20

Posted by u/cranp 4 years ago

Why is the Merlin 1D specific impulse so low?

Merlin 1D's vacuum Isp is 310 s, compared to, say, the NK-33-1's 331 s or the RD-180's 338 s, and all are RP-1/LOX.

Is it really just that some unburnt fuel gets dumped overboard by the gas generator? It seems insane to have a 10+% cut from just that. The Merlin 1A was 300 s, so there must be more going on.

So what is the physics behind why two different engines burning the same fuel would have such different exhaust velocities?

(Just to be clear, this isn't a dig at SpaceX. I'm sure they have their reasons, regarding price, reliability, etc. I'm just curious what the physical cause is.)

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Sluisifer 26 points · 4 years ago · *edited 4 years ago*

It's the combustion cycle, as well as the chamber pressure.

Engine	Pressure	Vac ISP
RD-180	26,700 kPa	338
NK-33	14,500 kPa	331
Merlin 1D	9,700 kPa	311
F1	7,000 kPa	304
RD-107	6,000	313
RS-27A	4,800 kPa	302

The Russians really pushed the limits with those engines. As you can see, increasing the pressure doesn't increase the ISP by a lot.

Ve = SQRT[(2*k/(k-1))*(R'*Tc/M)*(1-(Pe/Pc)(k-1)/k)]

where,
k = specific heat ratio
R' = universal gas constant = 8,314.51 N-m/kg-oK
M = exhaust gas molecular weight
Tc = combustion chamber temperature
Pc = combustion chamber pressure
Pe = pressure at the nozzle exit

So, it essentially boils down to the square root of (pressure x temp). SpaceX likely targeted a good balance of performance with manufacturing costs and reusability.

Edit:

I was being lazy looking at that equation. The pressure component has little impact on exhaust velocity, but you can also see that, aside from chamber temperature, everything else is constant for those various engines (save small differences in mixing ratios). So, what I really mean by those different chamber pressures is that they'll have higher chamber temperatures, which is what really drives the isp.

Ah, very interesting. So I guess there's some theoretical maximum efficiency when the chamber pressure is so high that the chemical potential of combustion goes negative (when more work is done pushing out the extra molecules than is released by the combustion)?

Can you explain why Tom Muller [described 9.7 MPa as the "sweet spot"]? He must have been talking about something other than efficiency?

[Edit: this is a sub-percent effect though, right?](https://www.google.com/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=plot+(1-100000%2Fx*(0.2%2F1.2))%5E0.5+from+x+%3D5E6+to+x%3D1E8)

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SoulWager 10 points · 4 years ago

There are a lot of constraints on a rocket engine, in this case he was probably talking about the tradeoff between turbopump exhaust and main engine exhaust. A higher chamber pressure with a gas generator engine means your turbopump uses a higher percentage of your fuel. The weight of the engine was probably also a consideration here.

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ManWhoKilledHitler 6 points · 4 years ago

You also tend to run engines rather rich to avoid them getting too hot. Very few operate close to the stoichiometric ratio and for things like hydrolox, it works out as being more efficient to have unburnt hydrogen in the exhaust due to the reduction in average molecular weight, even though there's less energy in the propellants for a given mass flow.

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cranp 2 points · 4 years ago

Ah interesting, that makes sense.

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Sluisifer 2 points · 4 years ago

Yeah, I kinda missed the point on that. I'm basically assuming the higher chamber pressure means that the chamber temperature will be higher, too. I just can't find that data.

If you really wanted to, you could figure it out, but that's more work than I'm willing to put in =P

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FoxhoundBat 3 points · 4 years ago

> As you can see, increasing the pressure doesn't increase the ISP by a lot.
>
> So, what I really mean by those different chamber pressures is that they'll have higher chamber temperatures, which is what really drives the isp.

My head is not operating at 100% today, but aren't those two statements at odds? I mean yeah, pressure has to be bumped up a lot before having good effect on ISP (ie it is not exponential). Basically it is:

-> higher chamber pressure -> higher temp -> higher ISP

So by having low chamber pressure one has low temp and hence low ISP. So really it seems that chamber pressure is fundamental and pretty much the only way to increase the temperature? (other than having other types of fuel)

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RadamA 2 points · 4 years ago · *edited 4 years ago*

In two stage rocket, if you increase lower stage isp from 311 to 331 (6.4%), the cargo increases by about 13%.

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SoulWager 5 points · 4 years ago

upper stage ISP is more important, because you're carrying that fuel mass much longer.

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RadamA 2 points · 4 years ago

If you keep the mass the same, 10% better isp engine would increase cargo by 25% even on the upper stage.

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cryptoanarchy 3 points · 4 years ago

SpaceX optimizes for cost. It takes less money to build a bigger less efficient first stage TO CARRY THE SAME WEIGHT then a smaller more efficient one. They may improve the efficiency over time if they can do it at the right price point.

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RadamA 2 points · 4 years ago

I know, im just stating the math behind it.

Just look at what happened with 1.0 to 1.1 change, its almost a new rocket. Tbh, F9 1.1 atm could carry almost 15t to orbit if its pushed to the limit. 13.1t figure is just so that they can keep it even after reusability.

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brickmack 2 points · 4 years ago

> They may improve the efficiency over time if they can do it at the right price point.

I suspect this will happen once they start reusing rockets. If they're reusing most of them, then they can afford to use more expensive parts. Higher efficiency engines, lighter tank materials, etc.

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deruch 2 points · 4 years ago

I think I remember reading that the M1D is somewhat under expanded as well (ie exhaust nozzle under sized for max ISP), but I'm not an engineer and don't know how to find out if that is actually the case.

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nyan_sandwich 11 points · 4 years ago

Underexpanding allows throttling, because when you throttle, it becomes more overexpanded, and gross overexpansion is fatal.

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gangli0n 3 points · 4 years ago · *edited 4 years ago*

Perhaps it also makes the whole assembly less brittle during reentry, which is apparently important for landing of the stages. And it probably simplifies having a lot of engines close to each other, especially on gimbals, as is the case of F9s.

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peterabbit456 1 point · 4 years ago

> ... And it probably simplifies having a lot of engines close to each other ...

I think I read somewhere that the 9 engines working together produced a good bit more thrust than expected, because the configuration had some unexpected aerospike-like properties. Sorry, no source. This may be a figment of imagination...

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Wicked_Inygma 1 point · 4 years ago

If that is the case then I wonder if they utilize the gimballing on the outer engines to optimize thrust for various altitudes.

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[deleted] 3 points · 4 years ago

Sorry for the dumb question but does that mean you could trade thrust for ISP by throttling down to a point where it's neither under or over expanded?

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adriankemp 3 points · 4 years ago

Not a dumb question. The answer should be yes, but there may be some intricacies that I'm not aware of.

The question you didn't ask (which someone inevitably will) is why they wouldn't do that... The answer is as simple as them having chosen a thrust for the 1D Vac that works for their mission profiles, running it at a lower thrust constantly defeats that.

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nyan_sandwich 3 points · 4 years ago · *edited 4 years ago*

Unsure, but I don't think you'd get more ISP from that:

You throttle by lowering fuel supply rate, which lowers chamber temperature and pressure, which lowers throat mass flow rate. Theoretical maximum ISP (m/s) is roughly proportional to the square root of specific energy (Lower Heating Value) of the propellant (kg*m$^{2/s2/kg}$ = m$^{2/s2)}$. Actual ISP is how much of that you can convert into actual exhaust velocity at nozzle mouth, which you do in a heat engine (adiabatic expansion) process, which is limited by carnot efficiency: eff = 1 - Tmouth/Tthroat. Lowering Tthroat (which throttling does) should therefore lower efficiency.

Therefore, I would expect worse ISP when throttled. I would expect that ISP for a given fuel mixture is a function of only expansion ratio and chamber temperature.

"Underexpanded" just means that Pmouth > Pambient. All engines are underexpanded in a vacuum, for example. Doesn't say much about efficiency.

(Good question, but if you think you're being dumb, keep it to yourself. Don't want to normalize stupidity or lower people's impressions of you. If we're not all geniuses here, we can at least pretend ;))

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darkmighty 2 points · 4 years ago · *edited 4 years ago*

The opening equation clearly shows that Pmouth is key to efficiency. In a vacuum of course that means the nozzle should be as large as possible, so at some point the extra nozzle material won't be worth the increase in ISP (i.e. net efficiency will go down), an optimum which I think designers seek among other constraints.

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> You throttle by lowering fuel supply rate, which lowers chamber temperature and pressure, which lowers throat mass flow rate.

Why does that lower the temperature? You're still releasing the same amount of energy per molecule.

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nyan_sandwich 1 point · 4 years ago

Oops. You are correct. Pressure is the only variable here. I think that may also invalidate my conclusion. Will have to rethink.

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darkmighty 2 points · 4 years ago

Can't you throttle rockets through "PWM"?

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nyan_sandwich 3 points · 4 years ago

Need reliable and precise restarts that you can do every second or so. Would rapidly break any existing rocket engine, and they wouldn't have enough precision.

Nuclear Pulse rockets on the other hand...

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ManWhoKilledHitler 3 points · 4 years ago

Pulse detonated engines have also been proposed for use as very high performance and high efficiency jet engines but have the difficulty of being hard to build and unbelievably loud.

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nyan_sandwich 2 points · 4 years ago

Yeah, I don't think anyone has shown that they are even possible. (Edit: looks like they've figured it out since I last checked, but no production yet.)

Also, not sure how throttleable they are.

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api 2 points · 4 years ago

There's been a persistent rumor of something called "Aurora" that was a test vehicle for such an engine, but no proof it was ever actually built.

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ManWhoKilledHitler 3 points · 4 years ago

I think i have a magazine somewhere from about 1992 that mentions Aurora and its PDE propulsion system. It supposedly ran on liquid methane and allowed the aircraft to fly at between Mach 5-8 at 100k ft.

Complete nonsense of course. There's no way to keep something like that hidden in this day and age.

I have a fondness for external burning jet engines which use the interactions between the body of the vehicle and the shockwaves it produces to achieve a kind of cross-over between an aerospike and a ramjet. Unlike pulse-detonated engines, these have actually been flown as part of the manoeuvring system for McDonnell Douglas's project UpSTAGE in the late 60s but never made it past the prototype level.

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ergzay 3 points · 4 years ago

The problem with PWM with any large potentials or large mechanical objects is that you are effectively hammering the device every time the pulse turns on then turns off. This is especially true with what is effectively a continuous explosion (burning of rocket fuel). Once the engine is started its more or less in a steady-state. When you start PWMing the engine you throw all sorts of issues into it like vibrations and harmonics that never existed before. Most engines would fall to pieces under PWM situations.

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darkmighty 1 point · 4 years ago · *edited 4 years ago*

Makes sense. I guess you could ramp up slowly the engine to compensate, but then the maximum switching frequency has to go down.

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ergzay 3 points · 4 years ago · *edited 4 years ago*

Only engine type I know of that people do this in is the old [pulsejet engine](). But thats mainly because the design is extremely simple (look up bent pipe jet engine or plumbers pulsejet) and not because its a good design. Plumbers pulsejet https://www.youtube.com/watch?v=KUSX_460L3k

Aircraft with pulsejet https://www.youtube.com/watch?v=r50DRou0LsM

These work because its literally an empty pipe with tapered ends. Dang simple, so there's nothing to vibrate to pieces. I should add that the pulsejet in those aircraft are usually valved pulsejets so they do have one moving part. The valveless autowikibot 1 point · 4 years ago

Pulsejet:

> A pulse jet engine (or pulsejet) is a type of jet engine in which combustion occurs in pulses. Pulsejet engines can be made with few or no moving parts, and are capable of running statically.
>
> Pulse jet engines are a lightweight form of jet propulsion, but usually have a poor compression ratio, and hence give a low specific impulse.
>
> One notable line of research of pulsejet engines includes the pulse detonation engine which involves repeated detonations in the engine, and which can potentially give high compression and good efficiency.
>
> ====
>
> Image i - Diagram of a pulsejet

Interesting: McDonnell TD2D ^Katydid | Curtiss KD2C ^Skeet | Messerschmitt ^P.1079 | Globe ^KD5G

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autowikibot 1 point · 4 years ago

Pulse-width modulation:

> Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a modulation technique used in communications systems to encode the amplitude of a signal into the width of the pulse (duration) of another signal. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors. In addition, PWM is one of the two principal algorithms used in photovoltaic solar battery chargers, the other being MPPT.
>
> ====
>
> Image i - An example of PWM in an AC motor drive: the phase-to-phase voltage (blue) is modulated as a series of pulses that results in a sine-like flux density waveform (red) in the magnetic circuit of the motor. The smoothness of the resultant waveform can be controlled by the width (number) of modulated impulses (per given cycle)

Interesting: PC ^speaker | ^Torchère | ^LV-ROM | Pulse ^wave

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peterabbit456 1 point · 4 years ago

Yes, with hypergolic fuels. They did this on the landing stage for Curiosity, and they may be able to do this on Dragon V2. They may have done this on the Shuttle maneuvering thrusters.

The down side to this is vibration. In stead of a smoother thrust, you get a series of hammer blows, that can shake things loose.

But you cannot use PWM with large, non-hypergolic, turbopump-fed engines. Too much chance for flameout or explosions.

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peterabbit456 1 point · 4 years ago

That's what I call a great answer. That's a lot of information, presented as concisely and accurately as possible.

PS. I've just located a supply of scrap Inconel, so this will be useful in designing my own rocket motor. (My plan is to pressure feed it with Nitrogen, and to put some kind of plastic piston in the O2 tank, or maybe just a heater to regulate the pressure.)

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Kirkaiya 3 points · 4 years ago

"Is it really just that some unburnt fuel gets dumped overboard by the gas generator?"

Pretty much. Not just unburnt fuel, but the untapped expansion of the pump's exhaust. I suppose to some degree it might be that larger rocket engines have some advantage in performance. But mostly the gas generator.

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cranp 4 points · 4 years ago

So more than 10% of the fuel/oxidizer mass goes through the gas generator? That sounds like a lot.

Also the gas generator exhaust pipe is shaped like an engine as well and produces some thrust, which must recover some fraction of that loss.

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deepcleansingguffaw 4 points · 4 years ago

The NK-33 chamber pressure is about half again that of the Merlin 1D. I don't know exactly how pressure relates to ISP, but in general higher pressure means higher efficiency.

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SpaceLord392 5 points · 4 years ago

Higher efficiency in the atmosphere. It's less important in vacuum.

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Wetmelon 6 points · 4 years ago

I haven't taken thermo 2 (which deals with choked flow and such) yet but as far as I can tell from thermo 1, it increases the enthalpy of the gas (U + Pv), which means it will exit at a higher velocity in a steady-flow process. The characteristic velocity of the exhaust is what determines Isp, and higher is more efficient.

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RadamA 8 points · 4 years ago

One of the main things is different cycle. That makes a few percent difference. The other is that with higher pressure you can have a larger bell even in low atmosphere. Like Merlin has 15:1 NK33 has 27:1. RD 180 has expansion ratio of 37:1...

The vacuum design of NK33 the NK 43 has that ratio of 70:1 and vacuum isp of 346. Compared to merlin 1DV that has 342 isp in vacuum. I think the expansion ratio of 1DV is like 100 or more.

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nyan_sandwich 6 points · 4 years ago

M1D Vac is 117:1 expansion

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Caldvan 3 points · 4 years ago

The Merlin is a gas generator, vs the staged combustion of the NK-33. Staged combustion is a more difficult technology to work with.

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cranp 0 points · 4 years ago

I know this, but I'm asking about what the physical cause of the lower efficiency is.

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ragingtomato 0 points · 4 years ago

That's basically it. The cycles are both different and yield different efficiencies.

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cranp 3 points · 4 years ago

"The engines are different because they are different." Thanks.

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ragingtomato -1 points · 4 years ago

This concept is a thermodynamic cycle design concept. It's literally undergraduate thermodynamics.

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cranp 2 points · 4 years ago

So your answer to my question is "go to college"?

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ragingtomato 1 point · 4 years ago

http://en.wikipedia.org/wiki/Gas-generator_cycle

edit: Google is an amazing thing, dude...

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autowikibot 2 points · 4 years ago

[Gas-generator cycle]:

> The gas-generator cycle is a power cycle of a [bipropellant rocket] [engine]. Some of the propellant is burned in a [gas generator] and the resulting hot gas is used to power the engine's pumps. The gas is then exhausted. Because something is "thrown away" this type of engine is also known as open cycle.

deal with the counter pressure of injecting the exhaust into the combustion chamber. This simplifies plumbing and turbine design, and results in a less expensive and lighter engine.

The main disadvantage is lost efficiency due to discarded propellant. Gas-generator cycles tend to have lower specific impulse than staged combustion cycles.

====

Image i - Gas-generator rocket cycle. Some of the fuel and oxidizer is burned separately to power the pumps and then discarded. Most gas-generator engines use the fuel for nozzle cooling.

Interesting: ^CE-20 | Rocketdyne ^RS-27A | ^RS-68 | Staged combustion ^cycle

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Dudely3 -2 points · 4 years ago

This is the problem. We humans always want it now.

Well, sorry, in this case you'll have to have a basic understanding of thermodynamics for you to get the answer.

Don't like it? Move to a universe where the rules are simpler.

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gangli0n 6 points · 4 years ago

When experts are being asked on TV about stuff, they're generally expected to give an explanation that is short while capturing the main issues without being factually wrong. Or, in other words, "if you can't simplify a problem (or correctly explain it in simplified terms), you don't really understand it" (that's a programmer's maxim, but very much applicable here). So if nobody here can explain it to this guy in this way, the conclusion is that there's no real expert here.

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Dudely3 3 points · 4 years ago

I think of it as more like asking "how does a magnet work". Unless you know the knowledge level of the person asking and what kind of explanation they want, you're not really able to give a good explanation. You wind up giving an explanation that simply raises more questions, if the person is astute enough.

For example, I could answer the question by saying that the merlin is of a type of engine that does not allow you to get anywhere close to the maximum efficiency of the fuel. It's just less efficient at using what it has because of the inherent design. There are lots of simple answers. Does this answer satisfy the question? Maybe, maybe not. It wasn't made clear.

That's all I mean. I do agree with you on what you said.

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mizfrizzle 3 points · 4 years ago · *edited 4 years ago*

You can think of it this way: In an unchoked compression and expansion (unchoked meaning the flow never reached mach 1 at the nozzle throat) during the converging section of the nozzle, the flow speeds up, peaks at the throat, then slows through the bell, yielding no significant increase in thrust compared to a nozzle without a diverging section.

In a choked flow, however, the flow reaches exactly mach 1 at the nozzle throat. At this point, since the fluid is traveling at the speed that pressure waves travel, the pressure from the combustion chamber no longer acts on the flow. So, instead of being forced to slow down through the expansion, the flow speeds up and cools down, trading thermal energy (temperature) and pressure for kinetic energy (velocity). So, you can think of the energy available in the flow to be converted to kinetic energy as the thermal energy in the gas. So you increase the thermal energy, you increase the change in kinetic energy of the flow, and in turn, the momentum change imparted on the rocket.

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hapaxLegomina 3 points · 4 years ago

Don't forget that Merlin engines are pretty much the best thing on the market when it comes to TWR. That has a big impact on overall ΔV.

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grandma_alice 2 points · 4 years ago

Does it?

Me thinks that, for the first stage anyway, using an engine with 5% greater ISP but with 10% more weight may be a good tradeoff. What's the additional weight for the engines - something like 1 ton for the 9 Merlin D's (am I in the ballpark?). What's the mass reduction for the fuel you will need? 5% of many tons is still a few tons.

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classicsky 2 points · 4 years ago

I think that one needs to remember the kind of company SpaceX strives to be. It is not necessarily about the best performance ratio on one specific part, but the system as a whole.

cycle. This may meaning making tradeoffs in one area to make major gains in another.

Tldr: SpaceX has a different view on rocketry and are attempting to optimize an entire system.

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cranp 3 points · 4 years ago

I addressed this in my post body. This is not the question I'm asking.

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classicsky 2 points · 4 years ago

I apologize I did not read the whole post body.

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peterabbit456 1 point · 4 years ago

Another question: Why is the Merlin 1D's reliability so high?

The answers to these questions may be somewhat related.

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wagigkpn 0 points · 4 years ago

Probably a combination of things...first of all simply size of the engines. The 1D is smaller than the others thus it loses efficiency right away. In rocket motors, bigger is more efficient. The 1D uses a design that is old news. Very reliable, good throttling and consistent performance. They use 9 1D engines on stage 1 so by their design they are not needing super powerful engines, unlike others that use 2-5 where if an engine under performs the rocket fails. In the same way, with fewer engines you really need the best you can get for performance.

honestly, I am surprised they are in the same ball park as the other engines. I would have expected them to be 20% or worse less efficient because why improve rocket technology if your return on r&d is less than 10% improvement?

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gangli0n 3 points · 4 years ago

I guess they're trying to improve the economic manufacturing and operation part more than the raw performance part. What is cheaper to operate, a Formula 1 car, or a Prius? If "improving rocket technology" meant RS-25, it would mean it's never going to get economical. The recent statement of the ULA guy that "all this reentry fuel should be used to improve the payload instead" (or what was it he said) is simply a matter of mindset.

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RadamA 0 points · 4 years ago

10% better isp means 25% more cargo.

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