Image Credit: NASA

Overview of The Saturn IB

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3/22/21

AERO1560 Introduction to Aerospace Engineering

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LIST OF SYMBOLS

SYMBOL	DEFINITION	DIMENSION
C-IB	Saturn 1B	N/A
S-IB	First (lower) stage of the Saturn 1B	N/A
S-IVB	Second stage of the Saturn IB (third stage on Saturn V)	N/A
HLLV	Heavy-lift launch vehicle	N/A
LEO	Low Earth Orbit (less than 1000km)	N/A
CSM	Command Service Module	N/A
MF	Mass to fuel ratio	N/A
G	Acceleration of gravity at sea level: 9.8	ms^{-2}
Max-q	Maximum Dynamic Pressure from aerodynamic loads	kPa
LH_2	Liquid Hydrogen	N/A
LOX	Liquid Oxygen	N/A
RP-1	Rocket-Propellant 1 highly refined kerosene.	N/A
cg	Centre of gravity	N/A
cp	Centre of pressure	N/A
L	Lift	N
D	Drag	N

ABSTRACT

The report aims to provide an overview of the technical, operational and safety aspects of the space launch system Saturn IB while analysing the failures and successes of associated components. While not going into great mathematical/scientific detail, the scope extends to the structural design and construction, unique aerodynamic features, propulsion systems, operational requirements and the safety features and safety records.

INTRODUCTION

The accelerating development of launch-vehicle systems such as SpaceX's *Starship* and NASA's *Space Launch System* for the Artemis program sees to the aim of returning humans the Moon and venturing beyond to Mars. For the *Moon to Mars* space program to succeed, lessons on the technical, operational and safety aspects of past space programs must be taken into account and applied to new technology.

An upgraded version of the medium-lift Saturn I launch system, the heavy-lift Saturn IB incorporated many improvements paving the way for the super heavy-lift Saturn V which ferried the first humans to the Moon. Specifically built by NASA with the purpose to test the third stage (S-IVB) of the Saturn V in Low Eath Orbit, the Saturn IB was successful in placing S-IVB and the Apollo Service Module in suborbital space. NASA officials aimed to try out the transposition manoevre, docking of the command and service module, the lunar module and the translunar sequence of the S-IVB.

TECHNICAL ASPECTS

Structural Design and Construction

In this section the following characteristics of the Saturn IB are presented:

- Structural requirements under flight loads
- Materials used in construction to satisfy requirements
- Design and construction
- Techniques used in construction

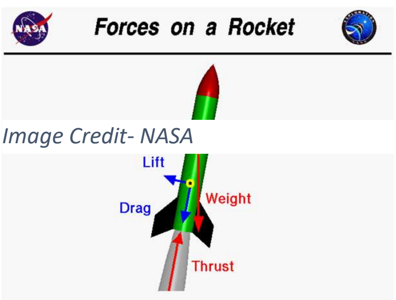


Image Credit- NASA

To meet the HLLV requirement, there was a need for compromise between lightweight materials to maximise payload to LEO while maintaining structural integrity when subjected to the forces associated with spaceflight as shown in the diagram below. The mass of C-1B (with CSM payload) was 610770kg[1] of which only 8.6% was structure consisting of fuel tanks, engines illustrating the need to save weight. A mass to fuel (MF) ratio value of 0.82 ranks the C-1B well to be a good compromise between payload capacity and range, close to the ideal value of 0.8[2]. Aerodynamic forces were a concern for engineers as the structural load is proportional to dynamic pressure. The maximum dynamic pressure (q) on C-1B was calculated to be 17 kPa when launched with Skylab. This in addition to compressive forces of gravity and the inertia of acceleration (thrust) which reached 4.35G required special construction design, techniques and materials. A NASA technical memorandum[3] detailing the results of wind tunnel tests of a 1.32% scale model of C-IB show the max-q to potentially reach 29 kPa outlined in figure 1 below.

Image Credit: Wikipedia Commons – Internal structure of the Space Shuttle.

The first stage S-IB consisted of a large central LOX tank surrounded by four fuel containers and four LOX containers. They are of the semi-monocoque construction type, incorporating circumferential rings at intervals and longitudinal stringers along the length of the containers while varying skin thickness at points of stress concentrations[4]. The strings and hoops resist compressive loading removing load on the skin while also breaking skin into smaller sections that are harder to buckle. The inherent cylindrical outer shell of a rocket behaves as a pressure vessel containing the pressurised propellants. Thereby the circumference increases creating a pressure-stabilisation effect by way of tensile stretching deformations that pre-empt gravitational and inertial loads[5]. Additionally while not shown above, slosh baffles were placed for slosh control in flight.

The overwhelming use of aluminium in C-IB was critical, specifically alloy 2219 was used for LOX and fuel tanks because of it’s variations in size, weldability and importantly resistance to stress corrosion. However the sheer scale of the operation required new techniques including:

- simultaneous age hardening and formation of aluminium alloy using special electric furnaces
- welding methods- welding tools travelled across tracks over components, temperature and humidity control to prevent defects, use of TIG processes
- development of a special “electromagnetic hammer” to remove distortions
- Preparation of cleaning vats for special cleaning processes due to volatility of LOX

The second stage S-IVB however did not use a skin and stringer design for the fuel tanks, nor did it use a monocoque design owing to weight and construction requirements. The design goal was extremely thin but rigid walls, which was achieved in the end using an integrally-stiffened shell by way of carving out ribs in a waffle-like pattern 75mm square. This increased the buckling strength of the tank walls[6]. Additionally the use of a hemispherical double-faced bulkhead between the LH_2 and LOX tanks reduced structural weight by up to 20%. The bulkhead was roughly 50mm thick, using 2014-T6 aluminium shells on both sides of a fibreglass honeycomb core.

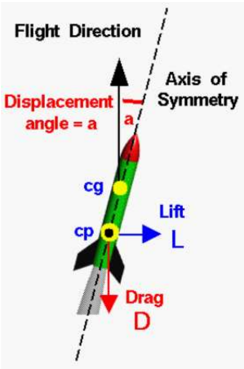
Unique Aerodynamic Features

In this section the following characteristics of the Saturn IB are presented:

- Special fins mounted at the base of the thrust structure
- Aerodynamic effect of engine fairings

In addition to aerodynamic stability when passing through max-q, the fins allowed extra time for astronauts to pull the abort handle in case one of the engines failed or gimaballed to an undesirable direction. The height of C1-B meant an enormous torque would be applied to the service module yanking an astronaut's hand away from the abort handle. The addition of fins provided a counter to the torque for long enough to let astronauts abort. Famous rocket scientist Werner Von Braun mentions "In Saturn 1B and V, the booster fins are not used to provide perfect aerodynamic stability under all conditions. It would take fins of excessive size. But the fins reduce the rocket's aerodynamic instability enough to make sure that the astronauts can safely abort, no matter what technical trouble may afflict their space vehicle"[7]. The fins were manufactured from titanium capable of withstanding the 1100°C from the engine exhaust. In addition Four conical engine fairings were used to smooth airflow at the base of the rocket protecting engines from aerodynamic loads.

Image Credit- NASA



The effect of these fins is illustrated by figure two, mapping the local pressure coefficient at each point along the rocket at high speeds. The increased pressure coefficient towards the tail end owing to the fins shifts the centre of pressure lower down, further away from the centre of gravity decreasing the tendency to tumble and wobble thereby increasing stability[8].

Given the centre of pressure (cp) is further down than the centre of gravity (cg), the diagram on the right illustrates why a rocket has positive static stability. The aerodynamic forces of lift and drag acting through the centre of pressure create a counter-clockwise torque back toward the flight direction. It should be noted however the engines could be gimaballed, negating the need for fins. However as outlined above, they serve a purpose in an emergency.

Propulsion System

In this section the following characteristics of the Saturn IB are presented:

- Engines
- Fuel
- Feed systems
- Fuel storage

The propulsion system on the C-IB consisted of two distinct stages, the S-IB first stage which propelled the rocket to an altitude of 60km at which point the second stage S-IVB would separate and propel the payload into orbit.

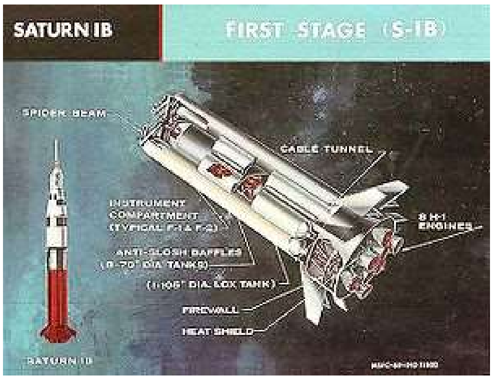


Image Credit- NASA

Considering the high ambient pressure (air density) detailed on figure 1, resulting in significant drag and the increased force of gravity at lower altitudes, a powerful first stage is required to overcome these forces. S-IB used eight Rocketdyne H-1 engines, a liquid fuel engine, burning liquid oxygen (LOX), the oxidiser, and Rocket-Propellant 1 (RP-1), the fuel, to produce a total of 7295 kN of thrust at sea level in it's final iteration. Of the eight H-1 engines, four were fixed inboard and four were outboard, mounted on gimbals which allowed for thrust vectoring[1].

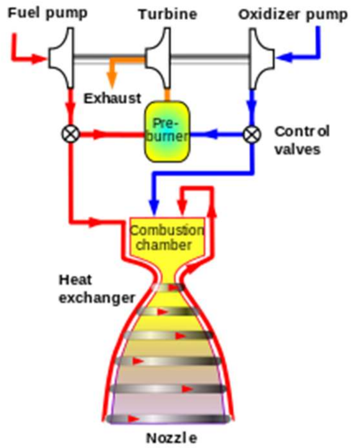


Image Credit- Wikipedia

Each engine was supplied LOX and RP-1 in the ratio 2.23, producing a specific impulse of 289 seconds. For clarification, specific impulse is the change in momentum per unit mass of a propellant and dictates how effective a propellant is in creating thrust. The S-IB engines burned for a duration of 155 seconds before jettisoning the first stage by means of four retro-rockets firing in the retrograde direction . The H-1 engines were of the gas generator cycle, detailed in the diagrams to the right. Simplified this means some propellant and oxidiser is diverted to the pre-burner (gas generator) which drives a gearbox with a single turbine that powers both pumps. The exhaust is discarded through a duct, the result of which is a lower specific impulse because of discarded propellant[9].

Inside the combustion chamber a 'waterfall injector', consisting of numerous small fuel injectors which sprayed RP-1 and LOX for ignition. While pumps were bringing main fuel lines to sufficient pressure, a complex system was used to start the turbopumps with a set of secondary fuel tanks and plumbing that led to the gas generator and the main combustors. Further, an elaborate set of electropneumatic valves controlled various fuel flows until the engine was started. Once started the fuel not diverted to the gas generator (vast majority) is used to regeneratively cool the combustion chamber and nozzle through thin tubing extending around the combustion chamber and nozzle, this tubing varies in cross section which varies coolant velocity to match the heat transfer rate at different points along the tube. This is illustrated in the coloured diagram above. In addition the bell-shaped nozzle as a pose to the standard conical allowed the reduction of weight, size and a 20% reduction in length with no reduction in performance[10].

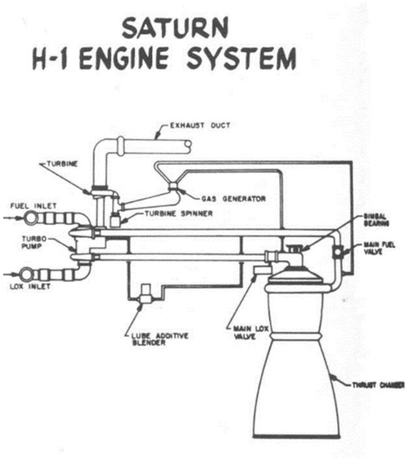


Image Credit- WikiWand

As a quick aside, it is worth discussing why liquid hydrogen (LH_2) was not used for the lower stage. Despite having a specific impulse 30-40% higher than RP-1, it has half the density leading to problems in tank weight and aerodynamic design.

This stage alone combusted 399400 kg of LOX and RP-1, held in the configuration detailed in the structural design and construction section of this report. These propellant (RP-1 fuel) tanks once filled were found to be susceptible to form strata of varying temperature and density. This was not ideal so a system was devised to agitate the fuel to prevent the formation of strata by continuously bubbling nitrogen gas through feed lines and fuel tanks prior to launch. Similarly helium was bubbled through LOX tanks to maintain circulation, keeping temperature stable at the pump inlets.

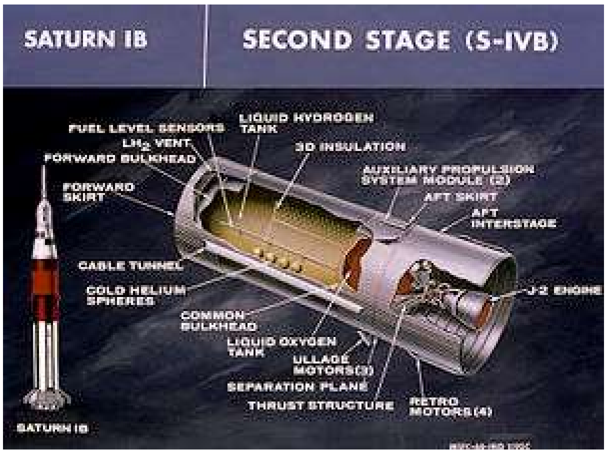


Image Credit- NASA

After separation the S-IVB second stage, powered by a single Rocketdyne J-2 engine using liquid hydrogen (LH_2), the fuel, and liquid oxygen (LOX), the oxidiser, is responsible for delivering the payload into orbit. However, immediately following the separation the rocket is in a momentary state of free fall. Since LH_2 tanks cannot be completely filled and pressurised due to temperature and pressure variations that can cause expansion and possibly explosion, there is considerable ullage space. Here arises a problem as the inertia of the propellants causes them to 'float' in free fall no longer in contact with feed pumps so the engine cannot be started. To alleviate this problem, ullage motors as illustrated on the diagram above to the left provided momentary thrust establishing contact between propellants and fuel-pumps to allow the main engine to ignite. The ullage motors were made of solid-fuel and hence were unaffected by ullage space or inertia[11].

The sole J-2 engine produced 1000 kN of thrust for a period of 420 seconds, performing a wide variety of roles depending on the mission objectives. It had a specific impulse of 424s, significantly higher than that of RP-1 when using a mixture ratio of 5.5 : 1. However the use of cryogenic propellants (LH_2 had to be stored at -253°C and LOX at -183°C) presented many technical challenges including-

- insulation from many sources of heat including exhaust, friction, radiant solar heat
- Provision of venting to allow heated hydrogen to escape, preventing explosion.
- Brittle nature of metals in contact with LH_2
- Leaking of LH_2 through miniscule pores in welded seams

Expanding on the common bulkhead mentioned in the structural features section of this report; this effectively serves as insulation to prevent heat transfer from the hotter LOX to cooler LH_2, which would have caused the LOX to freeze. It was engineered to cope with thermal stresses and a loss of pressure from either side. Within the LH_2 tank itself an internal insulation was required to prevent the boiling off of LH_2, this was done through the lining of the waffle-pattern tank walls with a matrix frame made of fibreglass threads cured inside of polyurethane foam creating a reinforced 'foam block', in a similar fashion to reinforced concrete. These tiles were then shaped to fit the unique shape of the waffle pattern and attached by an adhesive. Once the adhesive had set, a fiberglass cloth impregnated with resin was applied over the insulation tiles, sealing the wall.

OPERATIONAL ASPECTS

Operational Requirements

In this section the following characteristics of the Saturn IB are presented:

- Vehicle Assmebly Buildings
- Launch complexes
- Fuelling procedure
- Pressurisation of Fuel

The two stages of the C1-B were constructed separately, S-IB was made by the Chrysler Space Division at the Michoud Assembly Facility in New Orleans while the S-IVB stage made by the Douglas Aircraft Company, had a new Vechicle Assembly and Checkout building constructed at Huntington Beach, California. This building had mutiple vertical assembly towers where tanks, skirts, and thrust structures assembled at Huntington Beach would be mated with tank domes built at Santa Monica[12]. To supplement this facility another vehicle assembly and checkout builidng was built in Sacramento where stages would be painted and shipped by barge to a new testing facility at Marshall Space Flight Centre, Saturn Propulsion and Structural Test Facility, Huntsville Alabama. The S-IB underwent pre-static firing checkout at Michoud before shipping to MSFC test facilities detailed above where it performed successfully. It was then shipped back to Michoud for post-static checkout and evaluation. This was then shipped to Kennedy Space Centre for launch. The S-IVB stage however was static fired at the Sacramento Test Facility, passing successfully as well and eventually shipped to Kennedy Space Centre. Each mission flown by the Saturn IB required these tests before acceptance by NASA.

Image Credit- NASA

At Kennedy Space Centre the S-IVB was mated to the S-IB on Launch Complex 34, this was done by means of a large gantry crane shown in the image on the right. Once complete, vehicle checkout of the Saturn IB facilities commenced where propellant tanks to test LOX, LH_2 and RP-1 loading systems. For the S-IB, RP-1 fuel lines were connected to special fill/drain points to fill up tanks at 7300 litres per minute, with the requirement to 'agitate' fuel provided as described previously, by a ground source of nitrogen. To allow proper ignition and operation at start, an external source of helium provided pressurisation to the fuel tanks on the ground. LOX tanks however had a special procedure involving a slow fill rate of 5500 litres per minute to cool the insides of the tank, followed by a rate of 36000 litres per minute. This was 'agitated' by means of bubbling up helium from external source on the ground[10]. For the S-IVB, a more complex fuel loading process was required involving first a purge and pre-chill cycle. After which four phases involving a slow fill at 1800L/min to 5% capacity, followed by a fast fill at 3600L/min to 98% capacity, then at 0-110L/min to 100% and replenished at that same rate to account for boil off until launch. This was done to account for the interaction of cryogenic propellants with tanks, feed lines and other equipment. This process was used for both LOX and LH_2 fuelling and disconnected automatically at launch. Both fuel and oxidiser tanks were pressurised by external helium sources while on the ground.

SAFETY ASPECTS

Safety Features and Safety Record

In this section the following characteristics of the Saturn IB are presented:

- Safety records of launches
- Use of automated testing measures
- Other safety features

The Saturn IB launch system (specifically the S-IVB and S-IB propulsion stages) maintained a perfect record, however the tragic incident of Apollo 1 wherein astronauts Gus Grissom, Ed White, and Roger B. Chaffee perished when an electric fire broke out in the command module leading to major redesigns in cabin pressure and the use of non-flammable materials. The perfect record is a result of the advanced stringent automated checkout procedures, eliminating the need for checkout to be done manually. These were quite primitive in comparison with today's computers however at the time revolutionised processes, allowing greater confidence in the rockets since they were so complex manual procedures would not suffice. These computers also allowed engineers in firing rooms and test facilities to access automated test data and telemetry in real-time launches to monitor vital parameters and pinpoint the cause of a fault. At the time computers were new technology, rocket technology preceding them was fraught with guess work whenever faults occurred as the end result was usually an explosion, obliterating all evidence.

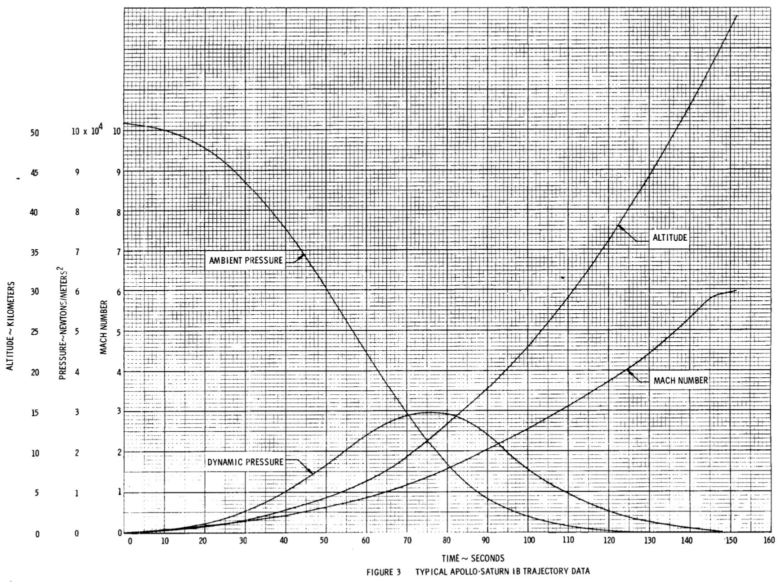
A key safety feature on the C-IB was the range safety system providing for situations where the rocket may malfunction posing a threat to people or property. When activated by ground command via radio, thrust would be terminated a self-destruction sequence would follow. Once safely in orbit the system was permanently disabled.

CONCLUSION

From the discussion and analysis of the technical, operational and safety aspects of the successful Saturn IB space launch system, important considerations concerning future developments of launch systems can be taken away. Given the valuable data collected on the aerodynamics, propulsion and structural aspects of Saturn 1B, trends and observations can be applied and extrapolated to the benefit of upcoming advanced space launch systems.

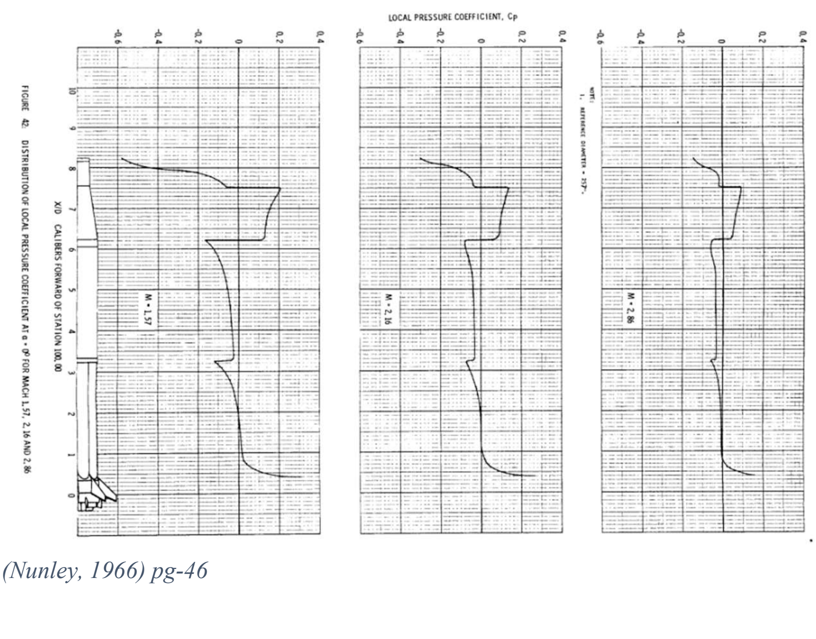
APPENDIX

Figure 1- Typical Apollo-Saturn IB Trajectory Data



(Nunley, 1966) pg-7

Figure 2- Distribution of Local Pressure Coefficient at angle of attack 0° for Mach 1.57, 2.16 and 2.86



N.B. Cp at lower speeds is available in from preceding pages in source.

(Nunley, 1966) pg-46

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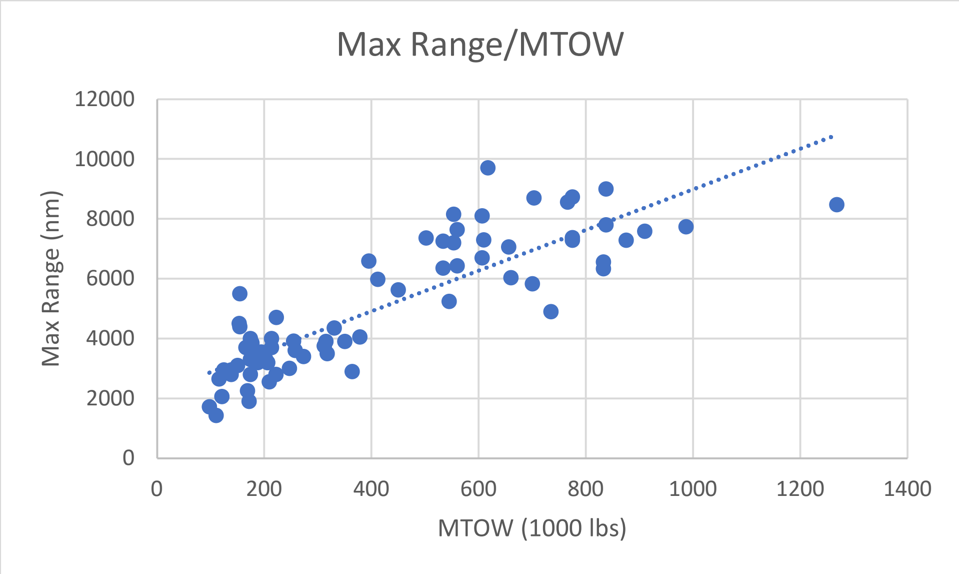
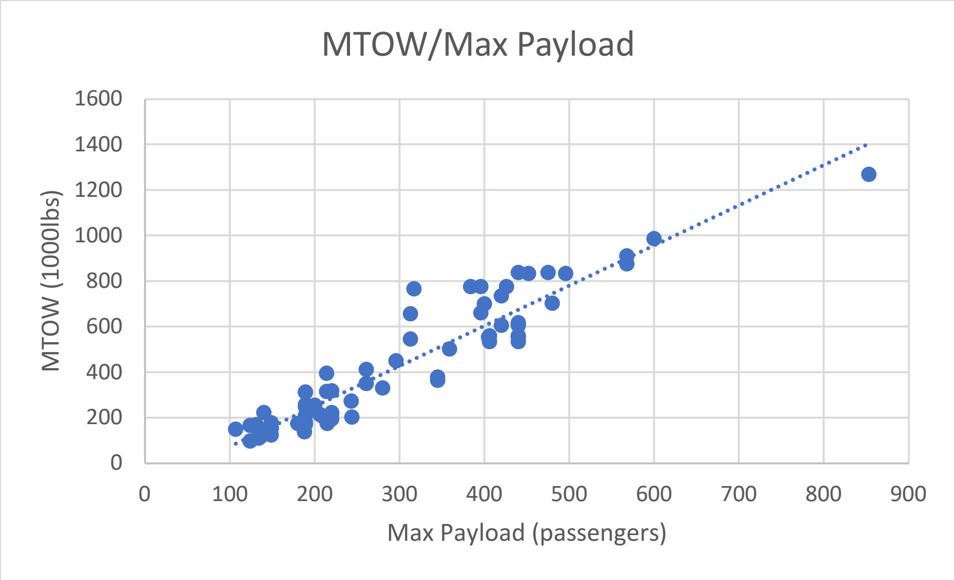
PART 2

ANALYSIS



The scatter-plot above shows the relationship between maximum-range versus maximum takeoff weight in nautical miles and pounds respectively. The bivariate data shows a relatively strong correlation below MTOW = 400 as the aircraft are closely bunched however diverges as MTOW increases. Using the CORREL function in excel the correlation coefficient was found to be 0.86 as plots were close to the least squares regression line indicating a strong relationship. However, the is some divergence past MTOW = 400.This is likely due to the older, heavy lift aircraft including the 747-100 and the inclusion of some short-range variants of some aircraft. Otherwise there is a fairly linear relationship with the notable exception of the Airbus A380 which sits far below the line. From the data it is observed the A380's MTOW of 1268 is significantly higher than others in this graph and the corresponding range is far below the least squares regression line, described by Max range = MTOW * 6.7904 + 2200.8. This creates a problem when extrapolating data because it is not known whether the extra MTOW weight is a result of a large plane with more passengers which negatively affects range or extra fuel on board which increases range.



This scatterplot shows the relationship between MTOW and Max payload of passengers. The bivariate data shows an almost perfect linear relationship as the plots closesly cluster around the least squares regression line. The coefficient was calculated to be 0.94, extremely close to a perfectly linear relationship of 1 suggesting the two variables MTOW and Max payload are definitely related. Hence this line can reliably be used to extrapolate the MTOW of an aircraft given a number of passengers it's required to carry. In this case Max payload (passengers) is the independent variable upon which the dependent variable MTOW depends governed by the equation of the line MTOW = Max Payload * 1.7656 - 102.43. However in this case the range of the aircraft is not taken into account. The main takeaway from this relationship is that the MTOW is proportional to the number of passengers, implying the same mass of aircraft (all components, fuel etc.) is present per customer regardless of how many passengers there are.

Bogong Moth Airways requirement for an airliner which carries 312 passengers with a range of 11,250nm is complex as most airplanes with payloads of 312 passengers correspond to an MTOW of 448437lbs. Using the first graph's equation however it is determined that the range of this 448437lbs aircraft will have a range of 5245.87nm. This is far short of the 11250nm required, hence to figure out what MTOW is required the follow steps were taken: We know that to carry 312 passengers an aircraft of MTOW 448437lbs (from the second graph), then taking that MTOW and substituting into the first graph we find that the range for this MTOW is 5245.87nm. Under the assumption that fuel consumption is constant we use cross multiplication to find what the MTOW would need to be if the range was 11250nm, this is done in the following manner. Hence the calculated value of 961692.96lbs MTOW is the predicted value of this concept airliner.

MTOW =
(448437*11250)/5245.87

=**961692.96lbs**

5245.87	448437
11250	MTOW

EVIDENCE OF RESEARCH

BOEING AIRCRAFT	MTOW (1000lbs)	Max Range (nm)	Max Payload (# passengers)	MTOW (1000lbs)
707-020	222	2800	140	222
707-120	247	3000	189	247
707-120B	258	3600	189	258
707-320	312	3750	189	312
707-420	312	3750	189	312
717-200	110	1430	134	110
717-200HGW	121	2060	134	121
727-100	169	2250	131	169
727-200	172	1900	189	172
727-200A	209.5	2550	189	209.5
737-100	97.516	1720	124	97.516
737-200	115.52	2645	136	115.52
737-300	124.521	2950	149	124.521
737-400	138.522	2800	188	138.522
737-500	138.525	2950	140	138.525
737-600	153.499	4500	149	153.499
737-700	154.5	4400	149	154.5
737-700ER	154.5	5500	149	154.5
737-800	174.17	4000	189	174.17
737-900	174.17	2800	215	174.17
737-900ER	187.7	3200	215	187.7
737 MAX 7	177	3850	149	177
737 MAX 8	181.299	3550	189	181.299
737 MAX 9	194.7	3550	220	194.7
737 MAX 10	202.825	3300	244	202.825
747-100	735	4900	420	735
747-SP	700	5830	400	700
747-200	833	6560	452	833
747-300	833	6330	496	833
747-400	875	7285	568	875
747-400ER	910	7585	568	910
747-8I	987	7730	600	987
757-200	255	3915	200	255
757-300	273	3400	243	273
767-200	315	3900	214	315
767-200ER	395	6590	214	395
767-300	350	3900	261	350
767-300ER	412	5980	261	412
767-400ER	450	5625	296	450
777-200	545	5240	313	545
777-200ER	656	7065	313	656
777-200LR	766	8555	317	766
777-300	660	6030	396	660

777-300ER	775	7370	396	775
777X -8	775	8730	384	775
777X -9	775	7285	426	775
787-8	502	7355	359	502
787-9	560	7635	406	560
787-10	560	6430	440	560
AIRBUS AIRCRAFT				
A300				
B4-200	363.763	2900	345	363.763
B4-600R	378.534	4050	345	378.534
A310				
-200	317.466	3500	220	317.466
-300	330.7	4350	280	330.7
A318				
Standard	150	3100	107	150
A319				
neo	166	3700	124	166
A320				
-ceo	206.1	3200	210	206.1
-neo	174.2	3300	180	174.2
A321				
ceo	206.1	3200	210	206.1
neo	213.8	3700	220	213.8
LR	213.8	4000	206	213.8
XLR	222.667	4700	220	222.667
A330				
-200	533.5	7250	406	533.5
-300	533.5	6350	440	533.5
-800	553.4	8150	405	553.4
-900	553.4	7200	440	553.4
A340				
-200	606.3	6700	420	606.3
-300	609.6	7300	440	609.6
-500	837.8	9000	440	837.8
-600	837.8	7800	475	837.8
A350				
-900	606.27	8100	440	606.27
-900ULR	617.3	9700	440	617.3
-1000	703.2	8700	480	703.2
A380				
-800	1268	8477	853	1268