto a tungsten target with an efficiency of 10^{-5}. The positrons themselves are produced via the natural decay of ^{22}Na which has a half-life of 2.6 years before emitting a gamma ray and positron and decaying into ^{22}Ne. The ^{22}Na is produced by dissolving proton irradiated aluminum into a sodium-enriched hydrochloric acid salt. The resulting positronium beam is stabilized within the crossed electric-magnetic fields and directed towards quantum dot nanochips of dimensions 1 cm × 1 cm × 11 µm. Each quantum dot within the chip suspends up to 1000 Ps in potential wells. Up to 10^{11} Ps atoms may be stored per chip which is kept at 25 mK. At full capacity, 15 billion chips may be produced and stored. Unfortunately, due to the nature of production and storage, rapid explosive annihilation is not possible but rather must occur at a steady rate via excitation with UV lasers. –K. Edwards, *Propulsion and Power with Positrons*, 2004; Ackermann, Schertzer, Schmelcher, *Long-lived states of Positronium in Crossed Electric and Magnetic Fields*, 1997.

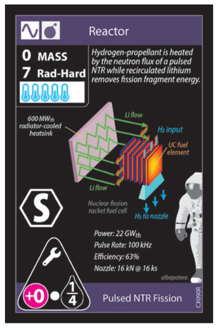
Project Orion Reactor – This fabled technology converts the impulses of small nuclear detonations into thrust. The small shaped-charge bombs each have a mass of 250 kg (including propellant) and a yield of a quarter kiloton (1 terajoule). The fissile material is curium-245, with a critical mass of 4 kg, surrounded by a beryllium reflector. The soft X-rays, UV and plasma from the external detonation vaporize and compress the propellant to a gram per liter, highly opaque to the bomb energies at the temperatures attained (67000 K). The propellant, a mixture of water, nitrogen, and hydrogen, interfaces with a pusher plate "nozzle", which can be either solid or magnetic. Shown is a solid plate, which tapers to the edges (to maintain a constant net velocity of the plate given a greater momentum transfer in the center). Pressure on the plate reaches 690 MPa in the center. The impulse shock is absorbed by a set of pneumatic "tires", followed by gas-filled pistons detuned to the maximum detonation frequency of once per 30 seconds. This corresponds to 33 GW_{th} of blast energy, of which 6.5% is utilized for thrust. The shock plate system becomes a useful shield if pointed towards the enemy. –George Dyson, *Henry Holt and Company*, Project Orion, 2002 (Ted Taylor's classic design, optimized for low yield bombs and 2 ksec specific impulse).



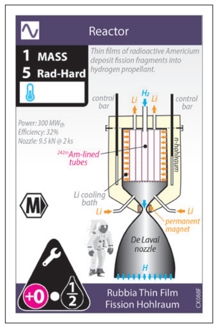
Project Valkyrie Reactor – This antimatter beam core rocket uses a high temperature (100 K+) superconducting magnetic nozzle to direct charged pions resulting from the annihilation of equal amounts of protons and antiprotons to produce thrust. These pions, travelling at near light speed travel 21m (in 70 nanoseconds) before decaying into charged muons and neutrinos. The muons may travel a further 1.85 km (over 6.2 microseconds at 0.995c) before decaying into electrons and positrons. Along with the produced charged pions, a neutral pion rapidly decays (within 60nm) into 200MeV gamma rays. The reactor chamber is made as transparent as possible, to allow these gamma rays to escape to space. Even so, considerable radiators are required to dissipate the heat absorbed by the magnetic coil shielding. Furthermore, critical components (such as crew) must be distanced by tens of kilometers from this reactor. By attaching tethers of this length to the back of the thruster, so that the cargo is towed instead of pushed, significant weight savings are achieved. A shadow shield of tungsten is mounted 2/3's of the way on the tether for additional shielding. Antimatter production and storage is the main limiting factor in realizing this engine design but foreseeable scaling from current technology (or from game technology of 10µg/year) makes it feasible for interplanetary missions. –R. Frisbee, *How to build an antimatter rocket for interstellar missions*, 2003.



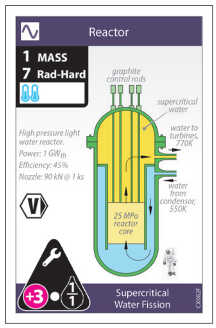
Pulsed NTR Fission Reactor – This nuclear thermal rocket uses solid fuel in the form of plates, but unlike most NTRs it operates in a pulsed rather than stationary mode. This changes the energy utilization from almost all fission fragments to almost all prompt neutrons. The intensive neutron flux imparts energy to the propellant kinetically, rather than thermally, allowing the propellant to get hotter than the reactor, such as in fission fragment propulsion. The propellant must be expelled as rapidly as possible (10's of milliseconds) so as not to lose heat by radiative cooling. Optical choppers or magnetic wheels operating the poison rods allow pulsation frequencies of 10 kHz. Energy from fission fragments, representing 95% of the pulse reaction energy, is unwanted and must be continuously evacuated by a lithium heat removal auxiliary system. This implies a large dedicated heat transfer surface, cooled by radiators. This drawback makes its claimed utility as a starship engine questionable, even with a high specific impulse (8 ks or more). –Francisco Arias, *On the Use of a Pulsed Nuclear Thermal Rocket for Interplanetary Travel*, 2016.



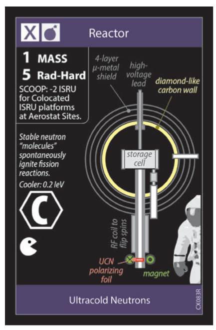
Rubbia Thin Film Fission Hohlraum Reactor – This concept can be seen as the inverse of a NERVA, in that the fissioning surface layer is deposited on the inside wall of the reaction chamber rather than as a core. This very thin layer of metastable ^{242m}Am can be kept at a reasonable temperature while half the fragments thermalize inside the pumped hydrogen propellant. However, the other half fragments, injecting into the walls, need to be cooled and radiated away. The primary advantage is that the propellant can become hotter than the solid reactor walls while still maintaining a simpler (and lighter) solid reactor system (compared to a NERVA). Because the ^{242m}Am can never become critical, an external neutron source, in the form of a proton accelerator against a tungsten target is required to start the fission. –C. Rubbia, 1998; Czysz and Bruno, *Future Spacecraft Propulsion Systems*, 2006.

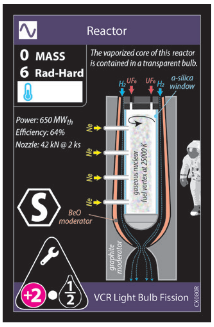


Supercritical Water Fission Reactor – A supercritical state is one in which there is no difference between a substance's gas and liquid state. Supercritical water is used as a working fluid by a generation IV reactor design, allowing for higher thermal efficiency compared to other light water reactor designs. This reactor eliminates the need for recirculation, jet pumps, pressurizers, steam generators, steam separators and dryers, simplifying the system and reducing containment volume. The heat transfer characteristics of supercritical water, although rather cold for thrust, is useful for power generation (at an efficiency of 44.8%). It can also be used as a breeder, converting thorium and long lived actinide isotopes. The reactor core operates at 25 MPa with a design tolerance up to 27.5 MPa. Water at 550 K is fed into the reactor at 527 L/s, exiting at 770 K resulting in 1 GW_{th}. This exhaust temperature is too cold for thrust. The core consists of 40 assemblies where 16 fuel rods surround a Zircaloy water box containing the graphite control rods lined by 1mm yttrium-stabilized zirconium oxide. The reactor mass is dominated by the high pressure containment vessel, with high-grade steel walls 25 cm thick, but this reduces the shielding required. –Buongiorno, Swindeman, ***et al.***, *Supercritical Water Reactor (SCWR) Survey of Material Experience and R&D Needs to Assess Viability*, 2003. Scaled down to 80 tonnes and 1 GW_{th}.



Ultracold Neutron Reactor – Neutrons are normally unstable particles, with a half life of 12 minutes. When polarized and ultra-cooled (using vibrators or turbines) to form a dineutron or tetraneutron phase, they are believed to be stable and storable in total internal reflection bottles, lined with diamond-like carbon as the neutron reflector. Ultracold neutrons (UCN) have a huge quantum mechanical wavelength as a consequence of their slow movement (typically 0.4 µm @ 1 m/sec), and thus can spontaneously initiate fission reactions such as n-^{235}U or n-^{6}Li. If the neutron source is a nuclear reactor, the neutrons must be cooled from 2 MeV to 2 meV using a heavy water moderator, and further cooled in a UCN turbine to 0.2 IeV.

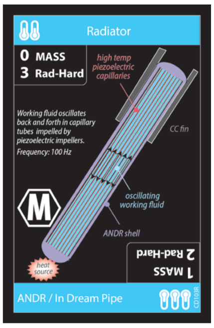




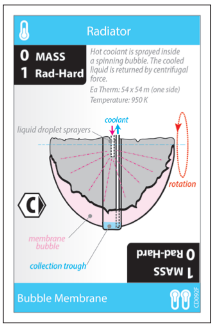
VCR Light Bulb Fission Reactor – Most fission reactors avoid meltdown, but the vapor core reactor (VCR) runs so hot (25000 K) that its core vaporizes. At this temperature, the vast majority of the electromagnetic emissions are in the hard ultraviolet range. A "bulb" transparent to this radiation, made of internally-cooled a-silica, bottles the gaseous uranium hexafluoride, while letting the fission energy shine through. The operating pressure is 1000 atm. The UF_6 fuel is prevented from condensing on the cooled wall by a vortex flow field created by the tangential injection of a neon "buffer" gas near the inside of the transparent wall. In a generator mode, the UV uses photovoltaics to generate electricity. In a propulsion mode, the UV heats seeded hydrogen propellant, which exits at a specific impulse of 2 ks.

Z7. Radiator Cards

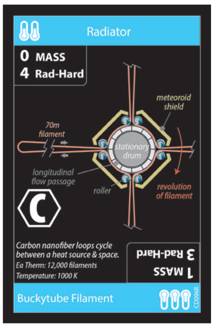
Every spaceship and space station accumulates waste heat from sunlight, habitats, reactors and engines. Without a convenient planet or atmosphere, there is no other way to get rid of heat other than by radiation. If the radiator fails, the spacecraft will eventually melt. Waste heat removed = (emissivity) * (radiator area) * (Stefan-Bolzman constant) * (temperature)^4. Because radiator size goes down as the fourth power of the radiation temperature, doubling the engine temperature (from 1000 K to 2000 K, say), means a radiator 8X smaller. Alternately, you can radiate 8X more waste heat out of the same size radiator operating twice as hot. If your waste heat is too low a temperature, you will need electric heat pumps to raise it to the operating temperature of the game's radiators, around 1200 K. Current technology heat pumps handle 0.5 MW/tonne. Otherwise you are faced with acres of radiators needed to reject lukewarm heat. The game's GW rockets are assumed to use advanced allows so as to run hotter, about 1427 K instead of 1200 K for MW rockets. This means that for GW rockets, each "Therm" of heat radiates twice as much power as for MW rockets: 240 MW_{th} instead of 120 MW_{th}. And TW rockets run hotter still, 2000 K or 960 MW_{th} for each therm. At this point, other than the thermally-insulated payload, the entire rocket glows white hot.



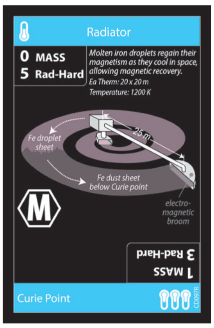
ANDR/In Dream Pipe – A heat pipe with Indium as a working fluid can operate between 2000 and 3000 K, higher than any other metal. However its lower limit of operation is also higher and ideally should operate above 2353 K (the boiling point at 1 atm). Furthermore, its low freezing point makes it particularly attractive from a cold start. However due to its high corrosion, indium has largely been ignored as a working fluid. At temperatures approaching 3000 K, only a carbon wall and a tungsten wick system would work. Here the wall is made of aggregated diamond nanorods (or hyper diamond) produced by the compression of fullerene. This material with an isothermal bulk modulus of 491 GPa is harder and less compressible than diamond and an increased wear resistance. Carbon aerogel is used as insulation in the adiabatic section. Due to the short life of the heat pipe (~2200 hrs or 3 months), multiple redundant pipes are on-hand while fouled pipes are automatically replaced and repaired by monitoring robots. Specific area is 275 kg/m^2 including spare pipes and repair system.



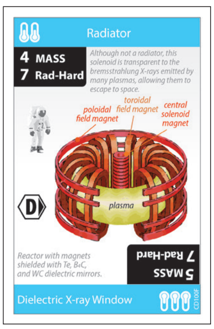
Bubble Membrane Radiator - This concept sprays hot coolant inside a spinning bubble-shaped membrane. The cooled liquid is returned by centrifugal force. The membrane is space-manufactured from carbon nanotubes, woven cermet fabrics, or other advanced materials. A two-phase working fluid (hot liquid or gas) is centrifugally pumped to the bubble membrane, where it is sprayed on the interior surface. The fluid wets the inner surface of the sphere and is driven in the form of a liquid film by centrifugal force to the equatorial periphery of the sphere; liquid metal pumps located there return the liquid out of the sphere through rotated shaft seals to its source. As the liquid flows along the inner surface of the envelope it loses heat by thermal radiation from the outer surface of the balloon. The specific area is 7 kg/m^2, which radiates from one side at 950 K.



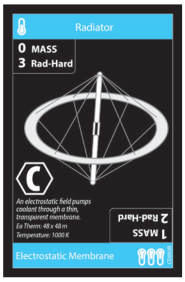
Buckytube Filament Radiator - Waste heat may be rejected by moving thousands of loops of thin (1 mm) flexible "Buckytubes" (carbon nanotubes), which radiate their thermal load prior to return to the heat exchanger. Cables constructed of Arm-chair type nanotubes are the strongest cables known, with design tensile strengths about 70% of the theoretical 100 GPa value. The moving filaments are heated by direct contact around a molybdenum drum filled with the heated working fluid, and then extended into space a distance of 70m by rotational inertia. Their speed is varied according to the temperature radiated (from 273 K to 1300 K). The loops are redundantly braided to prevent single point failures from micrometeoroids. Each element is heat treated at 3300 K to increase the thermal conductivity through graphitization to about 2500 W/mK. About 12,000 filaments are needed per therm, at 77 g/filament, which exit the spacecraft at 100 m/s and return a few seconds later. –Richard J. Flaherty, *Heat-transfer and Weight Analysis of a Moving-Belt Radiator System for Waste Rejection in Space*, Lewis Research Center, Cleveland, Ohio, 1964.



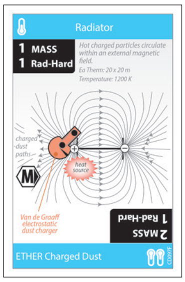
Curie Point Radiator - A ferromagnetic material heated above its Curie point loses its magnetism. If molten droplets of such a substance are slung into space, they radiate heat and solidify. Once below their Curie temperature, they regain their magnetic properties and can be shepherded by a magnetic field into a collector and returned to the heat exchanger. The mass for a 120 MW system operating at 1200 K includes a 13 tonne magnetic heat exchanger and a rotating dust recovery electromagnet on a 25m boom, plus 7 tonnes of dust spread in a spiraling disk 27 meters in diameter (35 kg/m^2). The usual medium is iron dust, which has a Curie point of 1043 K and is easily scavenged by magnetic beneficiation from regolith.



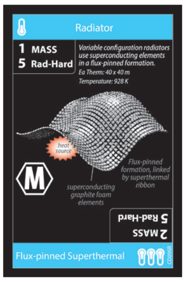
Dielectric X-ray Window Radiator – Fusion for propulsion emphasizes the efficient rejection of fusion products as propellant rather than maximizing energy production or the "Q". The aneutronic fuels preferred for propulsion unfortunately emit significant bremsstrahlung radiation (x-rays produced by "braked" electrons). For example, a magnetic-confined reactor burning ^{3}He-D fuel emits more than 16% of its energy as 100-keV x-rays. For H-^{11}B fuel, it is 63% at 300 keV. Such x-rays are readily absorbed and converted into heat in less than a millimeter of steel, increasing the ship's heat load. A dielectric window reactor avoids this by running the plasma hotter than normal and confining it by fields rather than solid walls, allowing the radiation to pass harmlessly into space. The high-temperature superconducting magnets of the reactor and nozzle are X-ray hardened by a dielectric mirror composed of layers of tellurium, tungsten carbide, and polymers. The reflectivity of multilayer thin films can be extremely high if the films are constructed of pairs of quarter-wave thick layers of low absorbance dielectrics. Prototypes made at MIT reflect 99% of light falling on them, at a maximum specific energy of 3 MW/m^2 and a specific mass of 1600 kg/m^2. The remaining 1% of the heat is removed by Li coolant and rejected by radiators or open-cycle cooling. A Carnot-limited portion is recovered in a heat engine (e.g. hot Li turbine) to run the igniters. –Ken Rachocki, LANL, 2006.



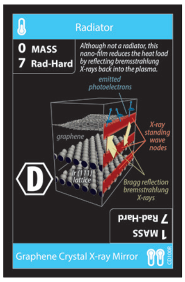
Electrostatic Membrane Radiator – This heat-rejection concept, also called a liquid-sheet radiator, encloses radiating liquid within a transparent envelope. It consists of a spinning membrane disk inflated by low gas pressure, with electrostatically-driven coolant circulating on its interior surfaces. The liquid coolant is only 300 μm thick and has an optical emissivity of 0.85 at a temperature of 1000 K. An electric field is used to lower the pressure under the film of coolant, so that leakage through a puncture in the membrane wall is avoided. The membrane has a specific area of 4.3 kg/m^2.



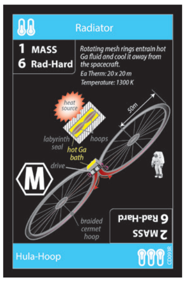
ETHER Charged Dust Radiator – To avoid the evaporation losses suffered by radiators that use liquid droplets in space, dust radiators use solid dust particles instead. If the particles are electrostatically charged, as in an *Electrostatic THErmal Radiator* (ETHER), they are confined by the field lines established by a charged generator and its collector surfaces. If the spacecraft is charged opposite to the charge on the radiating particles, the dust executes an elliptical orbit. The radiating particles must be charged to 10^{-14} coulombs to inhibit neutralization from the solar wind. The dust radiates at 1200 K with a specific area of 71 kg/m^2. –Prenger 1982.



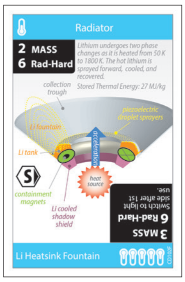
Flux-pinned Superthermal Radiator -Variable configuration radiators take advantage of the surprising physics of high-temperature flux-pinning superconductors. These materials resist being moved within magnetic fields, allowing stable formations of elements. No power or active feedback control if necessary. The radiating elements fly in a flux-pinned formation, not physically touching, but connected by superthermal ribbon. Superthermal compounds hypothetically conduct heat as effortlessly as superconducting materials conduct electricity. The radiating surfaces are graphite foams, which have both high emissivity (0.9) and a high thermal conductivity (1970 W/m°K) if the heat conducts in a direction parallel to the crystal layers. Operating at 928 K, the superthermal radiator has a specific area of 17 kg/m^2 and 76 kW$_{th}$/m^2. –Dr Mason Peck, 2005.



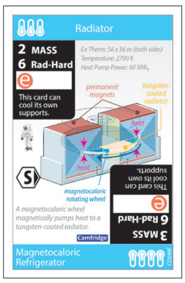
Graphene Crystal X-ray Mirror Radiator – An unrealized dream in fusion energy is a lightweight x-ray mirror able to reflect bremsstrahlung radiation back into the fusion core. One hypothetical scheme is a graphene on Ir(111) nano-film under active feedback. An x-ray standing wave (XSW) is created in the interface region of a graphene crystal using Bragg reflection. The XSW is periodic with Iridium (111) lattice planes spaced 0.3-nm below the graphene cell. The maxima of the XSW are shifted inward by half the lattice plane distance when scanning through the Bragg reflection according to the beam energy. Atoms exposed to the maximum of the standing wave field are strongly photo-excited. Monitoring the photoelectron signal with a pair of structured lasers allows for active feedback control. Although the mirror itself is not a radiator, the melting temperature of graphene is 4900 K, the highest in nature, allowing high temperature radiator cooling. Furthermore, the x-rays reflected dramatically reduce the amount of waste heat overall. The mirror operates at a maximum specific energy of 2 MW/m^2, and a specific mass of 320 kg/m^2. –Shu Nie ***et al***, Sandia National Laboratories, 2011.



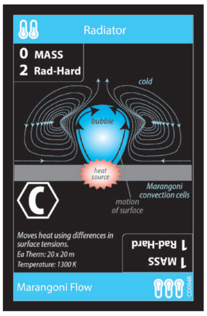
Hula-Hoop Radiator – By imparting heat to twin washer-shaped disks by direct conduction, the Hula-Hoop radiator avoids the diseconomies of scale that plague fluid radiators. Furthermore, they are robust against micrometeoroid strikes and hostile attacks. Each hoop is 100m in diameter and is made of braided cermets coated with graphite, and lubricated in the heat exchanger with tungsten disulfide (WS_2). Radiating at 1300 K, the Hula-Hoop has a specific area of 33 kg/m^2. –This design is an Eklund original.



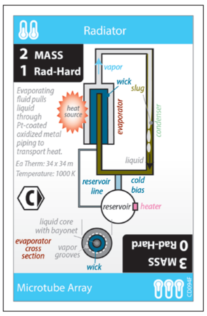
Li Heatsink Fountain Radiator – In order to do away with radiator walls, the fountain design sprays coolant forward from an accelerating spacecraft, where it is cooled and recovered as it falls back into a collection trough. The coolant is a liquid metal such as lithium, doped with nanoparticles of boron. This might produce a coolant with properties halfway between these materials, with the low density and high specific heat of lithium, and the high boiling point of boron. Doping with carbon may be necessary to improve the low emissivity of liquid metals. Lithium undergoes two phase changes as it is heated from 50 K to 1800 K.



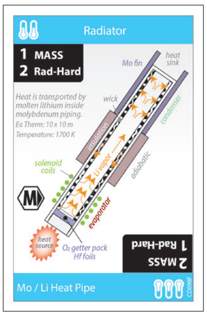
Magnetocaloric Refrigerator Radiator – A magnetic refrigerator takes advantage of the magnetocaloric effect, the ability of some materials to heat when magnetized and cool when removed from the magnetic field. Often used for cryogenic coolers, the external magnetic field is coupled with the magnetic sub-lattice heat source decreasing the total entropy in the solid and causing it to radiate heat. Although the element Gadolinium is usually used, numerous new complex alloy crystals have exhibited a 2-3 magnitude larger magnetocaloric effect at temperatures in excess of 350 K (coined the Giant Magnetocaloric Effect) in fields between 1-15 Tesla. This allows for radiation heat losses better than from a passive ideal black body (i.e. effective emissivities above 1). Such alloys can be used as a conduit to pump heat from the rocket's skin and ultra-thin foil radiators. Specific area is 0.9 kg/m^2 excluding power source at 450 K, pumping 2.3 × above an ideal black body.
–V.K. Pecharsky, K. A. Gschneidner, *Advanced Materials for Magnetic Cooling*, 2007; S. Jeppesen, Magnetocaloric Materials, 2008.



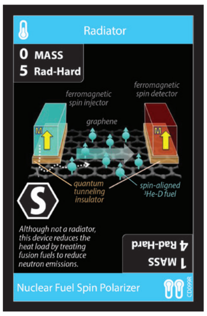
Marangoni Flow Radiator – In zero-g, a surface tension gradient can create a heat pump with no moving parts, or drive micro-refining processes. This phenomenon, called Marangoni flow, moves fluid from an area of high surface tension to one of low surface tension. Bubbles operating at 1300 K have a specific area of 24 kg/m^2.
–G. Harry Stine, *The Third Industrial Revolution*, 1979.



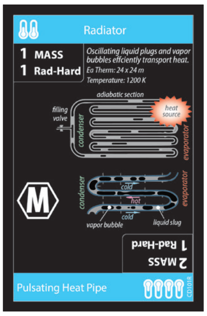
Microtube Array Radiator – Nanofacturing techniques can fabricate large, parallel arrays of very small diameter tubing for high performance radiators. The radiating surface comprises a heavily-oxidized, metal alloy with a 100 nm film of corrosion resistant, refractory platinum alloy deposited on it. The working fluid is hydrogen, which has low pumping losses and the highest specific heat of all materials. This fluid at 0.1 to 1 MPa is circulated through the microtubes, and most of the radiation occurs from their walls, which are only 0.2 mm thick. This allows a specific area of 34 kg/m^2, including hydrogen. The rejection temperature for titanium alloy tubes is from 200 K up to 1000 K, if a high temperature barrier to hydrogen diffusion is used. High speed leak detection capability and isolating valves under independent microprocessor control provide puncture survivability. The illustrated design is a pumped-loop system driven by the evaporating working fluid. –F. David Doty, Gregory Hosford and Jonathan B. Spitzmesser, *The Microtube-Strip Heat Exchanger--Space Power Applns. for Ultra-High Conductance Gas-Gas Exchangers*, 1990.



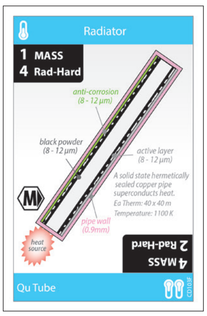
Mo/Li Heat Pipe Radiator - A heat pipe quickly transfers heat from one point to another. Inside the sealed pipe, at the hot interface a two-phase working fluid turns to vapor and the gas naturally flows and condenses on the cold interface. The liquid is moved by capillary action through a wick back to the hot interface to evaporate again and repeat the cycle. For high temperature applications, the working fluid is often lithium, the soft silver-white element that is the lightest known metal. Molybdenum heat pipes containing lithium can operate at the white-hot temperatures of 1700 K, and transfer heat energy at four times that of the surface of the sun. The specific area is 150 kg/m^2. –David Poston, *Institute for Space and Nuclear Power Studies at the University of New Mexico*, 2000; M. El Genk, J.M. Tournier, *Uses of Liquid-Metal and Water Heat Pipes in Space Reactor Power Systems*, 2011.



Nuclear Fuel Spin Polarizer – The fusion of helium-3 and deuterium suffers from side reactions such as D-D, increasing neutron production. Spin-polarizing ^{3}He-D and other aneutronic thermonuclear fuels not only suppresses the side reactions, it also increases the reactivity. Polarization is achieved by quantum tunneling across an MgO insulator into the single atom-thick sheet of carbon atoms arrayed in a honeycomb pattern known as graphene. Extremely strong and flexible, graphene exhibits good electrical conduction, heat resistance, and among the best spin-transport characteristics of any room temperature material known. After the quantum tunneling, the fuel is further treated with radiofrequency irradiations, symmetry species conversion catalysts, molecular species spatial arrangements, and anneal programs, before being stored and manipulated at liquid helium temperatures in solid, liquid and high density gaseous phases. Rapid depolarization of the plasma is prevented by providing a first-wall coating formed of a low-Z, non-metallic material having a depolarization rate greater than 1/sec.
–Roland Kawakami, Kawakami Laboratories, UC Riverside, 2012.

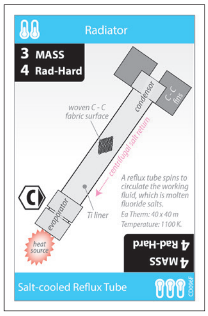


Pulsating Heat Pipe Radiator –A newer concept in heat pipe technology, a pulsating heat pipe, is a meandering capillary closed loop system with no wick structure that operates as a non-equilibrium heat transfer device. When working fluid is first added to the evacuated pipe, a system of naturally forming liquid plugs and vapor bubbles develops. Thermal energy generates a pulsating motion, driven primarily by surface tension, oscillating between the plugs and bubbles resulting in a very high heat transfer coefficient for a given volume (a water-copper PHP has a transfer coefficient 10 times that of diamond). PHP performs better in microgravity environments than on Earth. Varying diameter between parallel channels induces flow circulation and further increases transfer capacity. This technology has yet to be optimized and fully modeled. Here, a potassium working fluid embedded with diamond nano-particles (to increase thermal conductivity) flows through 0.7m diameter carbon-steel tubing. Specific area is 35 kg/m^2 and 212 kW$_{th}$/m^2.

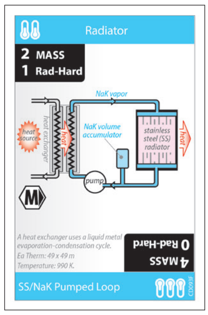


Qu Tube Radiator – Heat pipes, particularly over long distances, are limited in the rate of heat transfer by flow rate and transition times between liquid and vapor states. This limitation is circumvented in the Qu tube, first patented by Dr. YuZhi Qu in China in 1989. This hermetically sealed 0.9mm thick copper pipe contains three thin layers (8-12 µm) of a complex mixture of chemicals including over a dozen different metals from sodium and beryllium to aluminium and β-titanium and their various oxides. Starting from the inner wall, there is an anti-corrosion layer, an active heat-conductive layer, and a black powder layer. The active layer works by accelerating molecular oscillations and friction associated with the third heat-generating layer. This tube is a solid state (i.e. no liquids) thermal superconductor which can operate over a wide temperature range without a gradient (over 10,000× that of silver and hundreds of times better than conventional heat pipes). As the thermal superconductance is dependent on an even distribution of the black powder layer and a strong hermetic seal, the system is vulnerable to micrometeorite punctures. Shorter piping and redundant systems must rely on lower conductance carbon-carbon heat brushes for interconnection. As a result, the Qu Tube is particularly sensitive to diseconomies of scale. Specific area is 7.2 kg/m^2 at 630 – 650 K, oscillating at 280 MHz. The patent claims it can operate up to 2000 K, but tests have only been conducted in the 300-400 K range. I elected for a reasonable 650 K which is the upper limit of oscillations quoted in the patent. –Y. Qu, *Superconducting Heat Transfer Medium*, U.S. Patent, 2005; J. B. Blackmon, S. F. Entrekin, *Preliminary Results of an Experimental Investigation of the Qu Superconducting Heat Pipe*, 2005.

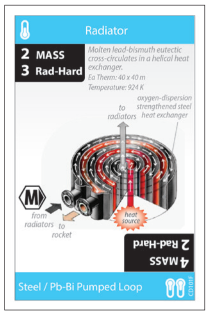
Salt-cooled Reflux Tube Radiator –In contrast to a heat pipe, that uses capillary action to return the working fluid, a reflux tube uses centrifugal acceleration. This design is more survivable than heat pipes, especially when overwrapped with a high-temperature carbon-carbon composite fabric. Unlike metals, the strength of these composites increases up to temperatures of ~2300 K. However, they degrade when subjected to high radiation levels. The working fluid is molten fluoride salts, the only coolant (other than noble gases) compatible with carbon-based materials. Radiating at 1100 K, this radiator has a specific area of 75 kg/m².
–Charles W. Forsberg, Oak Ridge National Laboratory, Proceedings of the Space Nuclear Conference 2005, San Diego, California, June 5-9, 2005.



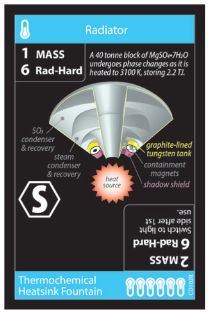
SS/NaK Pumped Loop Radiator –A Rankine evaporation-condensation cycle can exchange heat using a liquid metal as a coolant, which is vaporized as it passes through a heat exchanger connected to the radiator. A liquid metal near the liquid/vapor transition is able to radiate heat at a nearly constant temperature. The usual medium is sodium or sodium-potassium, which has a saturation temperature of nearly 1200 K at 1.05 atm. The heat pipes are oxidized aluminum or stainless steel tubes operating at up to 970 K with an emissivity of 0.9. A tube wall thickness of half a millimeter is determined by meteoroid-puncture considerations, and each pipe is an independent element so that a single puncture does not cause overall system failure. Molecular beam cameras on long struts scan for meteoroid leaks, which are plugged with pop rivets installed by a tube crawler. Radiating at 970 K from both sides, this radiator has a specific area of 61 kg/m², including fluid and heat exchanger.



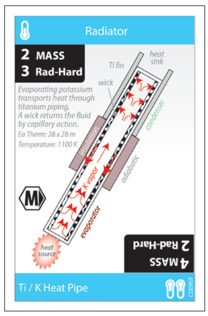
Steel/Pb-Bi Pumped Loop Radiator – The working fluid of this design is a Lead-Bismuth Eutectic (LBE). While more corrosive than NaK (particularly above 970 K), it is more stable and able to tolerate greater temperature fluctuations. Adding Bismuth to Lead lowers the melting point and keeps the fluid at a constant density as it is heated at the cost of increased corrosion. As an added utility, LBE is an excellent gamma shield (but transparent to particle radiation). LBE has been extensively studied at temperatures below 870 K but next generation stainless steels are needed at temperatures exceeding 925 K where corrosion greatly limits operating life. Radiating from both sides, this radiator has a specific area of 56 kg/m², including LBE fluid, heat exchanger and ODS stainless steel tubing. A spiral or helical heat exchanger configuration allows for a compact, high efficiency design whereby by maximizing contact between the hot and cold surfaces. This geometry minimizes fouling, which plagues heat-pipes, both because of the low pressure drop and because a localized increased velocity forms on a fouled surface resulting in a "self-cleaning" mechanism.



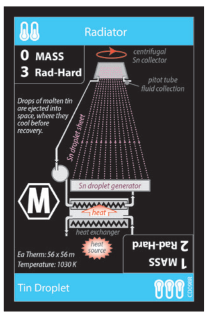
Thermochemical Heatsink Fountain Radiator – While latent and sensible heat storage have been well established, long term energy storage in the form of thermochemical bonds has yet to reach commercial development. Issues including catalysts and volumetric changes still need to be solved. Here solid $MgSO_4{\cdot}7H_2O$ sensibly absorbs heat until reaching 395 K whereupon the water dissociates (absorbing 1.1 MJ/Kg) and is boiled off and recycled. The solid $MgSO_4$ can continue to absorb heat energy until reaching 1470 K where it dissociates to MgO and SO_3 gas(absorbing 18 MJ/Kg). The remaining magnesium oxide is allowed to absorb heat in its graphite lined tungsten container until reaching 3100 K. Using this system, 40 tonnes of the thermochemical material can absorb a peak 240 MW_{th} load for up to 150 minutes. –A. H. Abedin, M. A. Rosen, *A critical review of thermochemical energy storage systems*, 2011; F. Barnes, J. Levine, Large Energy Storage Systems Handbook, 2011.



Ti/K Heat Pipe Radiator – A Rankine evaporation-condensation cycle heat pipe uses metal vapor as the coolant, which is liquefied as it passes through a heat exchanger connected to the radiator. A liquid metal near the liquid/vapor transition is able to radiate heat at a nearly constant temperature. The pipe is made from SiC reinforced titanium or superalloy operating at up to 1100 K, and the working fluid is potassium. The pipe is covered with a lightweight thermally-conductive carbon foam, which protects the pipe from space debris and transfers heat to the radiating fins. The total specific area is 100 kg/m².



Tin Droplet Radiator – Atomization increases the surface area with which a fluid can lose heat. A hot working fluid sprayed into space as fine streams of sub-millimeter drops readily loses heat by radiation. The cooled droplets are recaptured and recycled back into the heat exchanger. If tin is used as a working fluid, the kilos per power radiated is minimized, allowing heat rejection comparable to the game value of 120 MW_{th} per therm. The low emissivity of liquid tin (0.043) is increased by mixing in carbon black, which distributes itself on the surface of the droplet. Evaporation losses are avoided by enclosing the radiator in a 1 µm plastic film, which is able to transmit radiation in the 2 to 20 µm (IR) range. Such a film would continue to perform its function even if repeatedly punctured by micrometeoroids. The illustration shows a triangular liquid droplet geometry. The collector, located at the convergence point of the droplet sheet, employs centrifugal force to capture the droplets. Droplets are 50µm diameter, spaced 250 µm apart with an emissivity of 0.2 (after carbon is added). The sheet is 150m long and 62m wide at the generator end and 2.6m wide at the collector end giving an effective radiating area of 411m². The droplets exit at 1030 K and transit for 9 seconds resulting in an average effective temperature of 400 K. The specific area is 9.9 kg/m², and a specific mass of 0.034 kW/kg (doubled the value used in the sources due to scaling). The low emissivity limits the effectiveness of the radiator in regions of high solar flux.
–National Academy of Sciences. Proceedings of a Symposium Advanced Compact Reactor Systems, 1982; W. Chung, Droplet Heat Radiator; K. Alan White, *Liquid Droplet Radiator Development Status,* Lewis Research Center, 1987.



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