The Hot Equations: Thermodynamics and Military SF

"Amateurs think about tactics, but professionals think about logistics."

-- General Robert H. Barrow, USMC (Commandant of the Marine Corps), 1980

"And futurists think about thermodynamics."

The maxim about tactics and logistics has been truth on the ground since Napoleon, and has been alluded to by writers going back to Sun-Tzu. As combat moves from the bosom of the Earth, and into orbital and interplanetary space, it will be limited by logistics (which get much more complex) and by thermodynamics.

Ignoring thermodynamics is one of the cardinal sins of science fiction authors writing military SF; the same authors who wouldn't dream of saying that a Colt 1911A fires a .40 caliber bullet will blithely walk into even more galling gaffes through simple ignorance and unquestioned assumptions.

Thermodynamics and You

For those who stopped shy of doing thermo classes in college, or who took the class and went on to do something less mind-bendingly insane with their lives, the basic role of thermodynamics is moving heat from where you have it to where you want it to be. Anyone who's fired a gun and had hot brass hit them in the chest or arm has experienced the first rule of thermodynamics: It never quite works the way you want it to. Hot brass is why caseless ammo never took off in the late '80s and early '90s; ejecting hot brass is a surprisingly effective way to manage the thermodynamics of a breech-loading gun. The rifles firing caseless ammo had a high jam rate because the heat normally rejected by throwing the case out the slide was retained in the feed mechanism, which would expand and evaporate lubricants. While the manufacturer solved the problem with a much more expensive feed mechanism, it raised the price of the gun, and NATO didn't adopt it.

The current problem child of the Pentagon, the F-35 Lightning II, is also running into thermodynamic constraints. The exhaust from the vectored thrust on the F-35C is hot enough to deform steel, and require the ships slated to carry it to move temperature sensitive stores from the spaces under the landing deck. There are currently engineering studies on new surfaces for those decks that can sustain the pressure and temperature combination, and the reports are an exercise in schadenfreude if your mind runs to an engineering bent.

While these examples illustrate the mundanity of thermodynamic limits on the earth, in space, thermodynamics is even more constraining. There are three ways to remove waste heat from a system: Convection, conduction and radiation.

If you think of a pot of boiling water, you get to see all three of them in action: The interface where water converts to steam, and heats up the air, causing the air to circulate is *convection*. It's the most efficient way to remove waste heat from a system – heat up the gas or liquid of the surrounding environment, let its expansion trigger circulation, and thermodynamics gets easier to manage – at least until you're melting the deck plates under your quarter-billion-dollar jets on takeoff.

The part of the handle on the pan that gets hot – and the reason why there's an insulated grip for you to hold on to – is *conduction*. Thermal conduction, like electrical conduction, varies with the material; metals are mediocre conductors of heat; surprisingly diamond and carbon nanotubes are the top dog in this area. Thermal conduction, by and large, is a problem.

The IR signature of your pot of boiling water is radiation; you can detect IR by moving your hand next to the pot and feeling the heat radiating off of it. Radiation is the least efficient way of disposing of waste heat…and the only one available in space.

Space as a Sensor Environment

When you look at the night sky, the first impression your brain makes is "Gosh, that's dark, you can't see anything." Space, at least from the context of sensors, is an amazingly friendly environment for two reasons.

The first is the lack of a horizon. At the time this was written, I can be reasonably certain you were born and raised on the surface of a planet; you automatically assume that there's a horizon. You are inclined to think that there's a distance beyond which something can't be seen, due to the curvature of the assumed planetary body.

In space, the horizon assumption is almost always wrong. The one exception is Low Earth Orbit (LEO), where the limb of the earth can temporarily obscure something for roughly an eighth of an orbital period; this is about a 15-minute window, tops. Detection range is never limited by terrain for militarily significant increments of time.

In modern sensor paradigms, there's detection range, identification range, and targeting range. In space, object detection is fundamentally one of time. Current consumer-grade hardware is capable of processing full sky searches for anomalies against the background in seconds. The number of Earth-crossing objects we identify doubles every six to seven months, and that's before putting a skywatch platform in the Earth-Sol L1 position to see them as they reflect sunlight back at the sun from a different angle.

Thermodynamic radiation is what defines the detection parameter in space. Conduction means that objects develop hot spots and reach radiative equilibrium over their surface; this radiative equilibrium is called the black body temperature; at Earth's orbital distance, that temperature is about 250 to 260 Kelvin (K) depending on the material and surface color. If you look at the sky with an IR sensor, you can identify dark objects by their black body temperature. The background of space has a temperature of about 2 to 5 K, and spotting something a few hundred degrees warmer is easy, provided you can take enough pictures, stitch them together and compare them to your last data processing pass.

How much time do you have? Consider that going from LEO to Lunar orbit is roughly a three-day trip. Going from Earth to Mars is a 9-month trip at an optimum conjunction with current technologies. Even with long duration drives, minimum travel times from Earth to Mars will still take six to eight weeks.

Detecting Spaceships

We're spotting asteroids via the temperature differential between 250 to 260 K and the 2 to 5 K background temperature of space. Water ice melts at 273.15 K. Room temperature is 20 to 25 degrees C, which is 293 to 298 K. Human crews need some part of the ship at room temperature, and that's 30-40 K warmer than blackbody re-radiation temperature at Earth's orbit. If everything else is turned off, your life support systems make your ship a dim, but visually distinct object.

Power generation, even by solar collection, only makes it worse. Terrestrial power plants dissipate waste heat by circulating a working fluid. On a nuclear submarine, they can use the thermal mass of the surrounding ocean as a heat sink and gain vastly in efficiency. On a spaceship, that's not an option. You only get rid of heat by radiation, and power plants run hotter than life support systems.

Useful work is done by the temperature differential between the hot and cold side of a power plant. Using the archetypal hot equation – the Stefan-Boltzmann black body radiation law, $j=\sigma T^4$, radiative efficiency (j) increases at the fourth power of the temperature of your radiator times the Boltzmann constant. The radiance (brightness) of your radiator per unit area also goes up with the fourth power of your radiator temperature – the more effective your radiator is at dissipating waste heat, the brighter it will be. Optimizing your radiator mass and efficiency along with your power source means you want the smallest, hottest running radiators you can manage with the widest delta between radiator temperature and reactor temperature. The place where those curves cross is radiators running at 75% of your reactor temperature, radiating 3.5 to 5 Watts per Watt of useful energy generated.

A water-cooled nuclear reactor has a core temperature of ~575 K. In space, the radiators would run at 450 K. Smaller, lighter, more efficient reactors use liquid metals – like sodium on the Russian *Alfa*-class submarine – rather than water, and run with the reactor core at around 900 to 1,100 K. Gas-core nuclear reactors can use liquid sodium-potassium eutectic alloys with core temperatures in the 1,400 to 1,600 K range. These result in radiators running at 700 to 1,100 K, and that's a *very* bright signal that doesn't exist naturally in space. (Getting liquid metal to a radiator surface and back to the reactor in a free-fall environment is also a non-trivial engineering problem…)

The same equations that make your power plant and radiators visible make most reaction drives pushing useful payloads VERY visible. The archetypal fusion torch with an operating temperature of 3,000 K and putting out a few hundred megawatts of drive power, would be *naked eye visible* from a planetary surface most of the way to Jupiter, and would take most of a year to get there.

The usual counter-argument made is "I'll just drift in, with engines cold and go undetected." Your life support system and power plant will be detectable signal once your engine turns off – and they'll know where to look. Your engine brightness will give a decent approximation of your distance from the observation platform – multiple platforms will give you the ability to triangulate and narrow that down. With the distance and proper motion, forward-plotting your orbit is an easily automated mathematics problem, and you'll be on that plot until you turn on your engines again.

With an emissions spectrum on your drive flare, plus distance and proper motion, they can determine the mass pushed by that drive flare. Making your space battleship look like a space rowboat doesn't work, and and neither do decoys, which need the same drive signature apparent motion and mass as the ship they're duplicating.

Right around this point, people desperate to make stealth in space work throw up sunshades, expendable coolants, positioning radiators away from the sensors of the enemy, and attempts to slingshot around planets to get "invisible" course changes. Thermodynamics and travel times render those moot.

Between the lack of a horizon, travel times, and the thermodynamics of power generation and propulsion, reaction drive space fleets *will be* detected on passive sensors long before they get into combat range. Within combat range, you'll need active sensors for a target lock-on, and those may be spoofable.

Barring some method (which will be visible in and of itself) to take out all the possible sensor platforms, you will be detected in space, and you'll be seen weeks in advance of you reaching your destination.

Plausible Propulsion Systems

Another cherished trope will get cooked on the radiators of thermodynamics: The ship that can land on a planet and take off again without a major industrial civilization to refuel it. We've seen this ship – the *Serenity* and the *Millennium Falcon* and the *Corsair X1* and nearly every rocket ship Robert Heinlein ever wrote about.

There are three broad categories of propulsion systems that match physics as we know it: electromagnetic rockets and thermodynamic rockets, and sails.

There are three useful performance numbers to keep in mind: 5 milligees, 600 milligees, and 3,000 milligees (3 gravities). A milligee is 1/1000th of a g, or 0.00980665 meters per second squared. 5 milligees is the minimum thrust needed to break solar orbits and do direct thrust between two points in the Solar System. At less than 5 milligees, changing orbits means timing thrusts for opposite sides of that orbit around the sun. 600 milligees is a round number for "high thrust" short duration burns. These are for Hohmann transfer orbits and crossing the Van Allen radiation belts. 3,000 milligees is the minimum thrust to get from Earth's surface to low earth orbit with a useful payload. Where classic SF gets it wrong is assuming that you can have one propulsion system that meets all three requirements.

Rocket Basics

Rockets rely on Newton's Third Law – for every action there's an equal and opposite reaction. Rockets have two competing constraints: mass flow rate (shown as $\dot{m}$), which is how much mass you're throwing sternward per unit increment of time, and specific impulse (ISp), which is how fast each unit of mass is moving once thrown. $\dot{M}$ compared to the total mass of your rocket determines acceleration. ISp, when compared to the natural logarithm of the ratio of your rocket's fully fueled mass to its dry fuel tank mass, is a measure of your rocket's fuel economy and is expressed in seconds. The total amount of velocity change a rocket has is ΔV, and can be thought of as the total fuel in the tank; while you won't stop when you run out of ΔV, you won't be able to slow down at your destination, either. Your rocket will have a maximum thermodynamic limit; this is how much energy you can put through the rocket each second without melting it. Rockets with very high thermodynamic limits are hard on the real estate market near the launch facility. They don't have to be nuclear rockets to be objectionable; nobody wants to be downwind of a rocket exhaust of high molar concentration hydrofluoric acid either.

Within a given thermodynamic output, *m* ●nd ISp work in opposition – you can't increase one without reducing the other. It's possible to make high mass flow rockets with lots of thrust, and it's possible to make very fuel efficient rockets with thrust measured in gnat-belches. It's not easy to make a high thrust rocket with useful ISp.

ISp relies on how fast you can throw individual particles sternwards; it's easier to accelerate a lighter particle than a heavier one. In Heinlein's *Rocket Ship Galileo*, the namesake rocket uses Zinc as its reaction mass, filtered through a hot nuclear reactor. Zinc has an atomic mass of 65 or so, while real world rockets have exhaust byproducts with a mass of about 10. If the Zinc were leaving the back of the rocket at the same temperature and as the tail end of a LOX/H_2 rocket, you'd need 6.5x as much mass of Zinc as you'd need rocket fuel. Heinlein casually sidesteps this issue by using a nuclear heater, presumably to get the Zinc to vaporize at about 1400 K. Even if you accept the incredibly high temperature nuclear reactor, the Zinc-propellant NERVA engine is problematic thermodynamically and radiologically. You wouldn't want to be anywhere near where the *Galileo* took off without a HASMAT suit.

To get to orbit, you need a high *m*● rocket that also has an ISp high enough to make the payload fraction useful. The Space Shuttle, one of the most efficient chemical rockets ever built, had a payload fraction of 5%. SpaceX's Falcon 9 has a payload fraction of 2.5%. Nothing in science fiction has a payload fraction that small, and getting off planets is tricky and expensive. My gut hunch is that it will take laser-based launch systems to make standard SF-grade ground-to-orbit launches, but laser launchers mean your rocket doesn't come down from orbit, refuel at a lake, and take off again after the adventure is over.

ISp is more important than *m*● for every other use of a rocket, because it sets your fuel fraction for a given amount of ΔV . Space is much friendlier for high ISp drives – the low *m*● and low thrust isn't a handicap if you can get to 5 milligees, and nobody will notice the radioactive exhaust. Unfortunately, the higher the exhaust velocity, the likelier it is that the exhaust has a temperature in the 3000 K or higher range, which brings us right back to thermodynamic detection.

The Space Shuttle Main Engine had an ISp of 470, and was a Rube Goldberg contraption pumping cryogenic hydrogen and oxygen past the engine to regeneratively cool it, running a little bit past the rated design spec. The cheaper to operate, but less efficient Falcon 9 has an estimated ISp of about 290 seconds. NERVA open core nuclear rockets using hydrogen as propellant had ISps of 1200 seconds with a thrust of around 400 milligees. The ion thrusters used by NASA's probes to Pluto have ISPs of around 10,000 seconds with a thrust of around 4 milligees.

Electromagnetic and Thermodynamic Rockets

There are two ways to get reaction mass to exit your rocket at a high rate of speed: Electromagnetic repulsion and thermodynamic explosions. Of these two, electromagnetic repulsion is more fuel efficient, while thermodynamic rockets can vary their fuel flow rates and get higher thrust. Higher thrust rates don't reduce travel times by very much; they do give you wider launch windows. If you need to send something to overtake a rocket that launched two weeks ago, you need a higher thrust rocket and will spend fuel extravagantly.

You can't do the Heinlein-style "lead the destination by a bit, burn, flip over, burn to decelerate" brachiostone orbits without sustaining multi-week burns at 600 milligees. Unless something dramatic happens to our knowledge of physics, these drives are impossible as we currently understand physics.

Sails

Sails are the most primitive form of beamed-power propulsion; they get 2-3 milligees off of the solar photons or the solar wind, and can be boosted to 5 milligees with laser augmentation. From a worldbuilding perspective, light sails are for low priority cargos, and a typical light sail ship won't have a crew due to long travel times. As this essay is being written, Rolls Royce is trying to interest shipping lines in completely unmanned container ships that are piloted by telepresence in harbors, and solar sail ships aren't running in an environment where there's weather, and in a bath of corrosive fluid. Unlike Terrestrial piracy, everyone will see that the cargo was hijacked, so the pirate won't be relying on fences or economic intermediaries. The order of the day is something the pirates can use directly, not re-sell for capital. A light sail delivery queue will be like a pipeline, with regular, predictable launches and long transit times. The companies owning them will probably face vertical integration pressure to own the boosting lasers, but there may be space for leasing laser pushes as a service. Any company owning pusher lasers has a weaponizable military asset, and one that is losing revenue whenever it's not in use.

Orbital Mechanics Constraints

There are a number of constraints put on space commerce and space travel by realistic rockets. The first is that ΔV is a finite asset, and the second is that forward plotting your acceleration makes it very easy to figure out where you're going. There's no way to suddenly change course from Mars to Jupiter, any more than there's an easy way to drive from Florida to Greenland if you decide not to stop in Omaha. Your destination will be obvious based on the performance parameters of your drive, the direction you're thrusting in and the relative positions of the planets. This changes somewhat when working with the Jovian Trojan asteroids and the asteroids of the main belt.

Building a Setting

With those three types of propulsion systems, and a willingness to look at how science and physics (including thermodynamics) shapes operations, we can build a setting.

We have three viable forms of propulsion; sails are used for "bulk cargo" and are very predictable in their travel windows; sailships are probably completely automated. Electromagnetic rockets are the default propulsion system for civilian time-sensitive cargo. Thermodynamic rockets are used by the military or the military analogs, because they offer the most flexibility in launch window reactions. There will be specialized rockets designed to work as "high thrust" tugs to cross Earth's Van Allen belts, and Jupiter's radiation belts. Every planet and moon with a useful surface is easier to take off from than Earth, so we can all but ignore the ground-to-orbit problem; I'll handwave and say Earth has mature laser-based launchers.

Because of the 5 milligee thrust used for interplanetary travel, orbital position matters. Launch windows will be planned around for months in advance. Travel times will be around 2 months to 5 months between Earth orbit and Mars orbit. Travel times to Ceres or Vesta will vary from 3-5 months from Earth and could be from 1 to 5 months from Mars. Gaps between transit windows mean a long wait for the next one – six to nine months. Missing your transit window is a good way to have to find some other job to do until the next passage opens up.

Travel times from Earth or Mars to the Jovian moon system will be roughly a year, each way – and the same applies to going to either of the Jovian Trojan asteroid groups. The Jovian moons become, to some extent, the Wild West of the setting – the radiation zones are lethal, but they're the most easily accessible source of water ice and volatiles in the solar system, and shipping water ice from the Jovian systems with sailships is probably a big business. Having a family buy a stake in the ice and live on the towed ice-berg for its 2-year journey, selling ice and volatiles along the way seems a reasonable business model. That family probably made their money in the Jovians and wants to head back to some place civilized…and not all the visitors might be looking to buy what they can take by force.

It's not just the cargos that are valuable. If 3D printing takes off like it's expected to, transport of manufactured goods takes a serious hit in profitability. Transport of people who can solve local problems with the materials at hand without dealing with a light-speed lag may be worthwhile in places where telepresence can't hack it. Widespread use of 3D printing may solve one of the other great constraints of military operations: Keeping people fed. If you can feed protein stocks through a 3D printer to grow steaks, and have a way of turning your wastes into more protein, say through an algae tank, you get something that's pretty close to the cafeteria from the original Star Trek.

ΔV and Piracy

Rockets will have enough ΔV to reach their intended destination in a reasonable time frame, but they won't have any extra for "random tourism." In this, rockets are closer to being railroads than ocean liners; a rocket can't divert from the Sulu Sea to New Guinea the way a surface-going ship can. Interplanetary launch windows will have clusters of ships moving to the same destination – think of Heinlein's *The Rolling Stones*. If one ship has a medical emergency, or a mechanical problem, other ships will be close enough at hand to send help. Something akin to the dynamics of either version of *Battlestar Galactica* might occur – there may be ships on the routes working as agricultural sources or floating casinos or entertainment centers for other passengers in the convoy.

There are points in time where these convoys are vulnerable; any time where they have to expend a certain amount of ΔV to make their destination is a place where an enterprising pirate can ply his trade, particularly if the pirate has the ΔV to go somewhere else. These points include the "flip over" burn and the sequence of burns needed to reach an insertion orbit around the final destination; in the Jovian system, this is the place where you meet the tug to ferry you through the radiation zones, and in the Jovian system, transit around the moons is a secondary traffic control mess.

Many rockets ships will have the ability to do one or two 600 milligee burns, probably from a chemical rocket carried for emergency purposes. This is situational rescue capability, either for yourself or to respond to a distress signal. They can also be used to make a least-fuel transit to a known safe location using a (fairly easily) calculated Hohmann transfer orbit. Hopefully, your life support can hold out for the months that a least-fuel transit will take….but that's a framework to tell an interesting lifeboat-style story.

Space Combat

You'll notice that I haven't described the weapons used in this setting. I suspect space combat is going to be incredibly dull as a ship-to-ship action. With thrusts measured in single digit milligees to high performance military craft going into the tens of milligees, combat maneuvering won't matter for civilian craft, and might matter for military craft. In the Ten Worlds setting I made for *Attack Vector: Tactical*, I added a combat-mode thrust to give ships thrusts in the 0.75 to 1.5 G range; while the physics doesn't (quite) say that thrust is impossible, it is highly speculative engineering and is included to make the game fun to play. Without that high thrust combat mode, the primary weapon will be a two-stage rocket. The first stage is a recoverable high ISp ion drive that spends days getting up to speed, then decouples and maneuvers for recovery. The second stage is chemically fueled rockets that light up in when certain launch parameters are met. The warheads will be fragmentation shot meant to hit the target with shrapnel at 3-10 km/sec of relative velocity. To be survivable, ships will have a lot of dispersed structure – they won't be armored. Even without armor, ships can take a lot of abuse; unlike naval or air-to-air combat, the operating environment won't destroy you with a loss of hull integrity. You may die when the life support system sprouts holes, but your ship won't blow up, sink, or suffer rapid aerodynamic disassembly.

Kinetic impact weapons moving at these velocities have defensive mechanisms that rely on giving the projectile something to spend its energy on; these are similar to the Whipple shields proposed by NASA for micrometeoroid protection: There's a very thin shield of hard material, and a lot of aerogel behind it. A projectile will shatter on hitting the hard outer coating and the fragments, which more surface area, will convert their kinetic energy to heat as they move through the layers behind it. More active defensive measures are counter-missiles that run on opposite courses to kill the rocket before it fragments, or "spiderweb" drones aimed at setting up umbrellas of artificial fibers to catch fragments and let them break up on impact with something less valuable than the primary target.

Because kinetic energy goes up at the square of impact velocity, explosive warheads become passe in space combat. At 3 km/sec of impact velocity, an object delivers kinetic energy equal to its mass in TNT; at 3.5 km/sec of impact velocity, the kinetic energy conversion starts to exceed most reasonably stable military explosives. At 6-7 km/sec you're running four to five and a half times the energy density of TNT. Kinetic energy comparable to nuclear weapons start in the 80 to 100 km/sec of impact velocity. For those with a bent towards space opera, relativity gives a 1% boost to the kinetic energy of impact at 0.25 c, or 75,000 km/sec, and it rises rapidly from there.

In space, unlike air-to-air combat, firing solutions are easy – the target can't do a tight turn and change their direction of travel. Your firing solution will do Newtonian transformations, putting all the velocity in the firing platform, and will subtract the target's available thrust from the launch platform's, which is a simple enough trigonometry problem that I put it into a pen-and-paper wargame.

Expect a lot of drones in this environment, and close to planetary infrastructure, expect lasers and disposable focal mirrors designed to kill drones and missiles. Lasers will also be used to direct beamed power to ships that use it for propulsion. The forces near an industrialized planet can get significant performance boosts by simply using beam-rider rockets for their initial boost; every kilo of fuel they don't have to carry is a kilo of additional armament or defensive measures.

The combat actions won't be naval in nature, at least in the conventional Battle of Jutland sense. They'll be closer to anti-piracy actions in the Sea of Cebu or the Gulf of Aden; a pirate will lay in wait at a point where a ship must make a course correction – and where missing that correction by a few hours can result in everyone aboard dying of starvation – and capture the ship to hold for ransom. If you're using ice piracy from the Jovians with a crew on the sailcraft slinging ice, there's plenty of territory there for small unit actions and tense gunfights in hostile environments, both on the surface and in the caves carved in the iceberg.

Long range military actions will be fascinating; sending an expeditionary force will take months in transit, while sending an email or arranging a (very laggy) video conference could resolve the conflict in hours at any point while the expeditionary force is en route. If the expeditionary force is going for the Jovian water mines, the residents will have six months to a year and a half, depending on orbital geometry, to get ready for them. Those troops will also be in a win-or-go-home situation. Until they secure the facilities to re-launch and re-provision the ship, the trip is functionally one way. If there's no cheap and readily reliable way to use suspended animation, then troop morale and training in transit become interesting discussions and background details. How do you keep your fighting edge when at any point in that transit, you may discover that your trip was a complete waste of time, and how do you train in the fairly cramped confines of a low-thrust ship?

Major Military Actions

Major military actions will be in strategically important locations. By and large, that will be planetary orbit around Earth, cislunar space, and planetary orbit around Mars. The prior actions described happen in interplanetary space, and will be low intensity conflicts of a sort – the kind of thing that would be a great "SEAL Team 6" adventure. In near-planetary orbital space, it's like a surface-warfare centric naval battle using current satellite recon: Everyone knows where everyone currently is, nobody can change their vectors by enough to matter, and the aim will be to do enough damage to infrastructure until it gets expensive enough to talk it over.

Functionally, this becomes warfare over offshore oil platforms, not war to the knife over land that's been in the family since the days of Saladin or Washington.

Conclusion

Most things related to space travel and space habitation come down to thermodynamics, and those thermodynamic constraints put paid to many genre tropes, like "Space is an Ocean." Thermodynamically limited space opera is a greatly underserved niche, in the overlapping circles of a Venn diagram between hard SF and military SF.