

## Thrust frame mass estimation for rocket conceptual design purposes.

Zandbergen, B.T.C.

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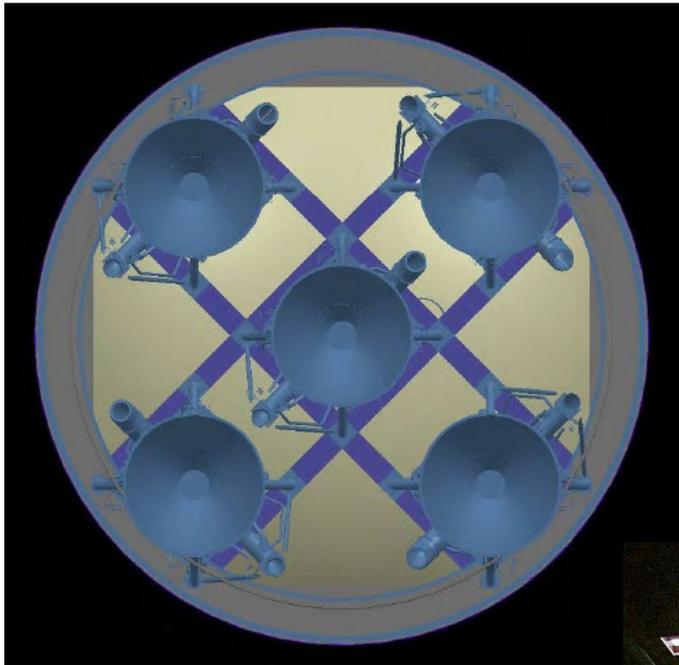
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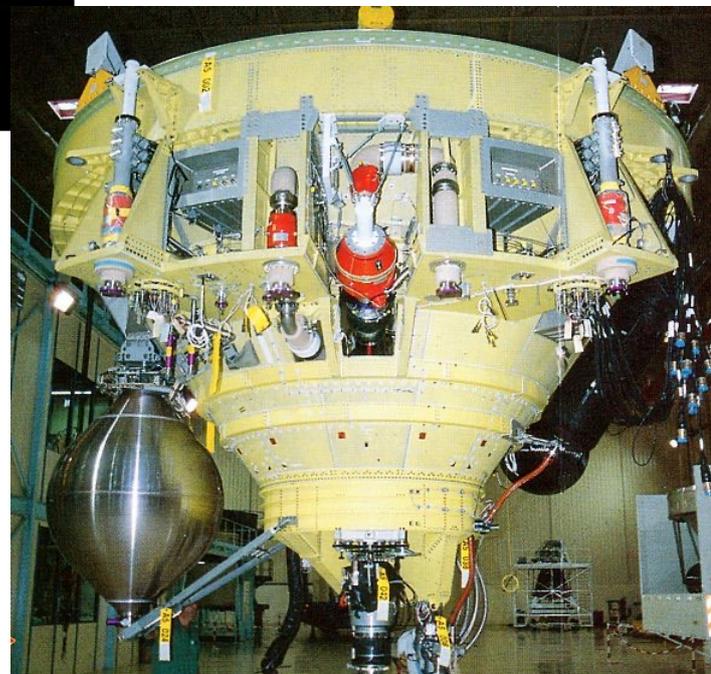
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# Thrust frame mass estimation for rocket conceptual design purposes.

B.T.C. Zandbergen, August 2025



SLS rocket first stage thrust frame (credits NASA)



Ariane 5 EPC stage rocket thrust frame (credits ESA)

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## Abstract

In this work an overview is provided of various rocket thrust frames found in open literature and of various existing single relation low-level models for rocket thrust frame mass estimation. Based on data obtained from literature, a new relation has been set up that supports making a distinction between three main types of thrust frames identified in this work. Some possible improvements have been pointed out that can lead to better low-level models.

In this work also foundational work has been performed towards an intermediate level model for thrust frame estimation. The resulting model provides clarity on how various important parameters like thrust, engine mass, acceleration level, frame dimensions, materials, etc. affect thrust frame mass. The accuracy of the results obtained could not yet be proven to agree with the required range for intermediate level models, but points for improvement have been listed.

# 1. Introduction

A rocket thrust frame or thrust structure, sometimes referred to as engine thrust frame (ETF) or engine thrust structure, is a crucial structural part of a rocket. It serves as the primary point of attachment for the rocket engine(s), transmitting the thrust generated by the engine(s) to the rest of the rocket's structure. Its importance is amongst others illustrated by that its mass can make up 2% to 20% of the stage dry mass. Hence, making proper design decisions in the early phases of a rocket design project is important<sup>1</sup>.

To allow making proper design decisions, we need insight in how thrust frames look like, their functions, the thrust transferred, what they are made of, their dimensions, their mass and most importantly how they differ and why. For this purpose, we will detail in chapter 2 the main functions of a thrust frame and provide descriptions of various existing thrust frames for which information is found available in open literature. We will close off the chapter by providing a results summary overview (our database) and discussion of the various frame types.

In next chapter (chapter 3), we will address thrust frame mass estimation. We will focus on models with a level of detail typically considered adequate for the early design phases of a rocket. For this, it is important to capture the major factors affecting the design. In literature several models exist that allow for computing the mass of rocket thrust frames. Such models range from quite simple models to more complex models of which the more complex models are usually the most accurate, but more labour intensive. All models generally use historical data to prove the validity of the models.

In subsection 3.1, we focus on various quite simple (low level) models for thrust frame mass estimation. These models all focus on the main function of the rocket thrust frame, which is to transfer the thrust from the engine to the stage body. Hence, in all models the basic assumption is that the mass of the rocket thrust frame can be estimated using information on the total thrust transferred to the stage body<sup>2</sup>. Some of these simple models also consider other aspects, like frame type, engine mass, number of engines, and acceleration loads to increase the accuracy. Hence, in this section, the models will be applied to the thrust frames in the generated database and information on accuracy of the models is obtained.

Above simple methods generally lack a more theoretically founded approach and can introduce errors when physics is not properly accounted for. Hence, in section 3.2, a more mechanics-based approach is followed to develop insight in how thrust frame mass depends on the structural material selected, the size and shape of the frame, the size, mass and number of engine(s), and the acceleration loads. The goodness of the method is proven by applying the method to the thrust frame of the EPC (*Étage Principal Cryotechnique*) stage of the A5G (generic) launch vehicle.

An overview of estimation results is presented in section 3.3, followed by a discussion of their accuracy.

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<sup>1</sup> Early design phases are crucial in any design process as they involve critical decisions that significantly affect the project's success and cost. In these phases, designers explore distinct options, evaluate feasibility, and set the overall direction of the project. Key decisions made early on can be very costly to change later, making it essential to get them right the first time.

<sup>2</sup> One can also consider a relation between rocket stage frame mass and stage dry mass. However, it is expected that such a relation will fail as it does not capture the dominant effect of rocket thrust on frame mass.

In the last section (section 4), the general findings are provided and recommendations for further work are given.

## 2. Overview of existing thrust frames

In this section, we will describe some existing thrust frames of rocket propelled stages for which information could be found with as purpose to identify distinct types of thrust frames as well as the major aspects relating to the design of such a thrust frame.

### 2.1. Space Shuttle Orbiter thrust frame.

The Space Shuttle Orbiter is propelled by 3 Space Shuttle Main Engines (SSMEs) that each provide a vacuum thrust of about 2.3 MN. Each engine is of size 4.3 m (height) by 2.25 m

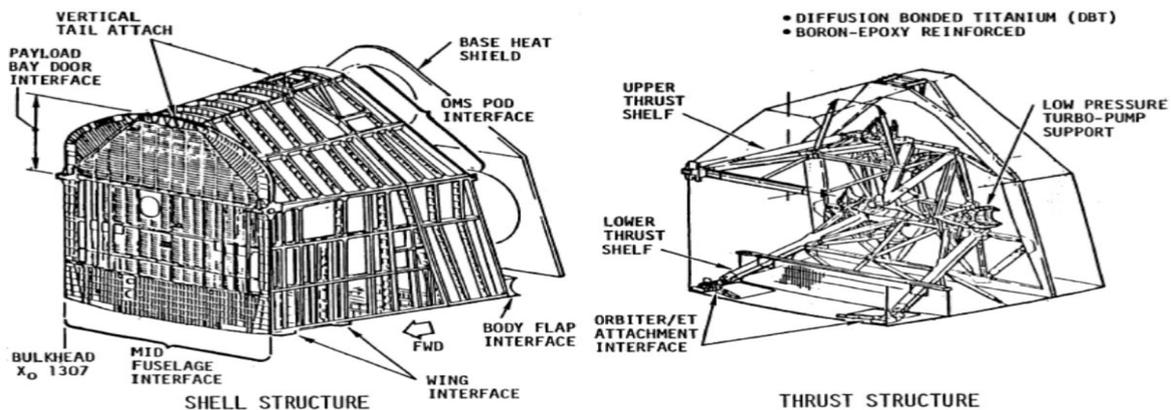


Figure 2-7. Aft Fuselage.

Figure 1: Space shuttle aft fuselage showing shell structure (on left) and thrust structure on right [Gilmore].

(diameter) and has a mass of about 3350 kg [NASA]. These engines are mounted onto a truss thrust frame that provides the primary load path for the engine thrust loads to the External Tank attach points and the sill and lower longerons of the mid-fuselage at the aft bulkhead, i.e. the interface with the mid fuselage (mid fuselage interface. The thrust structure is fabricated from diffusion-bonded titanium on Space Shuttle Discovery and Atlantis, and of forged titanium supports on Endeavor and is mounted onto the aft orbiter bulkhead. From [Shelton], we learn that the thrust frame mass is reported as 1734 kg. The height of the thrust frame is estimated by scaling from pictures, which gives a height of 3.4 m from base of thrust frame to top of thrust frame. The diameter of a virtual ring passing through the trusses at the base of the frame is assumed equal to the diameter of the Orbiter, which is 5.4 m. No information could be found on the supporting structure needed to attach the trusses to the orbiter. From the figure, it also shows that the thrust frame is mounted inside the shell structure. The latter ensures a proper aerodynamic shape of the orbiter.

### 2.2. Titan IV boost vehicle stage I thrust frame.

Titan IV first stage is propelled by a single LR-87 liquid-propellant rocket motor that is attached to the stage body by a truss-type ETF, see Figure 2. The Stage 1 LR-87-11 engine is a paired engine which consist of two separate AJ23-138 engines. The paired engine weighs 2165 kg [Purdue (a)] and produces a (total) vacuum thrust of 552,600 pounds (2458 kN). Individual engine mass is reported at 758 kg, which gives a mass of 1516 kg for the two engines together. The thrust frame is of a metallic (stainless steel (SS)) truss design and consists of 4 main trusses

with added support trusses. It connects to a skirt extension of the main body of the stage, which has an outer diameter of 3.05 diameter. The thrust frame mass is assumed to be identical to the difference in mass of the paired engine system and the summed mass of the individual engines. Given the earlier mentioned mass for the full engine of 2165 kg and the mass of 758 kg per individual engine, this gives a mass of 649 kg for the thrust frame. Typical inflight acceleration level experienced was around 4.0g with the engines actively thrusting. Based on scaling, it is estimated that the main truss elements have a length of 65 in or about 1.65 m and an outer diameter of about 5 in (0.125m).

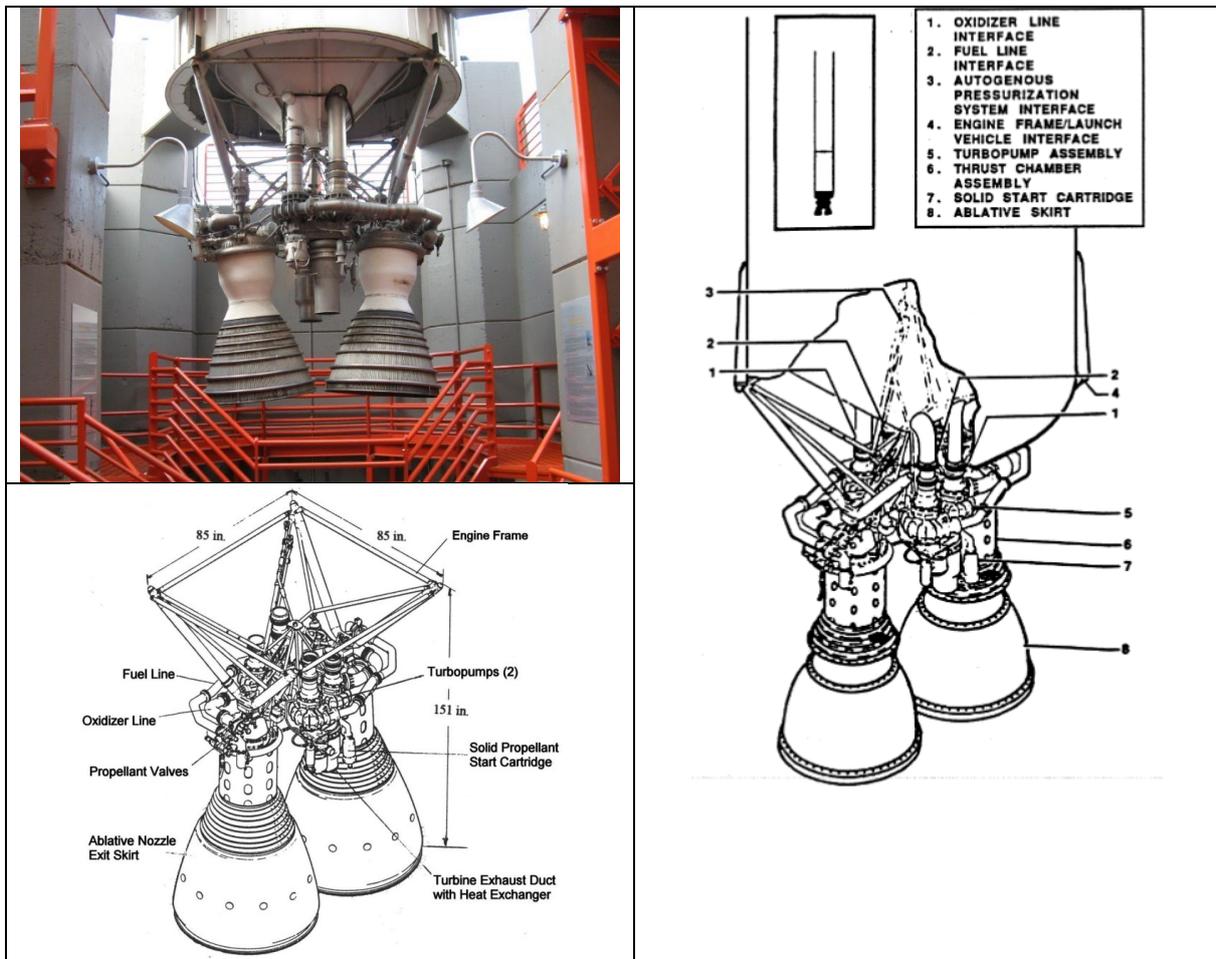


Figure 2: Titan IV first stage engine thrust frame; pictures taken from [Titan IV]. Photo on top left is used with courtesy to Aerojet. Photo shows an LR87 motor, but type is not clear.

### 2.3. Titan III stage 1 thrust frame

[Shelton] provides information on the mass of the thrust frame of the first stage of a Titan III rocket. Not clear is what type of Titan III Shelton is considering, but given the engine thrust reported of 464,000 pounds (2066 kN), this could be traced back to early Titan III versions, which all use the LR-87-9 engine consisting of 2 identical AJ23 engines. The paired LR-87-9 engine is reported [Wikipedia] to produce a combined sea level thrust of about 1900 kN and has a combined mass of around 1,814 kilograms. Using typical values for the mass of the individual engines as taken from [Wikipedia], we obtain a single engine mass of around 720 kg, which gives a two-engine mass of 1420 kg. This shows a mass of roughly 400 kg for the thrust frame. This agrees reasonably well with the ETF mass reported by Shelton of 784 lbm (356 kg). Not much more details of the ETF could be found, except that it is quite like that of the Titan IV first stage,

meaning that the frame is also made of steel and most likely also has 4 main structural members with supporting members.

## 2.4. Titan III stage 2 thrust frame.

Titan III stage 2 is equipped with a single LR-91-11 liquid-propellant engine, see Figure 3 with a vacuum thrust of 105,975 pounds (471.4 kN) and a mass of 589 kg. Engine length (or height) is given as 2.81 m and diameter as 1.63 m [Wikipedia].

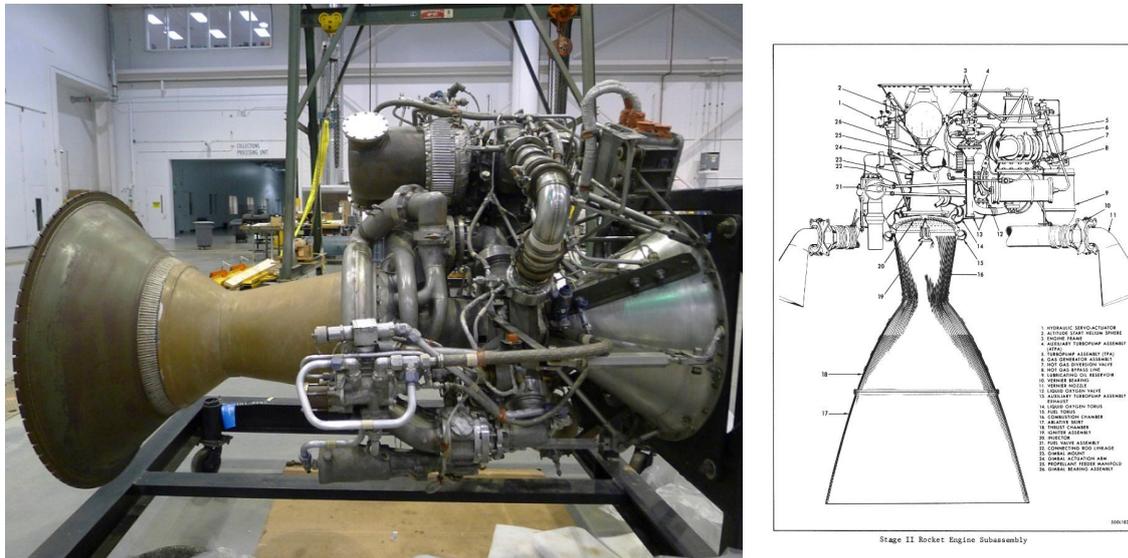


Figure 3: LR91 engine on left and schematic on right.

Engine support is provided by a skin-stringer reinforced aluminium aft fuel tank cone acting as the engine frame. On top of the engine (see photo) a small steel metallic cone is seen that connects to the fuel tank cone. This is also illustrated in next figure. This figure was taken from [Titan III]. Thrust frame mass for the second stage of Titan III is given as 245 lbm (111 kg) [Shelton]. Not clear is if this value is only for the conical element attached to the fuel tank or also includes the conical element attached to the engine.

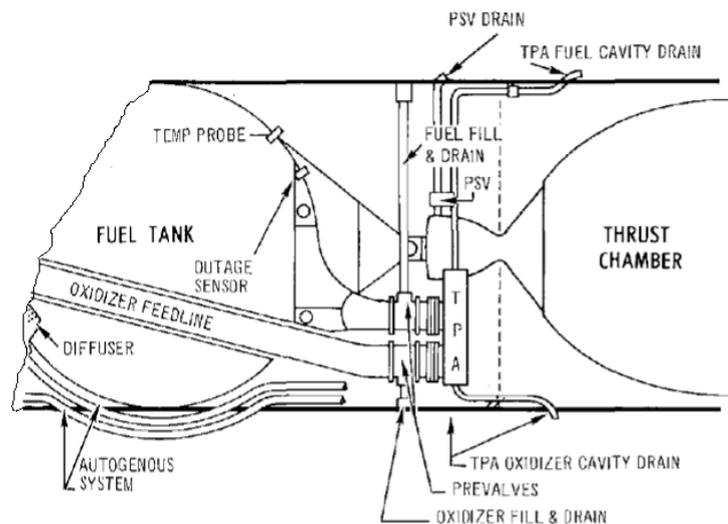


Figure 4: Schematic of engine mounting on second stage of Titan III [Titan III]

From the known stage diameter of 3.05 m, it is inferred from scaling from figure a base diameter of 2.0 m, a top diameter of 0.8 m and a truncated height of 0.8 m.

## 2.5. Saturn V, stage 1 (S1C) thrust frame.

Saturn V S1C data can be obtained from amongst others [S1C]. From this document, we learn that the S1C stage weighs about 2214 metric ton (4881 klbm) at start and provides a total thrust of 7.7 million pounds (34,500 kN) at sea level [McCutcheon]. Thrust is provided by five F-1 engines that each produce a sea level thrust of 6770 kN and a vacuum level thrust of 7770 kN. Each F1 has a dry mass of approximately 18,500 pounds (8,400 kg).

Engines are attached to a 24-ton, mostly aluminium alloy thrust structure, see Figure 5. There is 1 centre engine with four engines (the outboard engines) in a ring about this centre engine. The outer F-1s were gimballed, allowing the Saturn V guidance and control system to control roll, pitch and yaw during the S-1C's burn. The thrust structure measures about 9.9 m (30 ft) in diameter and about 6.1 m (20 ft) in height, which uniformly distributed thrust forces from the five engines to the fuel tank periphery. The thrust structure was composed of a lower thrust ring assembly, centre engine support, four hold-down posts/anchors (large aluminium forgings weighing 820 kg (1,800 lbs) each), four engine thrust posts, propellant distribution plumbing and an upper thrust ring assembly. Corrugated 7075-T6 aluminium alloy skin panels stiffened with intermediate aluminium alloy rings covered the thrust structure's internal components. A heat shield at the thrust structure's base protected internal components from engine heat.

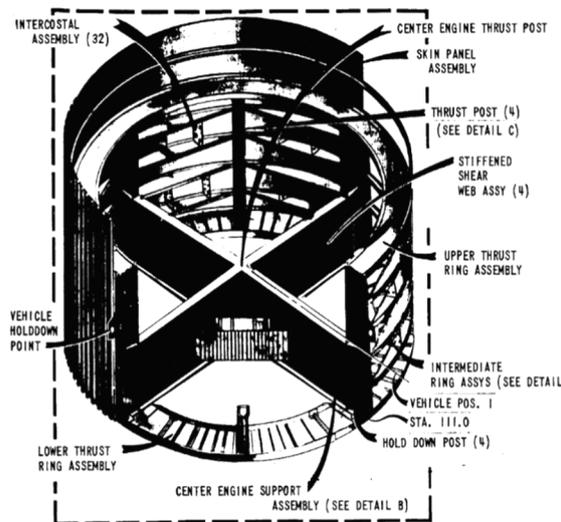


Figure 5: Saturn V, S1C stage thrust structure [Levine]

The thrust frame also provides support for:

- Engine fairings & fins<sup>3</sup>: The 4 outboard engines did not fit within the rocket diameter and hence they were each provided with a fairing encapsulating the part of the engine

<sup>3</sup> Saturn V, S1C stage has 8 fins of size 5 m<sup>2</sup>. Structural material is titanium as it had to resist the hot back flow of the exhaust gases that result from the presence of the launch pad. Fin mass per meter squared for a typical sounding rocket (Rexus) was found to be ~16 kg/m<sup>2</sup>. Assuming this value also applies for S1C stage, this would give a total fin mass for the S1C stage of around 680 kg. This is a bit speculative as we have not yet properly accounted for differences in acceleration loads and required stiffness.

sticking out at the sides. These fairings served to streamline airflow around the engines and housed retrorockets for stage separation.

- Propellant lines
- Four hold-down points to restrain the Saturn V onto the launch pad
- Environmental control ducts

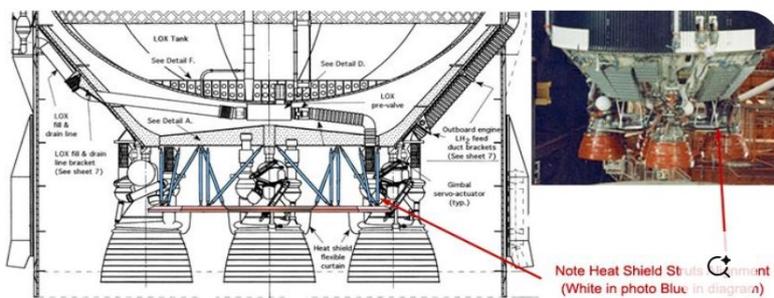
## 2.6. Saturn 1C-3B, stage 1 thrust frame

From [Wade], we learn that Saturn 1C-3B was a design study of an improved Saturn I (Saturn 1C) with a first stage carrying 3 F1 engines. Stage total mass is given as 1161 (metric) tons, and empty mass is ~72.5 tons. Stage diameter is identical to Saturn V first stage. From [Shelton], we learn that thrust frame mass is 14682 kg. No further information could be found. Thrust frame is considered comparable to that of the Saturn V, S1C first stage with 5 engines, except that it only needs to fit 3 engines. In that sense, frame mass is almost 60% of the frame mass reported for Saturn V, S1C. Hence, it is considered safe to assume that the thrust frame is of a similar cylindrical design with crossbeams to which the engines are mounted.

## 2.7. Saturn V, stage 2 (SII) thrust frame.

From [McCutcheon], we learn that the S-II stage of the Saturn V rocket, when fully loaded, had a total mass of approximately 480 metric tons (1,060,000 lbs). To propel it into space, the stage generated a thrust of 1,120,000 pounds-force (5250 kN) in vacuum. Thrust was provided by 5 J-2 engines of which each produced a thrust of 1050 kN and weighed 1789 kg. 4 of the five engines (except the centre engine) were capable of being gimballed  $\pm 7.0^\circ$  for thrust vector control.

The engines were mounted to the SII stage thrust structure, which transmitted the thrust to the aft skirt, which in turn transmitted the thrust to the propellant tank walls. The SII stage thrust structure was of semi-monocoque construction but in the form of a truncated cone increasing in diameter from the 21.6-foot S-IVB diameter to the 33-foot S-IC diameter. It was stiffened by circumferential ring frames and hat-section stringers. Four pairs of thrust longerons (two at each outboard engine location) and a centre engine support beam cruciform assembly accepted and distributed engine thrust loads. The shell structure was of 7075 aluminium alloy. The conical shell also served to support the major part of S-II system components; some were mounted in environmentally controlled equipment containers, others directly to the structure. It also carried a fiberglass honeycomb heat shield, which protected the stage base area from excessive temperatures during S-II boost.



## Saturn V

Saturn V SII Thrust Structure Detail

Figure 6: Details of aft part of SII stage showing details of the truncated conical thrust structure.

From [Wu], Some more detailed data of the thrust frame were obtained. These data have been collected in below table.

Table 1: Saturn SII stage thrust frame characteristics.

Parameter	Value
Height of truncated cone	9.3 ft (2.835 m)
Base diameter	33 ft (10.06 m)
Top diameter	17.5 ft (5.334 m)
Material	Al 2024 T3 [Wu] / Al7075 [McCutcheon]

A bit peculiar is the type of aluminium as Wu gives a different type than McCutcheon. Later we will introduce a more detailed structural analysis of a thrust frame, which allows one to assess the effect of changing the material.

## 2.8. Saturn V/S-IVB stage thrust frame.

The third stage of the Saturn V rocket is the S-IVB stage. From amongst others [McCutcheon, we learn that this stage is propelled by a single J-2 engine. The thrust exerted by the J-2 engine is transferred to the stage body by the thrust frame. This thrust frame is of an inverted truncated conical shape attached at its large end to the LOX tank aft dome and attached at its small end to the engine mount. The thrust frame was of a build-up aluminium (Al7075-T6) skin and stringer design.

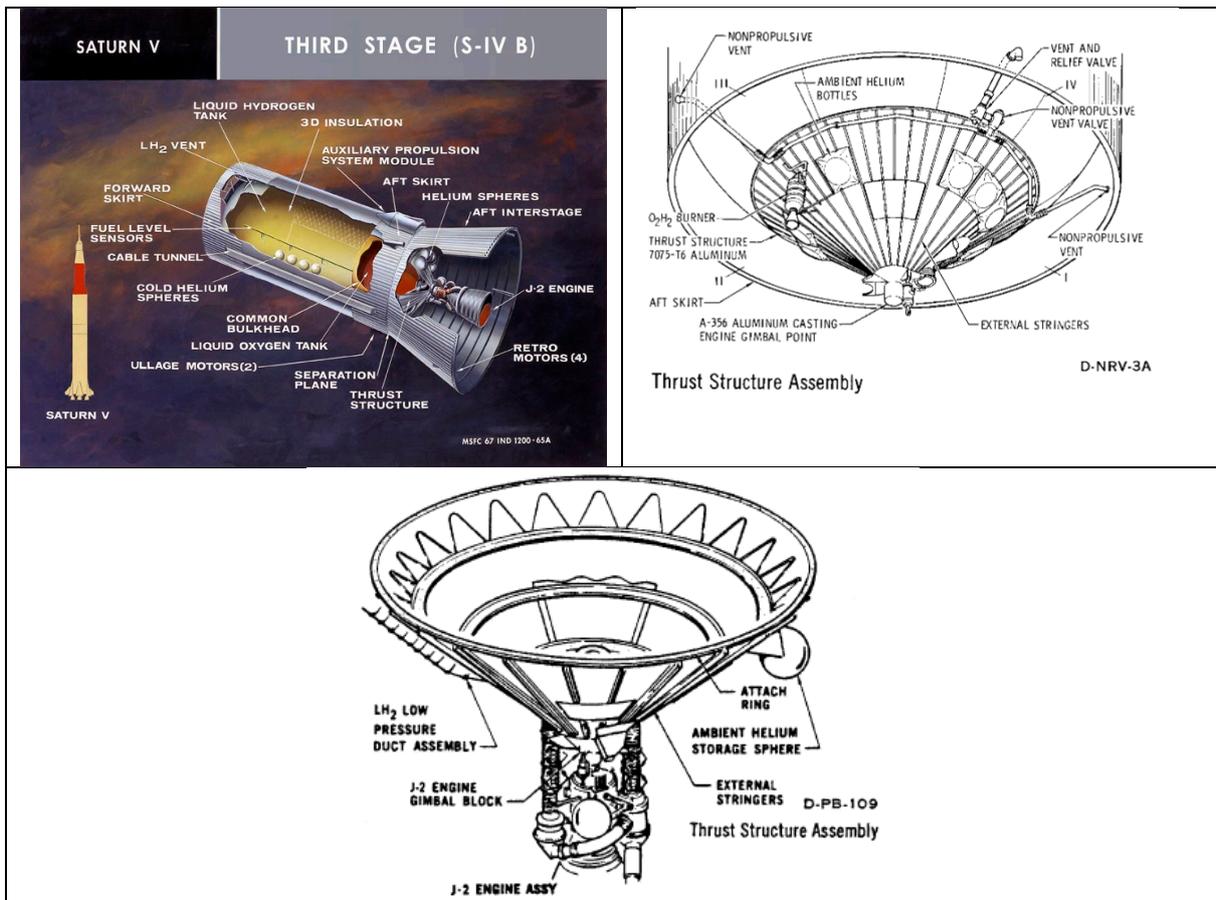


Figure 7: Saturn V-S-IVB stage with focus on the thrust structure (frame); Credits to NASA for all schematics.

Note that this thrust frame is comparable to the thrust frame of the second stage of Titan IV and Titan III, except for one difference. For the second stage of the Saturn rocket the tank has an ellipsoidal tank end onto which the conical ETF is mounted, whereas for the Titan III and IV the tank end was conical and only needed to be strengthened to carry the engine and to pass on the loads to the main body of the stage.

The thrust structure distributes J-2 engine thrust over the entire tank circumference. In addition, hydraulic and pneumatic system components, propellant feed lines, propellant pressurization systems and various other components are mounted on the thrust structure. The top of the truncated conical thrust frame is made up of an A-356 aluminium casting gimbal point. Total thrust transferred is 235.35 klf (1.02 MN) and structural mass is 510 lbm (231 kg) [Shelton, 2004]. Using the known diameter of the Saturn V, SIVB stage (21.75 ft or 6.63 m) and height of the thrust frame of 5.2 ft [McCutcheon], the following dimensions were derived from the schematic given in Figure 7.

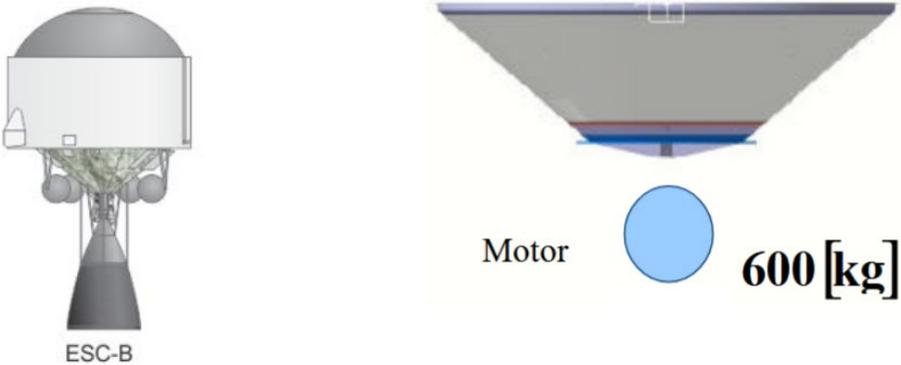
Table 2: Characteristic dimensions of S-IVB truncated cone thrust frame.

Parameter	Value
Base diameter	4.22 m
Top diameter	0.837 m
Height of truncated cone	5.2 ft (~1.59 m)

### 2.9. Ariane 5 ESC-B thrust frame.

Ariane 5 is propelled by a single Vinci engine. From Wikipedia, we obtain an engine mass of about 550 kg and an engine height in range 3.80 to 4.20 m. Acceleration loads are maximum -6 g (-4.6 g steady load) in axial direction (at burn out of boosters) and  $\pm 1.8$  g in lateral direction during lift off and flight through the atmosphere [Ariane 6, User’s manual]. This engine is mounted onto a metallic (aluminium) thrust frame.

A schematic view of the Esc-B stage with upper frame visible is illustrated in Figure 10 (left). The associated thrust frame that holds the Vinci engine is to transfer the thrust loads from the engine to the main body of the rocket. Figure 10 (right) shows a schematic of the bare thrust frame structure, which is composed of a top-ring (also referred to as base ring), a cone structure and a cone-cap. The base-ring has a diameter of approximately 4 m, and frame height is 1.3 m (i.e. distance between base ring and Vinci interface). The thrust frame is mounted to the upper stage tank at its base. The cone-cap of the ETF provides interface with the engine and two steering actuators. It has a diameter of 1.33 m. The cone is a stiffened aluminium shell structure which has various cut-outs for accessibility. Stiffeners are incorporated to increase stiffness and buckling stability.



Schematic of Ariane 5 ESC-B stage      Schematic of bare ETF showing main shape and position and mass of engine.

Figure 8: Schematics of Ariane 5 ESC-B stage (left) [HistoricSC] and bare ETF (right) [Driessen]

Engine mass is reported in figure as 600 kg as this includes a design load factor of value 1.1 (so, it is essentially the engine mass times a factor 1.1).

Actual frame mass could not be found, but [Driessen] reports a theoretically calculated value of 178 kg. In the work of [Fatemi] wherein a composite frame is compared with the existing design, a mass of around 200 kg is inferred. No further information could be found.

## 2.10. Ariane 5 EPC stage thrust frame.

The EPC stage provides (part of) the required thrust for the Ariane 5G rocket. The stage has a cylindrical shape/envelope with an outer stage diameter of 5.4 m (5.46 m including insulation) and a total length/height from top to bottom of 30.5 m [LVC]. The EPC comes into two versions, one with a propellant mass of 157.3 tons (designation H158) and one with a propellant mass of 175 tons (H175) [LVC].

The stage is equipped with a single Vulcain 1 engine (H158 stage), see Figure 9, or Vulcain engine (H175 stage). Vulcain 1 provides a vacuum thrust of 1140 kN and Vulcain 2 1360 kN. Vulcain 1 has an engine height of 3.05 m and engine mass is around 1.68 ton [ESA]. Vulcain 2 has an engine height of 3.44 m and an engine mass of ~1.8 ton (installed mass of ~1.935 ton). For both stage versions, the engine is mounted onto a conical shaped mostly aluminium thrust frame that at its base ends in a ring segment of the same diameter as the stage, see also Figure 9. At the top, an end ring holding a crossbeam (“croix” in French) structure is attached to the frame. This crossbeam structure holds at its centre a support that allows for attaching the Vulcain engine to the frame.

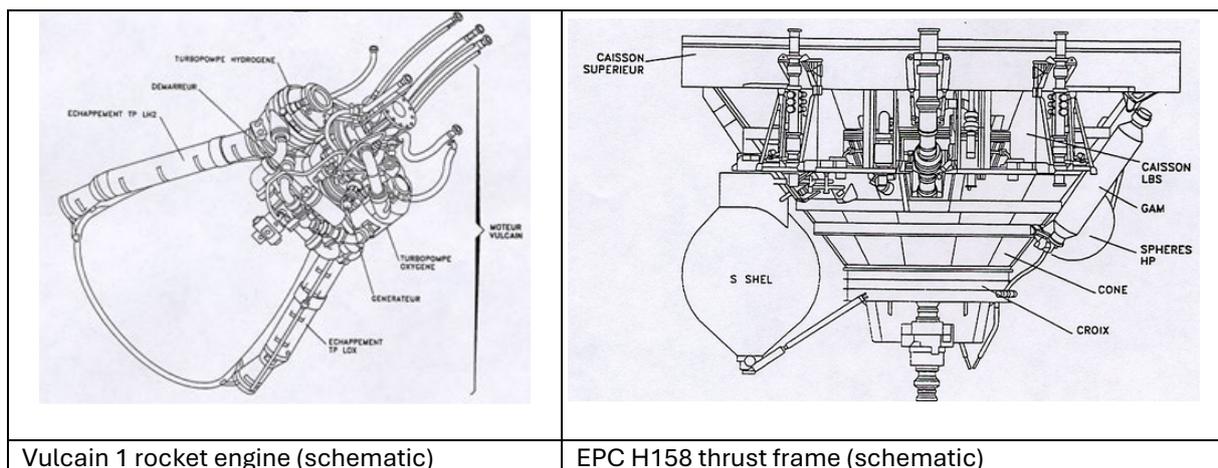


Figure 9: Schematic of Ariane 5 main engine (left) and thrust frame (right) [CAPCOM]

The thrust frame also provides for attachment points of some additional equipment. The most important one maybe being the aft points of attachment for the two SRBs (each with a wet mass of ~275 ton). Other attachment points are for the LOX tank pressurization system including a large liquid helium tank (S SHEL in figure), the engine activation unit and the high-pressure hydraulic tanks, and for the hydraulic actuator/s needed for engine thrust vector control (TVC). The latter system consists of two hydraulic actuators, an engine actuation unit, and a hydraulics system including a pressurized 180-litre oil tank (GAM) and high-pressure (HP) helium tank.

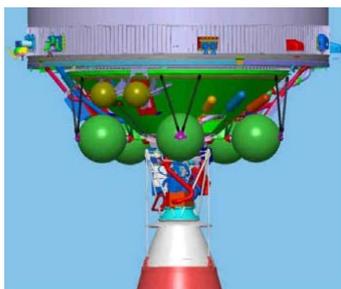
The mass of the thrust frame is estimated at 2030 kg [Airbus] and 1754 kg [Castellini]. The second value is presumably the mass of the H158 thrust frame and the former of the H175 thrust frame. However, this is not confirmed. Thrust frame height is estimated from the schematic shown in Figure 9, thereby considering that the maximum outer diameter is 5.4 m. It follows a total thrust frame height of ~3.4 m (from base to top of conical part extending above crossbeam ring).

The design loads for the thrust frame include structural, thermal, and acoustic stresses induced by the thrust force, the weight of the engine and associated equipment during flight, acoustic load and thermal loads [Brooker].

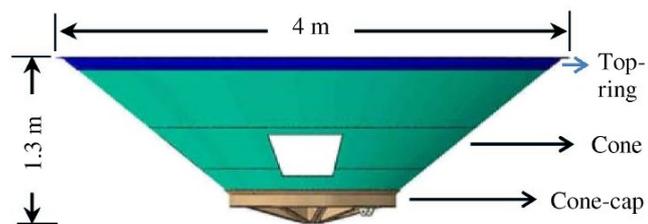
### 2.11. Engine thrust frame for generic launch vehicle

To guide the development of a composite engine thrust frame (ETF) Dutchspace (currently Airbus Netherlands) in 2012 conducted a study of a full carbon fibre reinforced plastic ETF [Fatemi]. As a starting point for this study, they used the metallic ETF design as used for Ariane 5's ESC-B stage as a reference point.

A schematic view of the ETF of the upper stage of a Next Generation Launch (NGL) launch vehicle is illustrated in Figure 10 (left). The green structure in this figure, which is between the upper stage tank and Vinci engine, shows an equipped ETF. Figure 10 (right) shows the bare ETF structure, which is composed of a base-ring, a cone structure and a cone-cap. The base-ring has a diameter of approximately 4 m and the frame has a total height of 1.3 m (i.e. distance between the ETF/Tank and ETF/Vinci interfaces). The ETF mates the upper stage tank at its base-ring. The cone-cap of the ETF provides interface with the engine and two steering actuators. The cone is a stiffened shell structure which has three cut-outs for accessibility reasons. The stiffeners can be placed at inside or outside of the cone. The primary function of the ETF is to transfer the thrust loads from the engine to the main body of the rocket.



Schematic of equipped ETF for upper stage of NGL



Schematic of bare ETF showing its main components.

Figure 10: Schematics of equipped ETF on upper stage of NGL (left) and bare ETF (right) [Fatemi]

Important design loads as reported include thermal loads and mechanical loads. For the thermal loads especially the temperature difference between the top ring (90 K) and the cone-cap or Vinci interface (300 K). Important mechanical loads stem from thrust loads (see table) and actuator loads (not shown). Additionally, during the firing of the first stage (2<sup>nd</sup> stage engine not active), there is also a load due to the combination of high g-forces and the engine mass. From Wikipedia, we obtain an engine mass of about 550 kg and an engine height in range 3.80 to 4.20 m. Acceleration loads are maximum -6 g (-4.6 g steady load) in axial direction (at burn out of boosters) and ±1.8 g in lateral direction during lift off and flight through the atmosphere [Ariane 6, User's manual]. During thrusting though, more benign acceleration loads should be accounted for. No detailed information on this could be found.

Table 3: Thrust frame loads [Fatemi]

Loads	Limit load	SF	Ultimate load
$F_{axial}$ [N]	307000	1.25	383750
$F_{lateral}$ [N]	42000	1.25	52500

Following the design, a final ETF mass was reported of 152.8 kg. A mass breakdown is given in next table. The final mass showed to be almost 50 kg less than the metallic variant and would indicate a mass saving of around 25%. The mass breakdown also shows a large contribution of the top ring and the cone cap, which together make up almost 45% of the frame mass (a mass increase of a factor  $\sim 1.8$ ).

Table 4: ETF mass breakdown [Fatemi]

ETF Parts	Mass [kg]
Top-ring	25.1
Cone	84.9
Cone cap	42.8
<b>Total</b>	<b>152.8</b>

## 2.12. Falcon 9 first stage thrust frame.

The Falcon 9 rocket's first stage generates thrust through nine Merlin D engines, each providing (full thrust version) 845 kilonewtons of thrust at liftoff and 981 kilonewtons in a vacuum [SLR-F9]. The nine Merlin engines on this stage are arranged in a cluster with 1 engine in the middle and 8 engines configured around the middle engine [SpaceX]. Each engine is connected to a central thrust structure, also called 'Octaweb' via a quadropod (pyramidal) structure, see Figure 11. Both structures are of a metallic origin. The Octaweb compares well with an 8-spoke wheel with an inner- (central) and an outer ring. The main material used in the Falcon 9's first stage, including the Octaweb, is aluminium-lithium alloy, a material known for its strength and lightweight properties, [says NASA](#). No further details could be found in open literature, podcasts and other types of disclosures.

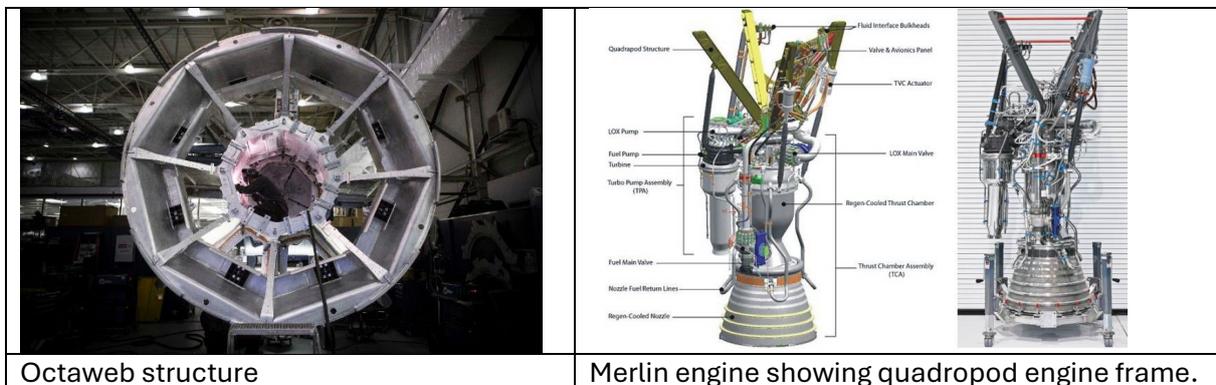


Figure 11: Falcon 9 Octaweb structure (left) and merlin engine with quadropod structure on top (right); Figures courtesy of SpaceX.

## 2.13. Results summary overview and discussion

Various rocket engine thrust frames have been described in foregoing sections. The main functions of this frame are to:

1. securely hold and support one or more rocket engines, thereby ensuring they are properly positioned and aligned during launch and flight.
2. transfer the thrust generated by the engine(s) to the main body of the stage and hence to the rocket.
3. withstand various structural and thermal loads during distinct phases of flight, including ground phase, ballistic phase (when the rocket is accelerating), and coasting phase

(when the rocket is traveling without thrust). Thermal loads are especially important in case of stages for which the thrust frame is below a cryogenic tank with the hot engine on the other side of the frame.

Additionally, the frame may also be used to provide support for other components and equipment. For instance, the frame often serves as the base for the thrust vector control system, providing anchorage for the servo-actuators that manipulate the engine for thrust vector control. Additionally, it may also serve as a mount for pressurization system elements like helium tanks and hydraulic or pneumatic equipment that are needed to actuate valves in the feed system or for aerodynamic caps (Saturn V S-1C frame) or as an aerodynamic shell (most cylindrical thrust frames). In some cases (first stage thrust frames), it may also allow for pad attachments or for points of attachment for SRBs.

From the information provided, three distinct types of thrust frames are distinguished based on how the thrust loads are introduced in the stage body and hence in the rocket. These types are:

1. Truss frame (TRUSS): A truss frame is build- up from a system of trusses that form a stiff structure. It offers good access and efficient load distribution with minimum material. It is noted that a truss frame concentrates forces at discrete node points, which require **stiff load introduction points**—which means the truss must anchor to a **heavy and rigid base structure** to avoid high stress concentrations or local buckling. A main disadvantage is that it does not offer a nice aerodynamic shape.
2. Cylindrical frames with crossbeams (CYL): Compared to truss frames, cylindrical frames provide **continuous load paths**, spreading thrust loads smoothly across a shell surface. Hence, loads are **distributed over a wider area**, allowing for **lighter, thinner mounting structures** on the vehicle and avoiding high local stresses. This frame can be used for single engine designs but is mostly used for stages that have multiple engines, like the US SLS first stage, Falcon 9 first stage, and the Saturn V S-1C stage. Note that crossbeams provide anchor points for the engines and hence must withstand high bending loads. This makes them quite heavy. Also, they need some local strengthening as cross beams are typically attached to cylindrical shell frames via reinforced pads or stiffened zones on the shell. The cylindrical frame also allows for a smooth aerodynamic shape as compared to a truss frame.
3. Truncated conical frame (CON) usually with crossbeams or spokes at truncated top. This frame is essentially comparable to the cylindrical frame but aims to minimize mass as compared to the mass of a cylindrical frame by reducing the length of the crossbeams or spokes at the top of the frame. This type of frame is mostly used for single engine designs, like for the first stage of Ariane 5 (and Ariane 6), but can also allow for multiple engines, like for Saturn V, second stage thrust frame supporting 5 engines. In that case a smaller cone half angle will result. For first stage designs, the conical shape also allows for reducing wake drag.

All three types of thrust frames require an attachment interface, meaning they must ultimately be **mounted** to some support (like a bulkhead, tank base, skirt, or ring). In the case of trusses this may require quite some mass. However, the mass associated for this support structure usually is not given as part of engine thrust frame. It is also expected that this mass is highest for truss structures, see below. We could also consider comparing the frames on cost, but this is left for the reader to explore for him/herself. Table on next page provides for a summary comparison of the three frame types with respect to the aspects mentioned above.

Table 5: Comparative overview of different thrust frame types.

Feature	Trust type	Truncated conical	Cylindrical
Mass (for same load)	Lowest mass.	Intermediate.	Heaviest due to need for heavy crossbeams to anchor the engines and to transfer the thrust force to the stage wall
Integration access	Good access from all sides.	Worst. May need to include doors to access the inside of the frame. Space may be cramped.	Intermediate. May need doors but inside of frame is spacy due to cylindrical shape.
Aerodynamic smoothness	Worst; Needs a fairing to reduce drag- and/or heating effects from shock waves.	Best as it creates smallest wake.	Good
Impact on supporting structure mass on vehicle side	High due to need for <b>distributed reinforcements</b> or ring frames.	Low to moderate: Loads naturally spread to cylindrical skins or tank domes.	Low to moderate.

The main loading of a thrust frame occurs during the thrust phase of the stage, when the engine(s) is (are) active. In other phases, like coast or when other stages are active, we also need to consider that the frame needs to withstand the load from the weight of the engine. The latter depend on the acceleration load experienced by the rocket. For this reason, we have collected data on frame type, total (vacuum) thrust ( $F_{tot}$ ), number of engines ( $N_{eng}$ ), total engine mass ( $M_{eng}$ ), thrust frame mass ( $M_{TF}$ ) in Table 6. In this table, we have also included some additional data taken from [Shelton] for a Saturn 1C stage, most likely the C3-B version, which has a cylindrical thrust frame, but this could not be confirmed. Still, we will list it as such.

Table 6: Thrust frame characteristics overview.

ID	Vehicle, stage	Frame type	$F_{tot}$ [MN]	$N_{eng}$ [-]	$M_{eng}$ [kg]	$M_{TF}$ [kg]	$M_{TF}/M_{eng}$	$M_{TF}/F_{tot}$ [kg/N]
1	Space Shuttle, Orbiter	TRUSS	6.84	3	10050	1734	17.3%	2.54E-4
2	Titan III, S-I	TRUSS	2.07	2	839	356	42.4%	4.05E-4
3	Martin Titan IV, SI	TRUSS	2.46	2	2165	659	30.4%	2.68E-4
4	Saturn V, S-IC	CYL	34.5	5	42000	24000	57.1%	6.95E-4
5	Saturn C-3B <sup>4</sup> , S-I	CYL	22.4	3	25200	14682	58.2%	6.55E-4
6	Saturn V, S-IVB	CONE	1.02	1	1788	231	12.9%	2.26E-4
7	Saturn V, S-II	CONE	5.25	5	8941	2894	32.4%	5.51E-4
8	Titan III, S-II	CONE	0.47	1	589	111	18.8%	2.36E-4
9	Ariane 5 ECB, ESC-B	CONE	0.18	1	600	178	29.7%	9.88E-4
10	Ariane 5 ECA, EPC (H175)	CONE	1.34	1	1935	2030	104.9%	1.51E-3
11	Ariane 5 ECA, EPC (H158)	CONE	1.14	1	1800	1754	97.4%	1.54E-3

NA = Not Available; ND = Not Defined.

It is noted that all data is not to be considered as 100% exact as different values appear in literature. Also, there is a difference between bare engine mass and installed engine mass. Literature is generally unclear on which mass is reported. Still, most values reported are

<sup>4</sup> Saturn 3C version first stage with 3 F1 engines, see <http://www.astronautix.com/s/saturnc-3b.html>.

considered close (within 5%-10%). For the thrust frame mass reported comes the added problem that it is not clear if the support structure on the stage itself is included in the frame mass. This is notably so for the Titan III, SII stage, which has only a small thrust frame as a large part of the thrust frame is integrated in the lower bulkhead of the tank structure. Current understanding is that the mass of this supporting structure on the main stage body is not included in the mass value except for the reported thrust frame mass of the Titan III, SII stage. Another consideration is that, when applying a truss frame, an aerodynamic shell may be needed as to improve flow aerodynamics. This has also not been accounted for. The cylindrical and conical frames this smooth flow surface is already integrated in the structure. Also, when compiling the above table, added loads (from TVC, SRB attachment, equipment attached to the frame) have been neglected thereby assuming that engine thrust is the main determining parameter. It is noted that engine thrust levels included in table are believed to be 100% thrust level and hence the effect of thrust control is not considered. As an example, the Space Shuttle Orbiter engines can increase thrust with 10-20%. Moreover, design thrust may be different from the actual thrust. This was noted for e.g. the thrust frame for the NGL launch vehicle where engine thrust was found to be 180 kN, but design thrust was noted as 300 kN.

The table has two added columns showing frame mass to engine mass and frame mass to thrust ratio to perform a first sanity check. Results show that thrust frame mass varied from about 10% of engine mass up to 100% of engine mass for the Ariane 5 EPC thrust frames. It shows that Ariane 5 thrust frames have a relatively high mass to thrust ratio. These relatively high values are most likely due to that this thrust frame also holds the aft attachment points for the two SRBs (some literature indicates that the added mass of the SRB attachments to total EPC stage mass is of order 1010 kg as reported by [Castellini]. Part of this should be attributed to the thrust frame and part to the interstage 1/2.). Something similar is also expected for Martin Titan IV rocket as of an overall similar configuration, but literature [Titan IV] shows that for this rocket the boosters attach to the core vehicle above the engine frame. Hence, this mass is not included in the Titan IV stage 1 thrust frame mass. We also note a relatively high percentage of thrust frame mass for Saturn V, S1C stage and S1C first stage. This is partly due to the addition of the fairing mass for the 4 outboard engines and the presence of the fins on the respective thrust frame of this stage. However, no concrete mass data of these items could be found. Most likely this also plays a role in the mass of the Saturn 1C thrust frame.

Finally, the thrust frame also supports other equipment that bring their own mass. Not always is clear if this mass is included or not in the mass data quoted.

Next table shows more information of the various frames relating to size, material and acceleration loads.

Data shows that all frames tend to be stubby, meaning their height is less than their diameter. Furthermore, acceleration loads differ with lowest value for upper stages and highest for first stages.

Table 7: Thrust frame geometrical characteristics, static loads and materials used.

#	Rocket	Frame type	Frame diameter [m]		Frame Height [m]	Max load [g]	Frame material
			Base	Top			
1	Space Shuttle Orbiter	TRUSS	5.2		3.1	4.5	Ti
2	Titan III, S-I	TRUSS	3.05		1.8	5.5	SS
3	Martin Titan IV, S-I	TRUSS	3.04		0.71	5.5	SS
4	Saturn V, S-IC	CYL	10.06		5.9	5.4	Al
5	Saturn C-3B, S-IC	CYL	10.06		5.9	5.4	Al
6	Ariane 5 ECB, ESC-B	CONE	4.00	1.33	1.30	2.0	Al
7	Saturn V, S-IVB	CONE	4.22	0.84	1.58	2.1	Al
8	Saturn V, S-II	CONE	9.90	5.32	2.82	3.3	Al
9	Titan III, S-II	CONE	2.0	0.84	0.78	3.3	Al
10	Ariane 5ECA, EPC (H175)	CONE	5.4	1.875	3.40	6.0	Al
11	Ariane 5G, EPC (H158)	CONE	5.4	1.875	3.40	6.0	Al

Summarizing, the data collected is believed to be as accurately as possible, but for some data substantiation is somewhat lacking and hence some errors may still be in. However, having 11 data points for a wide range of thrust levels, stage diameters and acceleration loads offer an excellent opportunity to investigate their importance for the design. This is pursued to some detail in next section.

### 3. Thrust frame mass estimation.

In this section we will turn to estimating the mass of a rocket thrust frame. Below we will first discuss some basic estimation relationships that are used for order of magnitude estimation (level 0) and or conceptual design (level 1). Then, we will turn to a higher (medium) level of fidelity (level 2). Level 3 mass estimation (or higher) will not be dealt with here. For this, the reader is referred to e.g. [ECSS].

Level 0 and -1 models form the lowest level of model distinguished. Such models are mainly empirical or analytical models, developed based on historical data and using simple scaling laws. They are quick to use and require little input. Level 1 models generally offer an inaccuracy in range  $\pm 30\text{--}50\%$  and are considered sufficient for trades or early architecture studies. If estimation inaccuracy is higher than we refer to the model as a level 0 model.

Level 2 is an intermediate model level. For structural elements, such models may be based on simplified structural analysis using 1D or 2D model using classical mechanics with idealized load paths. Such models generally offer an estimation inaccuracy of  $\pm 15\text{--}25\%$  and are considered good for trade studies, concept down-selection, and budgeting mass margins.

Some more background on fidelity levels used in aerospace industry can be obtained from [Robinson].

#### 3.1. Low-fidelity level estimation

Various relationships exist that allow for low fidelity level estimation of the mass of the thrust frame.

The first one is a relation accredited to B. Brothers and given in an overview generated by Rohrschneider [Rohrschneider]. It relates thrust frame mass to the maximum total (all engines) thrust load transferred. For this work, the relation has been adapted as to allow for using SI units instead of US units (kg instead of lbm and N instead of lbf):

$$M_{TF} [kg] = 1.79E - 4 * (T_{vac} [N])^{1.0687} \quad (1)$$

A second related is accredited to M. Sippel and A. Herbertz and published in [Herbertz]. Like the first relation, it relates frame mass to the (total) thrust load transferred to the stage body. It reads:

$$M_{TF} [kg] = 2.04E - 5 \times (T_{vac} [N])^{1.15} \quad (2)$$

A third relation was taken from course notes produced by D. Akin at the university of Maryland [Akin]. This relation also relates frame mass to (total) thrust load transferred by the frame.

$$M_{TF} [kg] = 2.55E - 4 \times T_{vac} [N] \quad (3)$$

Above relations mainly use maximum thrust in vacuum as the main parameter determining thrust frame mass. In next table, estimated mass results are given for the thrust frame of rocket stages listed in Table 6.

Table 8: Low level mass estimate of rocket thrust frames based on relationships from open literature.

ID	Vehicle, Stage	Frame type	F <sub>tot</sub> [N]	"Real"	M <sub>TF</sub> [kg]		
					Herbertz	Akin	Brothers
1	Space Shuttle, Orbiter	TRUSS	6.84E+06	1734	1479	1744	3613
2	Titan III, SI	TRUSS	2.07E+06	356	373	527	1005
3	Martin Titan IV, SI	TRUSS	2.46E+06	659	456	627	1210
4	Saturn V, SIC	CYL	3.45E+07	24000	9509	8798	20364
5	Saturn C-3B, S-I	CYL	2.24E+07	14682	5786	5712	12835
6	Ariane 5 ECB, ESC-B	CONE	1.80E+05	178	23	46	74
7	Saturn V, S-IVB	CONE	1.05E+06	231	171	267	486
8	Saturn V, S-II	CONE	5.25E+06	2898	1091	1339	2723
9	Titan III, SII	CONE	4.71E+05	111	68	120	207
10	Ariane 5ECA, EPC (H175)	CONE	1.50E+06	2030	258	383	714
11	Ariane 5ECA, EPC (H158)	CONE	1.14E6	1754	188	291	532

Looking at these results, we see that results of Herbertz and Akin are quite similar. Furthermore, we find that results of Herbertz and Akin compare better with the "true" value than the estimates of Brothers for truss-type of frames. In contrast, Brothers is much better for cylindrical frames. For conical frames, the difference is not that clear. The results obtained using the relation of Herbertz show continuously an underestimation (as for the cylindrical shell). Results obtained using Akin's relation show similar except for an overestimation of the Saturn V, S-IVB thrust frame. Brothers' relation provides highest frame mass for all three types. For conical shells, the values are more scattered about the true value. Our interest is in which method is most accurate, so we used the discrepancy between the estimated value and the "true" value to figure out a mean percentage error using:

- Relative Error = Absolute Error / True Value

- Percentage Error (PE):  $PE = (\text{Relative Error}) * 100\%$
- Mean percentage error is the summed errors divided by N, where N is the number of datapoints.

Results are provided in next table. Results clearly show that the mean error percentage is at the upper bound of the range indicated for a level 1 fidelity model. Individual estimates though sometimes are much more off, which sheds doubt on the applicability of these three methods for trade studies or conceptual design studies. Best method for cylindrical and conical thrust frames (lowest mean percentage error) is for the relation accredited to Brothers. For truss frames either the relation from Akin or Herbertz offer better results.

Table 9: Low level model errors in mass estimation of rocket thrust frames.

ID	Vehicle, Stage	Frame type	$F_{tot}$ [N]	$M_{TF}$ [kg] "True"	Percentage error in estimate		
					Herbertz	Akin	Brothers
1	Space Shuttle, Orbiter	TRUSS	6.84E+6	1734	-15%	+1%	+108%
2	Titan III, SI	TRUSS	2.07E+6	356	+5%	+48%	+183%
3	Martin Titan IV, SI	TRUSS	2.46E+6	659	-31%	-5%	+84%
4	Saturn V, S-IC	CYL	3.45E+7	24000	-60%	-63%	-15%
5	Saturn C-3B, S-I	CYL	2.24E+7	14682	-61%	-61%	-13%
6	Ariane 5 ECB, ESC-B	CONE	1.80E+5	178	-87%	-74%	-58%
7	Saturn V, S-IVB	CONE	1.05E+6	231	-26%	+16%	+110%
8	Saturn V, S-II	CONE	5.25E+6	2898	-62%	-54%	-6%
9	Titan III, SII	CONE	4.71E+5	111	-39%	+8%	+87%
10	Ariane 5ECA, EPC (H175)	CONE	1.50E+6	2030	-87%	-81%	-65%
11	Ariane 5ECA, EPC (H158)	CONE	1.14E+6	1754	-89%	-83%	-70%
Mean percentage error					-50%	-32%	+31%
Mean percentage error (truss frames excluded)					-64%	-49%	-4%

In more detail, the results do confirm the relatively high mass of the Ariane 5 EPC thrust frames as all three methods from literature clearly underestimate the mass of the H158 and H175 thrust frame. Same is also the case for the Ariane 5 ESC-B stage. A specific cause could not be found. It is hypothesized that this may also be because of the applied safety factor for the real design being higher than standard. However, no confirmation on this could be found.

Next, we used the collected data to investigate an improved regression relationship using information on the thrust force in vacuum as well as information about the type of thrust frame. The following relation was obtained:

$$M_{TF} [kg] = 6.96E - 4 * T_{vac} [N] * K_S \quad (4)$$

This relation provides stage thrust frame mass with  $T_{max}$  is maximum total stage thrust in vacuum,  $K_{ST}$  is a factor that accounts for the type of structure.  $K_{ST}$  is 0.345 case of a truss-based thrust structure, 0.93 in case of cylindrical type of frames and 1 in case of conical thrust frames<sup>5</sup>. This relation is considered valid for Shuttle era technologies, which include cylindrical and truncated conical frames made of aluminium or truss-based frames made of steel or titanium.

<sup>5</sup> The relatively low mass of truss structures is presumably due to that no consideration is given to the equipment needed on the stage side necessary to attach the truss frame to the stage.

The derived relationship is considered valid over the thrust range of 180 kN (Vinci motor on ESC-B stage) to 22 MN (Saturn V, S1 stage). To illustrate the goodness of the fit, it is mentioned that the relation has an  $R^2$  value of 0.984. Still, results showed an average error of 29% with maximum error of +215%. For instance, for the conical thrust frame of the Saturn V, SIVB stage a mass is estimated of 677 kg, which is a factor 2.15 higher than the true value reported. To improve the accuracy of the estimation relationship, it is considered that more detailed modelling, thereby also considering parameters like, frame dimensions, frame materials as well as acceleration loads, are needed.

As another measure for the goodness of fit, also a scaled or *relative root mean square error* (RRSME) was determined. To do so, we first determined the relative error for each data point. Here we use the estimated value as the reference value. Second, we squared and summed the relative error for all data points, thus providing the *sum of squared relative errors* (SSRE). Next, we divided the outcome by the degrees of freedom ( $n-m$ ), where  $n$  is the number of data points and  $m$  is the number of estimated parameters. as to obtain a mean squared relative error (MSRE). As a last step we take the square root of the MSRE, which provides us with the RRSME value. This value can be seen as a  $\pm$  “percentage bound” that holds roughly 65% of all true data points. For the relation (4), we found an RRSME value of 55%, again confirming that the fit needs to be improved for true level 1 purposes. This value was introduced in this work as even though the quality of fit was good, it does not tell a full story yet.

A fourth relation for mass estimation of thrust frames was found in the work of [Castellini] based on the work of D. Raymer as reported in [Rohrschneider] and adapted by Castellini to allow for the use of SI units. Additionally, Castellini added the last two terms in the relation as to include acceleration loads, structural safety, and the use of advanced materials like carbon composite. Inputs used include number of engines ( $N_{eng}$ ), engine mass ( $M_{eng}$ ), structural safety margin (SSM; Castellini uses a value of 1.5), max acceleration load ( $n_{ax,max}$ ) and whether some advanced material is used or not ( $K_{SM} = 0.62$  for composite materials. For all other materials, a value of 1 is used).

$$M_{TF} [kg] = 0.013(N_{eng})^{0.795} \times \left( 2.2481E - 4 * (T_{vac} [N])^{0.579} + 0.01N_{eng} * \left( \frac{M_{eng} [kg]}{0.45} \right)^{0.717} \right) * \left( 1.5 * SSM * n_{ax,max} * g_o \left[ \frac{m}{s^2} \right] \right) * K_{SM}$$

The reasoning offered of selecting this relationship offered by Castellini was that it was the only relationship found that accurately estimated the thrust frame mass of the first stage of Ariane 5ECA, which was also mentioned as being the only data point available to check the correctness of the relationship. This has been verified using the given maximum axial acceleration of the Ariane 5ECA launch vehicle and was found to be correct.

When studying the relationship in some more detail, some problems arise, being:

1. To check this relationship, we need to collect a lot more info. Now, generally, obtaining data on number of engines and engine mass is readily available. The maximum axial acceleration is harder to find. Also, it is not clear if this is the maximum acceleration in flight or the maximum acceleration experienced when the stage is active, i.e. thrusting.

2. Another more critical issue is that the original relationship developed by Raymer is stated to be applicable for aircraft [Rohrschneider]. So even when considering the relationship to be exact for one data point, it seems a bit overenthusiastic to also assume that it will also do well for other design conditions. To name one concern, there is the effect of engine mass on frame mass. Literature is clear on that compression loads resulting from thrust generation is a prime parameter determining frame mass. Now, for a vertically oriented rocket thrust frame, generally, the weight of the engine reduces the compression load on the frame. This is even more so in accelerated flight. Still, when increasing engine weight, we see that the mass of the thrust frame increases contrary to our expectations. A second one is that the frames used to develop the relationship already have an SSM and a maximum axial acceleration different from 1. This is not accounted for in the revised relation by Castellini. The current relation suggests that when increasing the acceleration load from 1g to 6g also the frame mass increases with a factor 6. Given that thrust force is main dimensioning load and that increasing acceleration would reduce the compression load, this would be an area for further research.
3. Application of the relation showed an average error in the range of 80% for the frames included in this document with some errors in range 160-360%.

Based on the above, it is advised to be careful when using the relation as reported by Castellini. All in all, none of the relationships seems to be good under all circumstances and for all frame types. Maybe if more data on existing frames come available, these relationships can be further improved. Until that time arises, best is to go to the next estimation level.

### 3.2. Intermediate fidelity level estimation

In this section, an alternative estimation method is presented thereby focussing on thrust frames of type truncated cone and cylindrical<sup>6</sup>. In this method, we will take a more fundamental approach, where the cone/cylinder shell thickness is determined based on the ability of the shell structure to withstand buckling during thrust generation. This is considered in line with shell buckling being identified as the primary design driver in many recent NASA (and ESA) launch vehicle designs<sup>7</sup>. A calibration factor is then added to bring the results into agreement with the true data in our database. This will be explained in next section. In section 2 of chapter 3.2, an example case is worked out to illustrate the method for those that would like to apply the method themselves. In section 3, the results of applying this method to all the frames in the data base are provided. In section 4 then a suitable calibration factor is determined for selected frames. The calibrated relations are then applied to estimate frame mass for all cases in our data base and the results are compared. In the last two sections of chapter 3.2, we briefly investigate other failure modes as well as the effect of considering the effect of bending on the frame's ability to withstand buckling failure.

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<sup>6</sup> The frames with numbers 1 to 3 are not considered in this work for detailing.

<sup>7</sup> <https://ntrs.nasa.gov/api/citations/20160007439/downloads/20160007439.pdf>

### 3.2.1. Modelling approach

We follow an approach taken from [SP8007] and [SP8019] for an isotropic cylindrical or conical shell subjected to axial thrust only<sup>8</sup>, see Figure 12. By adapting the shell thickness, the critical load ( $P_{cr}$ ) at which the shell buckles are brought in line with the axial load for which the shell is being designed. The basic relation determining the thickness of the shell determine the critical load is taken from [SP8019]<sup>9</sup> and is valid for conical and cylindrical shells of uniform thickness:

	$P_{cr} = 2\pi E t^2 \left( \frac{\gamma}{\sqrt{3(1 - \nu^2)}} \right) \times \cos^2 \alpha$	(5)
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Here E is Young's modulus, t is shell thickness,  $\gamma$  is knock down factor (or KDF),  $\nu$  is Poisson's ratio, and  $\alpha$  is cone half angle (zero for a cylindrical structure), see figure.

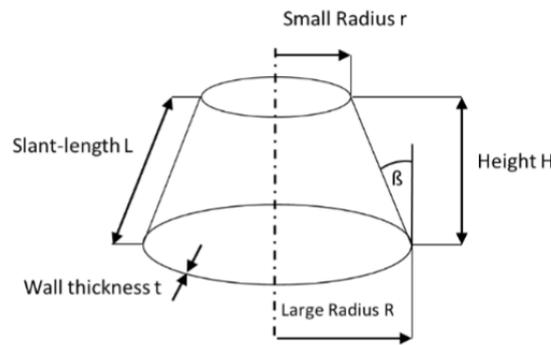


Figure 12: Schematic of truncated cone with important dimensional parameters.

As information on knockdown factor (KDF) for thrust frames is largely lacking in open literature, we will use<sup>10</sup>:

	$KDF = 0.65$	(6)
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For the approach chosen in this work, where we essentially neglect the loading resulting from thrust vector control and still other axial loads, we will design for a critical load that is only 80% of the critical load that can be withstood by the shell structure of the frame:

	$\frac{P}{P_{cr}} \leq 0.7$	(7)
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It is of course an assumption that this will be sufficient to account for the effects of an eventual bending of the structure. Later we will show that for a first approach this is reasonably realistic.

Once the thickness of the shell is known, the mass of the cone/cylinder is determined using:

<sup>8</sup> In practice, the thrust frame must also deal with other axial loads as well as lateral loads and/or external moments. These lateral forces and external moments do introduce bending moments in the frame that should be accounted for.

<sup>9</sup> A similar approach can be followed for truss frames. However, for the sake of this study this is not considered here.

<sup>10</sup> Typical values for the knockdown (KDF) are given in [SP8007] for cylinders and [SP8019] for truncated cones. Minimum (safe) value for a purely axially loaded cylinders/cones is 0.33. However, in for instance, [SP8007], [SP8019], [Seide] and [Wagner] experimental data is provided showing that values of KDF for **aerospace quality structures** rarely go below 0.65.

	$M_{TF} = \rho_{mat} \times K_{cal} \times S_{TF} \times t_{cr}$	(8)
--	--	-----

Here  $\rho_{mat}$  is the mass density of the material,  $K_{cal}$  is a correction (calibration) factor for neglecting the presence of end rings, that allow for attaching to the stage body and or protect the thin shell, and the crossbeams that allow for mounting the engines onto the cylindrical or truncated cone shell frame. Additionally, it also corrects for neglecting cut-outs, like doors, present in the frame for accessibility, which require local strengthening of the structure as well as the presence of fins and engine fairings (as in the case of Saturn V and Saturn C-3B first stage).

### 3.2.2. Example case

To illustrate the method, we will work out an example case for the Ariane 5G EPC thrust frame. Engine thrust and mass are given in Table 10. Frame dimensions and in-flight acceleration levels are taken from Table 6. Additionally, we use Al7075 T6 as the frame material. The main dimensioning load is maximum engine thrust, which was earlier mentioned to be 1140 kN. To this we add a design load factor of 1.1 and a factor of safety on buckling of 1.25. The latter agrees with as specified in [ECSS]. An overview of material properties, and factors used is provided in Table 10. A schematic of the load case is given in Figure 13.

Table 10: Material characteristics, DLF, KDF and FoS used as input for detailed mass estimation of A5 EPC thrust frame.

Characteristic	Value	Remark
Structural material	Al7075 T6	Assumption
Material properties		
Young's modulus	71.7 GPa	Typical material properties for Al 7075-T6.
Poisson's ratio	0.33	
Mass density	2810 kg/m <sup>3</sup>	
Maximum acceleration level	6g	
Knockdown factor (KDF or $\gamma$ )	0.65	
Design load factor (DLF)	1.1	Accounts for uncertainties in thrust level (and or engine mass).
Factor of safety (FoS) for buckling	1.25	Taken from [ECSS].

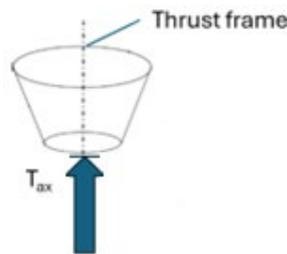


Figure 13: Conical thrust frame with engine thrust load.

It follows for the design thrust load:

$$P_{design,T} = DLF \times T_{ax} = 1.1 \times 1140 \text{ kN} = 1254 \text{ kN}$$

Applying the given factor of safety leads to the dimensioning load for buckling. We obtain:

$$P_{buckling} = FoS \times P_{design,T} = 1.25 \times 1254 \text{ kN} = 1567.5 \text{ kN}$$

To account for a bending moment due to for instance, lateral engine thrust from TVC and/or lateral loads from engine inertia (due to dynamic accelerations in lateral direction), we obtain an ultimate buckling load to be designed for:

$$P_{ult} = \frac{1}{0.7} \times P_{buckling} = \frac{1}{0.7} \times 1567.5 \text{ kN} = 2239 \text{ kN}$$

Using relation (5) It follows for the critical shell thickness:

$$t_{estimate} = \left( \frac{2239E3 \text{ N}}{2\pi \times 71.7E9 \text{ Pa}} \times \frac{\sqrt{3(1 - 0.33^2)}}{0.65 \times (\cos(0.478 \text{ rad}))^2} \right)^{0.5} = 3.98 \text{ mm}$$

Here the cone half angle  $\alpha$  of  $\sim 0.478 \text{ rad}$  ( $\sim 27.4^\circ$ ) has been determined using information on the geometry of the Ariane 5 EPC thrust frame, given in Table 7.

With the thickness known, we can now estimate the mass using relation (8), but first we determine the lateral surface area of the cone using information on the geometry of the Ariane 5 EPC thrust frame. see Table 7. It follows a surface area of  $43.8 \text{ m}^2$  ( $= \pi * (R + r) * S_{cone}$ , where  $S_{cone}$  refers to slant height of truncated cone).

This gives for the mass of the conical thrust frame (using a calibration factor equal to 1):

$$M_{TF} = 2810 \frac{\text{kg}}{\text{m}^3} \times 1 \times 43.8 \text{ m}^2 \times 3.98E - 3 \text{ m} = 490 \text{ kg}^{11}$$

### 3.2.3. Results overview (all conical/cylindrical frames, no calibration applied)

Using the same procedure, thickness values and associated mass values were computed for all other thrust frames. For all frames, Al 7075 T6 was selected as structural material except for the Titan III, S-II stage for which steel was selected with a Young's modulus of 196 GPa and a Poisson ratio of 0.28. Furthermore, for the cylindrical thrust frames a KDF of 0.75 was selected instead of 0.65. This was based on that cylindrical frames tend to have on average a higher KDF. Results are provided in next table.

Table 11: Comparison of thrust frame estimated mass and true mass (no calibration included)

#	Rocket	Frame type	$t_{estimate}$ [m]	$M_{estimate}$ [kg]	$M_{true}$ [kg]	$M_{true}/M_{estimate}$
1	Space Shuttle Orbiter	TRUSS				
2	Titan III, SI	TRUSS		Not applicable		
3	Martin Titan IV, SI	TRUSS				
4	Saturn V, S-IC	CYL	1.94E-02	10233	24000	2.35
5	Saturn C-3B, S-IC	CYL	1.57E-02	8245	14682	1.78
6	Ariane 5 ECB, ESC-B	CONE	2.01E-03	88	178	2.02
7	Saturn V, S-IVB	CONE	4.96E-03	258	231	0.90
8	Saturn V, S-II	CONE	9.77E-03	2385	2898	1.22
9	Titan III, SII	CONE	2.84E-03	35	111	3.17
10	Ariane 5ECA, EPC (H175)	CONE	4.57E-03	562	2030	3.61
11	Ariane 5G, EPC (H158)	CONE	3.98E-03	490	1754	3.58

Table provides calculated values for shell thickness ( $t_{estimate}$ ) and estimated mass for conical and cylindrical thrust frames ( $M_{estimate}$ ). Additionally, are shown true frame mass ( $M_{true}$ ) and the ratio between true and estimated mass ( $M_{true}/M_{estimate}$ ). Shell thickness is included as it allows for assessing if this thickness is sufficient to prevent failing due to yield load or ultimate load, see

<sup>11</sup> Small errors may result as of intermediate rounding.

for instance material presented in Annex A. Mass ratio is included as it allows for determining a calibration factor.

Results show different values for true to estimated mass ratio. This shows that a single calibration factor is not realistic. One result obtained for the Saturn V, SIVB thrust frame shows a true mass less than the theoretically estimated mass. Potential causes include, for instance, 1) the true KDF for this frame is larger than 0.65, 2) bending does not play as big a role for this frame as is assumed in the model, and 3) the frame is supported in part by the tank dome on which it is mounted, thereby reducing the effective length of the frame for buckling. Re-examining open literature did not confirm any of these cases, nor could any of them be excluded. So, further study is needed to get clarity.

For most frames except one, we find a true to estimated mass ratio larger than 1. This is expected as we have not included top and bottom end rings, nor did we consider the presence of crossbeams or spokes or the presence of cut-outs. Still, values in table are in range of slightly above 1 to almost a factor 4. Is this realistic. To answer this question, more detailed data is needed showing the shell mass of such structures in relation to overall thrust frame mass. Not a lot of data is found on this subject except for two cases. The first case is based on work reported in [Fatemi] where it is shown for a conical thrust frame that end rings can almost double (factor ~1.8) the mass of a conical frame, see Table 11. A second case is taken from the work reported in [Gómez-Molinero], where the Ariane 5G stage 1/2 interstage of diameter 5.4 m and height 2.9 m. was considered. [Gómez-Molinero] reported for this interstage a total cylinder mass of 921 kg with a shell mass of 576 kg. This shows a difference of a factor 1.6. For the cylindrical frames in our database, we also need to correct for the presence of engine fairings and fins. So, a value of up to 2 to and maybe slightly higher this seems reasonable.

#### 3.2.4. Calibrating the model

Based on the foregoing section, we selected the cases with numbers 4-8 for determining calibration factors, thereby making a distinction between the cylindrical frames and the truncated conical ones. The frames with numbers 9-11 were not considered because all three frames were considered to have either more complicated loading conditions and/or distinctive design features not yet considered in the theoretical model applied.

Following some trials, the following values were selected for the calibration factor:

	<ul style="list-style-type: none"> <li>- Truncated cone thrust frame: <math>K_{cal} = 1.4</math></li> <li>- Cylindrical thrust frame: <math>K_{cal} = 2.05</math></li> </ul>	(9)
--	--	-----

For the cylindrical frame, the value chosen is close to the arithmetic average. For the conical frame, the value is chosen slightly higher than the arithmetic average. This is not based on solid reasoning and hence this value is open for improvement. To this, I add that when trying to explain the difference between the A5 ESC-B thrust frame and the two other frames, it was found that the ESC-B frame is equipped with a true end ring at the base (next to the end ring at the top and the crossbeams), whereas for Saturn SIVB, such a clear end ring is absent as it interfaces with a tank bottom. For the Saturn SII stage, the pictures lacked clarity and hence no certainty could be obtained. Still, a likely cause for the difference between the ESC-B thrust frame and the other two then is that for the latter the end rings at the base are either absent or

are much less present than for the ESC-B stage for which the end ring is used to connect directly to the cylindrical tank.

### 3.2.5. Frame mass (with calibration factor included)

Using the above determined calibration values, the mass of the various frames was redetermined and compared with the true value in Figure 14.

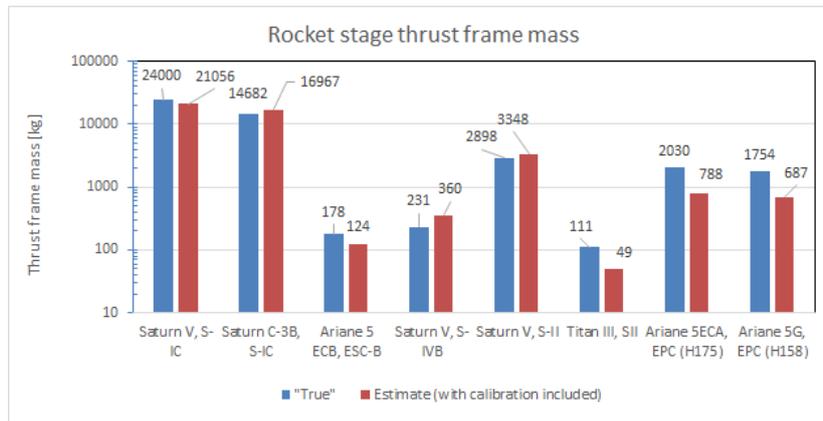


Figure 14: Mass estimation of rocket thrust frame using level 1 method (actual versus estimated value).

Results show an improved comparison for all (as expected) as compared to the uncalibrated results. Average error now is 55% with still large error contributions of the thrust frames of Titan III, S-II and Ariane 5 EPC (both versions). Both average and individual error percentages do not abide with the set goal for intermediate-level fidelity models of within  $\pm 15\text{--}25\%$ .

This still leaves us with no explanation of why the cases 9-11 are so much heavier. Hence, let us revisit these 3 cases. Potential avenues for explaining the relatively high calibration factors include, amongst others, a too low estimated KDF or safety factor and/or incorrect thrust frame dimensions or a more complex load case than what has been assumed for the simple load case as presented in this work.

For the Saturn III, S-II stage no clear cause could be identified. There may be an issue though related to the steel cone attached to the engine and whether this is included in the mass estimate or not. Theoretically, it was found that this steel conical part could add a shell mass of up to 10 kg. Adding end rings and gimbals an increase in mass up to 15 to 20 kg is considered reasonable. This would still leave about 40 kg on a total of 111 kg unaccounted for. Unfortunately, no confirmation on the above numbers could be obtained from a reliable resource.

For the two Ariane 5 EPC thrust frames, it is postulated that the high true to estimated mass ratio is potentially due to a vastly more complex load case to which the thrust frame is subjected as the frame also needs to cope with the lateral loads exerted by the two SRBs<sup>12</sup>. For instance, when considering the thrust frame as shown in Figure 5, we see, apart from the end rings, an additional three rings that support the shell structure. If end rings increase the frame

<sup>12</sup> In [Brooker], it says that for thrust frame structure verification Vulcain 2 thrust is taken as 1500 kN, with lateral loads reaching 181 kN and servo-actuator loads  $\pm 226$  kN. The SRB strut loads range from 498 kN in tension and 348 kN in compression. LBS disconnection force at lift-off reaches 221 kN and highest fuel line force is 105 kN, next to several smaller loads.

mass with about a factor 2 as compared to shell mass, and the three additional rings also add a mass 2 times the shell mass, this brings the total frame mass to 1200 to 1500 kg. Unfortunately, more substantiation or proof for probable causes could again not be found. Still, it is an avenue that can be explored in future studies.

### 3.2.6. Ability to withstand yield and ultimate load.

In the foregoing sections related to the intermediate level model, we have estimated frame mass based on the thickness of a cylindrical/conical shell of uniform thickness based on a simplified load where buckling load is taken as the main dimensioning load.

However, we should also check if the shell does not fail as of yield and ultimate load. This has been checked for all cases, and it was found that for all cases considered the required thickness to cope with yield and ultimate load is much lower than the required thickness to resist buckling.

As an example, this checking has been worked out for the thrust frame of the Ariane 5 ESC-B stage in Appendix A. It showed a required thickness of well below 1 mm, whereas the required thickness for buckling is around 1.6 mm.

### 3.2.7. Effect of bending load

Next to thrust load in axial direction, thrust frames also do experience various other loads that can affect the shell thickness. Such loads include:

- **Axial loads from engine inertia.** As the engine is hanging on the frame, engine inertia (and thrust frame inertia) loads will cause a reduction in the compression load experienced by the thrust frame shell and hence result in a reduction of the shell thickness.
- **Lateral loads from TVC and/or engine inertia.** For rocket engines that allow for thrust vector control, one must reckon with a lateral thrust force. Likewise, for an engine of some mass hanging on a thrust frame which experiences lateral dynamic accelerations, one must reckon with lateral loads due to engine inertia. These lateral loads can cause a thrust frame to deflect (bend) and induce both shear forces and bending moments. Both need to be accounted for and may increase the required thickness of the thrust frame shell.

In the simple model presented in section 3.2, axial loads from engine- and thrust frame inertia as well as transversal loads have been considered negligible. To demonstrate the validity of this assumption Appendix B provides a more detailed work out of the example case used in the foregoing. Next table compares the estimated results obtained earlier and the results from appendix B.

	This section	Appendix B
Shell thickness	3.98 mm	4.05 mm
Shell mass	490 kg	498 kg
$P/P_{cr}$ [-]	0.70	0.67

It shows that the two are quite comparable, be it that the thickness (and hence the shell mass) resulting from appendix B is slightly higher. This is attributed to that the applied load to critical load ratio is slightly lower when considering the bending moment properly. For the

work at hand, the difference is considered sufficiently small. It is left to the reader if he/she wants to also check the other cases.

### 3.3. Results overview and discussion

Estimation results for rocket thrust frames have been produced using models that represent two different fidelity levels (low and intermediate), which are thought to fit conceptual and preliminary design purposes. Next table provides an overview of the results obtained.

Table 12: Overview of estimation errors for different thrust frame mass estimation methods

Level	Method	Average error (incl. truss)	Average error (excl. truss)	Max absolute error
Low	Herbertz	-50%	-64%	89%
	Akin	-32%	-49%	83%
	Brothers	+31%	- 4%	183%
	This work	+29%	+37%	215%
Intermediate	This work	NA	-1%	158%

All low-level estimation results show an average error percentage outside the error range ( $\pm 30\text{--}50\%$ ) considered acceptable for such methods. This shows that all methods are open for improving upon. A similar result is obtained when excluding the truss-based frames. Results also show that the three truss-based frames are reasonably well predicted. The intermediate model has a low average error, but the max absolute error is still quite high. Furthermore, the low average mean error only holds for applying the method to the five thrust frames used in the calibration. When extending the method to also include the three thrust frames left out of the calibration, the mean percentage error increases to  $+55\%$ , meaning that the model results on average tend to be too low.

To obtain improvements for these methods, the most important option identified is:

To develop relationships that allow for a more detailed distinction in the type of thrust frames considered, like cylindrical thrust frames with and without engine fairings, and/or aerodynamic fins, conical frames with and without end rings and frames with and without launch pad attachments.

Next to this, a main drive should be to get more exact data. As of limited data availability, data used as input has been estimated with likely some inaccuracies. This effect should not be disregarded. Given the amount of data uncovered thus far, it is considered very doubtful, whether sufficient detailed data of proper quality can be uncovered so that meaningful statistical analysis can be performed.

The in this work developed intermediate-level model does allow for investigating more factors than accounted for in the low-level models, like effect of acceleration loads<sup>13</sup>, dissimilar materials, effect of bending, effect of KDF, effect of safety factors. Still, it does not yet allow for improved estimates as compared to the low-level models nor is the accuracy attained in the

<sup>13</sup> From the current model and especially the determination of the most important design loads, it is inferred that acceleration effects are much more limited than suggested in the low-level model reported by [Castellini], see also the discussion linked to this model expression elsewhere in text of this document.

range ( $\pm 15\text{--}25\%$ ) fit for trade studies, concept down selection, and budgeting mass margins. For model improvement, the following steps are considered essential:

1. Get more accurate information on the actual design loads. In this work the design load resulting from engine thrust has been based on nominal engine thrust found in literature. It cannot be excluded that some engines can produce higher thrust levels than here used. Also, the thrust frames may have been designed with some margin for (future) growth or with higher safety factors in mind. In the current design method, a factor of safety on buckling have been design with a FoS of 1.25.
2. Same goes for the geometry of the frames investigated. Some dimensions have been estimated made by scaling them using photos or sketches of the objects considered. Some uncertainty exists when using sketches is if these are to scale. Secondly, it the right dimensions are selected. For instance, when using the schematic of the thrust frame, it is a challenge to exactly determine in the figure where the engine attaches. In this work all estimations have been performed with limited means and hence may have led to some errors.
3. A particularly important improvement is the inclusion of the design of the end rings as well as the crossbeams and the actual engine attachment points. It should also be considered to include SRB attachment points and launch pad attachments as these also are expected to have a large mass effect. By extending the model to also consider these aspects, it will at least allow for updating (decreasing) the calibration factor, but more importantly lead to a more versatile method.
4. Development of a database including more thrust frames than currently considered but also providing more detailed information for model validation purposes. The need for the intermediate model in this respect is much more extensive that for the lower-level models.

## 4. Closure

In this work an overview has been made of existing rocket thrust frames with as purpose to support mass estimation for the early design phases. For the work, only data obtained from public sources was available. Although the data found was limited, it showed that distinct types of frames exist with sometimes quite different load cases and additional functionalities for these frames that affect the design. For instance, some frames also serve as an aerodynamic shell or harbour pad- and/or SRB-attachments.

In this work, also various low-level methods for mass estimation of these thrust frames have been investigated including a new one that is purely based on the data collected in this work. Results for these models do not adhere to requirements related to performing early conceptual design studies. Still, they will allow for use as a level 0 model, allowing for rough order of magnitude (ROM) estimation.

Foundations have been laid down for the development of an intermediate-level mass estimation method for cylindrical or conical type of thrust frames. Results show reasonable agreement, but not within the range required for an intermediate level method. Areas for improvement though have been identified in the work and the author is confident that this will bring the model closer to a true intermediate level model.

It is also advised to develop an intermediate level model for truss-based thrust frames. These are quite different from the cylindrical and conical frames we focussed on. When developing

such a model, it is also advised to consider the necessary support attachments on the stage side as it is expected these will add considerable mass probably offsetting part of the gain in mass for the thrust frame itself. Also important is to consider that the truss frame is not aerodynamically clear which may require the addition of an aerodynamic shell, which also adds mass to the vehicle.

All in all, the author feels confident that the foundational work reported in this document allows for selecting a more proper mass margin for the thrust frame. In addition, the work forms a good starting point for further improvement.

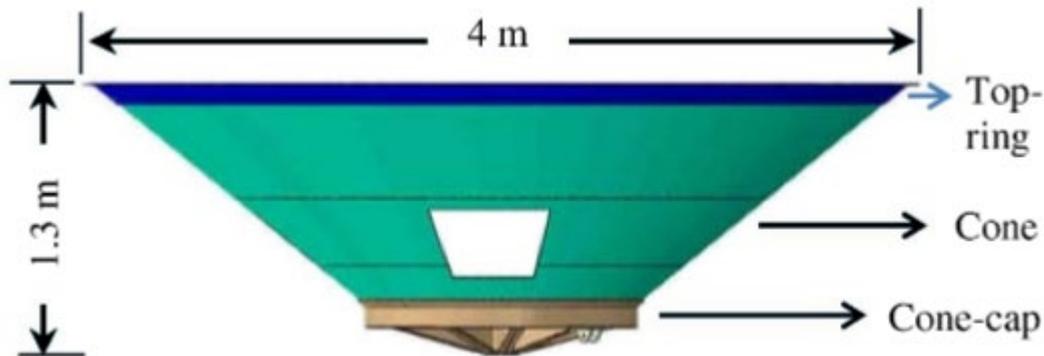
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## Appendix A: Checking for yield and ultimate strength.

In this section, we will demonstrate how to design a truncated conical structure for its ability to withstand yield and ultimate load. A schematic of this frame is given in:



The loads on the frame stem from thrust generation, TVC, engine mass and acceleration loads. For the case at hand, we consider a single engine attached to the frame at the cone-cap. The mass of the engine is 600 kg and engine height 3 m. We furthermore use a maximum thrust load of 180 kN (along the axis of the cone) and a max TVC angle of 5 degrees. This 5° TVC angle leads to a maximum thrust force in lateral direction of ~22 kN. Additionally, it is assumed an axial acceleration of 6g and a maximum lateral acceleration of 2g. As cone material, we use Aluminium alloy Al7075 T6 with a yield strength of 503 MPa and an ultimate tensile strength of 572 MPa. Furthermore, we use a safety factor of 1.25 on yield and 1.5 on ultimate strength.

Below we will determine in 3 main steps if a wall thickness of 1 mm is sufficient to prevent failing from yield or ultimate load.

### 1) Determine Loads

The cone sees an axial load from the thrust force generated and the inertia force from the engine being accelerated, a transversal force at the top of the cone as from TVC, and a bending moment resulting from engine inertia from transversal accelerations and from the transversal thrust force which increases when moving towards the base of the cone.

#### Axial load:

a) From engine thrust:

$$F_{a,T} = 180,000 \text{ N (for the case with no TVC).}$$

b) From engine inertia:

$$F_{a,e} = M_e \cdot a_{axial} = 600\text{kg} \cdot 9.81 \frac{\text{m}}{\text{s}^2} = 5,886 \text{ N}$$

c) Total axial load:

$$F_{tot,axial} = F_{a,T} - F_{a,e} = 180,000 - 5,886 = 174,114 \text{ N}$$

#### Lateral load:

a) From engine TVC thrust at maximum deflection angle of  $\theta=5^\circ$ :

$$F_{lat,TVC} = T \cdot \sin \theta = 180,000 \text{ N} \cdot \sin(5^\circ) \approx 180,000 \text{ N} \cdot 0.0872 = 15,696 \text{ N}$$

b) From engine inertia is:

$$F_{lat,e} = M_e \cdot a_{lat} = 600 \text{ kg} \cdot 2 \cdot 9.81 \frac{\text{m}}{\text{s}^2} = 11,772 \text{ N}$$

c) Total lateral load:

$$F_{lat,tot} = F_{lat,TVC} + F_{lat,e} = 15,696 + 11,772 = 27,468 \text{ N}$$

### Bending Moment

a) From lateral inertia:

$$M_{inertia} = 11,772 \text{ N} \cdot 1.5 \text{ m} = 17,658 \text{ Nm}$$

b) From TVC thrust:

Lateral thrust is applied directly at the attachment. We neglect forces related to actuators holding the engine. Essentially the bending moment would be zero at the top, but we need to consider that this will induce a bending moment when moving towards the base of the cone. For now, we select as moment arm half the height of the cone. This gives:

$$M_{TVC} = F_{lat,TVC} \times 0.5 \times H_{cone} = 15,696 \text{ N} \times 0.5 \times 1.3 \text{ m} = 10,202 \text{ Nm}$$

c) Total Bending Moment:

$$M = M_{inertia} + M_{TVC} = 17,658 + 10,202 = 27,860 \text{ Nm}$$

## 2) Stress Limits

In this step, we determine the maximum allowable stress in the cone.

For Yield:  $\sigma_{allow,yield} = \frac{\sigma_y}{SF} = \frac{503}{1.25} = 402 \text{ MPa}$

For Ultimate:  $\sigma_{allow,ult} = \frac{\sigma_u}{SF} = \frac{572}{1.5} = 381 \text{ MPa}$

Clearly for the case at hand, the ultimate stress is the critical one.

## 3) Stress Calculations

We assume we are dealing with a thin-walled conical shell with a uniform wall thickness  $t$ , which will allow us to apply **membrane theory** to get axial and bending stresses. We will also approximate the cone as a cylinder with an average radius as determined from the top and base radii, given by  $R_{av} = \frac{R+r}{2}$ .

a) Axial Stress

The axial force is spread over the **conical shell** area. From membrane theory it follows for the membrane stress in the cone:

$$\sigma_{axial} = \frac{F_{axial}}{A_{axial}} = \frac{F_{axial}}{2\pi \times \frac{(R+r)}{2} \times t}$$

b) Bending stress

We assume a circular ring at top of cone, and that the moment is resisted by the circular shell section. In that case bending stress in the cylindrical shell is given by:

$$\sigma_{bending} = \frac{M \times R_{av}}{I}$$

Where M is bending moment,  $R_{av}$  is average radius of cone, and I is area moment of inertia of the cross section given by (for a thin-walled circular shell):  $I = \pi \times R_{av}^3 \times t$ . It follows:

$$\sigma_{bending} = \frac{M}{\pi \times R_{av}^2 \times t}$$

c) Thickness of the shell

In this step, we determine the critical thickness by finding the minimum thickness required to satisfy ultimate load while using the total axial and bending loads as calculated earlier<sup>14</sup>. We can do this in an iterative way where we pick a value of t and check if the sum of the axial and bending stress is below the allowed ultimate stress level.

For this section, we pick a value of just 1 mm, and we will check if this is sufficient to withstand yield and ultimate load. Results are provided in next table.

Table A-1: Results from strength calculations

Parameter	Value and unit used
Total axial load	175114 N
Total bending moment	27860 Nm
Average cone radius	2.9375 m
Shell thickness	1 mm
Mean cone cross sectional area	1.846E-2 m <sup>2</sup>
Mean cone area moment of inertia	7.963E-2 m <sup>4</sup>
Max allowable stress	381 MPa
Axial stress (wall thickness of 1 mm)	9.43 MPa
Bending stress (wall thickness of 1 mm)	1.03 MPa
Total stress (sum of axial and bending stress)	10.46 MPa

When comparing the total calculated stress (10.46 MPa) with the maximum allowable stress (381 MPa), yield and ultimate strength are not an issue for this structure. Even when applying a design limit load factor of 1.1, the resulting stress is still about a factor 33 (= 381 MPa / (10.46 MPa \* 1.1)) below the maximum allowable stress.

<sup>14</sup> In principle, we also need to check if the transverse load itself can be carried, but we leave this for the reader to check for him/herself. It is considered that the stresses related to the transversal load are limited.

## Appendix B: Example combined bending and axial load.

To illustrate the method, we will work out an example case for the Ariane 5G EPC thrust frame. Engine thrust and mass are 1140 kN and 1686 kg. Frame dimensions and in-flight acceleration levels are taken from Table 6. Additionally, we use Al7075 T6 as the frame material. We also use a design load factor of 1.1, a factor of safety for buckling of 1.25 and a knock down factor (KDF) for the truncated conical frame of 0.65. An overview of material properties, and factors used is provided in Table B-1. A schematic of the load case is given in Figure B-1.

Table B-1: Material characteristics, DLF, KDF and FoS used as input for detailed mass estimation of A5 EPC thrust frame.

Characteristic	Value	Remark
Engine nominal thrust	1140 kN	
Engine mass	1686 kg	
Engine height	3.10 m	
Thrust frame dimensions:		
Height	3.4 m	
Base diameter	5.4 m	
Diameter at top	1.875 m	
Cone half angle	0.478 rad (27.4°)	
Lateral surface area of cone	43.8 m <sup>2</sup>	
Maximum TVC angle	5 deg	Assumption
Structural material	Al7075 T6	Assumption
Material properties		Typical material properties for Al 7075-T6.
Young's modulus	71.7 GPa	
Poisson's ratio	0.33	
Mass density	2810 kg/m <sup>3</sup>	
Largest axial acceleration level	6g	[LVC]
Maximum lateral acceleration level	2g	Worst conditions taken
Design load factor (DLF)	1.1	Accounts for uncertainties in thrust level (and or engine mass).
Knockdown factor (KDF or $\gamma$ )	0.65	
Factor of safety (FoS) for buckling	1.25	Taken from [ECSS (b)].

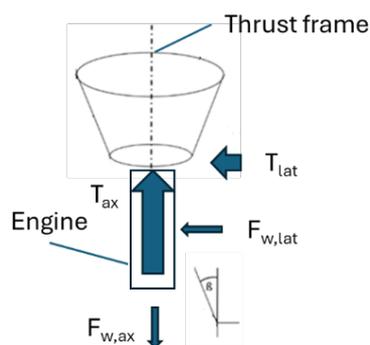


Figure B-1: Engine thrust loads and inertia loads (lateral engine inertia load is located through engine CoM).

Engine weight tends to be much smaller than thrust force. Hence the much smaller arrows used in the figure. From figure, we also see lateral loads on the frame from engine inertia and thrust vector control. As a result, the frame will also experience external moments leading to a bending of the frame.

In this section, we will consider this combination of axial load and bending in more detail. To do so, we use theory presented in [SP-8919] for buckling of an isotropic truncated conical shell of uniform thickness.

### 1. Method used.

In the approach followed, we select a frame thickness and check if the critical axial load and critical bending moment are not surpassed for the given load case. The basic relations for the critical buckling load and bending moment are taken from [SP8019] and are valid for both conical and cylindrical shells of uniform thickness:

	$P_{cr} = 2\pi Et^2 \left( \frac{\gamma}{\sqrt{3(1 - \nu^2)}} \right) \times \cos^2 \alpha$	(B-1)
	$M_{cr} = 2\pi r Et^2 \left( \frac{\gamma}{\sqrt{3(1 - \nu^2)}} \right) \times \cos^2 \alpha$	(B-2)

Here E is Young's modulus, t is shell thickness,  $\gamma$  is knock down factor (or KDF),  $\nu$  is Poisson's ratio, and  $\alpha$  is cone half angle (zero for a cylindrical structure), and r is radius of the truncated cone top.

As we have combined loading (from axial thrust load) and bending loads, we need to adapt the thickness until the following criterium is met [SP8019]:

	$\frac{P}{P_{cr}} + \frac{M}{M_{cr}} \leq 1$	(B-3)
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### 2. Load calculation

The thrust cone must withstand an axial load from the thrust force generated by the engine as well as the inertia force related to the mass of the engine. Additionally, the thrust cone also must withstand a lateral force at the top of the cone resulting from TVC and from engine inertia (from lateral accelerations), and a bending moment resulting from engine inertia and from the lateral (or transversal) thrust force. In this section, we determine the ultimate loads for which the thrust frame should be designed. For this, we need insight in the flight limit loads.

#### Flight limit load in axial direction

a) From engine thrust:

$$F_{a,T} = 1140 \text{ kN (for the case with no TVC).}$$

b) From engine inertia:

$$F_{a,e} = M_e \cdot a_{axial} = 1686 \text{ kg} \cdot 58.86 \frac{\text{m}}{\text{s}^2} = 99 \text{ kN}$$

c) Total axial load<sup>15</sup>:

$$F_{\text{tot,axial}} = F_{a,T} - F_{a,e} = 1140 \text{ kN} - 99 \text{ kN} = 1043 \text{ kN}$$

Clearly can be seen that the engine weight reduces the total axial load on the frame. It becomes clear that the thrust phase at start of flight is most important as accelerations are lowest. This then would lead to a flight limit load in axial direction of:

$$F_{\text{lim,axial}} = \sim 1140 \text{ kN}$$

Here actually the weight of the engine should be subtracted but this for now we ignore as it is only a minor change.

#### Flight limit load in lateral direction

a) From engine TVC thrust at maximum deflection angle of  $\beta = 5^\circ$ :

$$F_{\text{lat,TVC}} = F_{a,T} \cdot \sin \theta = 1140 \text{ kN} \cdot \sin(5 \text{ deg}) \approx 1140 \text{ kN} \cdot 0.0872 = 99 \text{ kN}$$

b) From engine inertia is:

$$F_{\text{lat,e}} = M_e \cdot a_{\text{lat}} = 1686 \text{ kg} \cdot 2 \cdot 9.81 \frac{\text{m}}{\text{s}^2} = 33 \text{ kN}$$

c) Total lateral load:

$$F_{\text{lat,tot}} = F_{\text{lat,TVC}} + F_{\text{lat,e}} = 99 \text{ kN} + 33 \text{ kN} = 132 \text{ kN}$$

#### **Bending Moment**

a) From lateral inertia (using engine height is 3.1 m and assuming that centre of mass is in the middle of the engine):

$$M_{\text{inertia,top}} = 33 \text{ kN} \cdot 1.55 \text{ m} = 51 \text{ kNm}$$

$$M_{\text{inertia,base}} = 33 \text{ kN} \cdot (1.55 \text{ m} + 3.4 \text{ m}) = 163 \text{ kNm}$$

b) From TVC thrust:

Lateral thrust is applied directly at the attachment. We neglect forces related to actuators holding the engine. Essentially the bending moment would be zero at the top, but we need to consider that this will induce a bending moment when moving towards the base of the cone. For now, we select as moment arm half the height of the cone. This gives:

$$M_{\text{TVC,base}} = F_{\text{lat,TVC}} \times H_{\text{cone}} = 99 \text{ kN} \times 3.4 \text{ m} = 337 \text{ kNm}$$

c) Total Bending Moment:

$$M = M_{\text{inertia}} + M_{\text{TVC}} = 163 \text{ kNm} + 337 \text{ kNm} = 500 \text{ kNm}$$

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<sup>15</sup> Note that in our load estimations, we have neglected the axial load due to thrust frame inertia. We expect this mass to be lower than engine mass and hence for reasons of simplicity, we neglect this contribution in the current simplified approach.

From this limit loads, design limit loads and ultimate loads are determined using Design load factor and Factor of Safety. Applying the given factor of safety leads to the dimensioning loads for buckling. Values are summarized in next table.

Table B-2: Thrust frame design limit and ultimate loads.

Type	Design loads	Design limit loads	Ultimate loads
Axial	1140 kN	1254 kN	1568 kN
Bending moment	500 kNm	550 kNm	687 kNm

Lateral load is not included here as it is not directly important for buckling. It is important though for the total stress in the material and it is recommended to check if stresses do not exceed material limits.

### 3. Iterate for proper value of shell thickness.

In this step, we select a value for the thickness, calculate the critical axial load and the critical bending moment determine the ratio of the applied loads to the critical loads and check if relation (B-3) is fulfilled.

As a first guess we use a shell thickness of 3 mm. It follows using relations B-1 and (B-2):

$P_{cr} = 2\pi Et^2 \left( \frac{\gamma}{\sqrt{3(1 - \nu^2)}} \right) \times \cos^2 \alpha$ $P_{cr} = 2\pi(71.7E9 Pa)(3E - 3 m)^2 \left( \frac{0.65}{\sqrt{3(1 - 0.33^2)}} \right) \times \cos^2 0.478 rad = 1.27 MN$	(B-1)
$M_{cr} = 2\pi r Et^2 \left( \frac{\gamma}{\sqrt{3(1 - \nu^2)}} \right) \times \cos^2 \alpha$ $M_{cr} = P_{cr} \times r = 1191 kNm$	(B-2)

Comparing ultimate loads with the critical loads, we find that the condition (B-3) is not fulfilled. To this end, we increase the thickness of the shell. Until this condition is fulfilled. This process is shown in next table.

Table B-3: Effect of shell thickness on buckling stability.

Shell thickness (t) [mm]	P <sub>cr</sub> [kN]	M <sub>cr</sub> [kNm]	P/P <sub>cr</sub> [-]	M/M <sub>cr</sub> [-]	P/P <sub>cr</sub> + M/M <sub>cr</sub> [-]
3	1270	1191	1568/1270 = 0.45	687/1191 = 0.57	> 1
3.73	1963	1841	0.8	0.4	> 1
4	2260	2118	0.7	0.32	> 1
4.05	2315	2170	0.678	0.317	0.995

It follows that to be safe for buckling, the thickness should be taken equal to 4.05 mm.

This gives for the mass of the conical thrust frame (using a calibration factor equal to 1):

$$M_{TF} = 2810 \frac{kg}{m^3} \times 1.4 \times 43.8m^2 \times 4.05E - 3 m = 498 kg$$