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CONCEPT DESIGN OF A LOW BOOM SSBJ TO SATISFY SOCIAL ACCEPTANCE

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Abstract

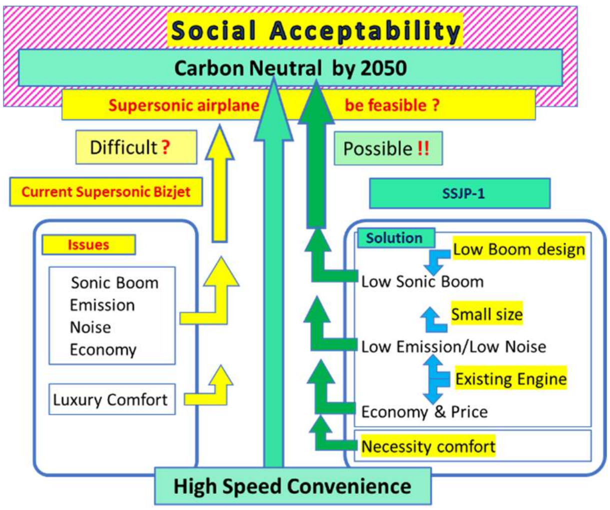
Currently, several supersonic business jet development programs are on-going. Those programs are seamed to target wealthy, high-end business jet users; however, environmental impact while considering the worldwide Carbon Neutral movement and social acceptance of supersonic aircraft including economic issues have become more stringent requirements to overcome. This paper shows an example of more practical and simplified supersonic aircraft which is the light/mid class supersonic business jet, “SSJP-1” that is designed to achieve Mach 1.4 low-boom over-land supersonic flight capability while coping with those issues but with consequently less luxurious specifications features. In addition, the development of a civil aircraft should be financially easy to start for manufacturers and affordable for the majority of business jet operators.

Keywords: SSBJ, Low Boom, Low CO2, Sustainable, Conceptual Design

1. Introduction

Although supersonic aircrafts offer high speed convenient air-travel, and there seems to be a certain market there, it is undeniable that the development might have difficulties with various issues such as social acceptance for environmental issues like sonic boom, carbon neutral policy, and along with economy and financial prospect.

Especially for supersonic business jet, the sonic boom measure is essential because the primary scenes of their expected usage are flight over land. For easy, ready to start and low risk development, it is important to keep the size of airplane small and incorporate the existing engine that are already available on the market, also application of existing technologies as much as possible. To alleviate these issues and achieve social acceptance, SSJP-1 is conceptualized with 4 points as shown in Figure 1.



Concept point
▪ Low boom technology
▪ Existing turbo-fan engine
▪ Small airplane size
▪ Practical comfort

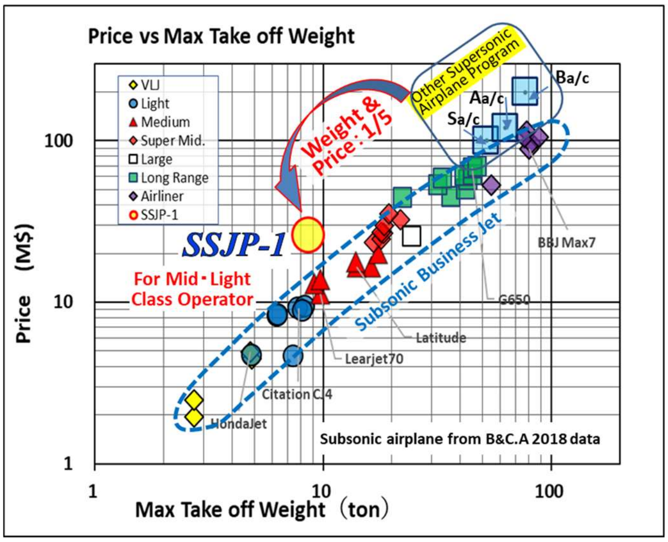
Note
- On-going supersonic Bizjet
  passengers >10 or more
  weight >130,000 lbs
  price >100m$
- SSJP-1
  passengers < 8
  weight <19,000 lbs
  price; 20 to 30 m$

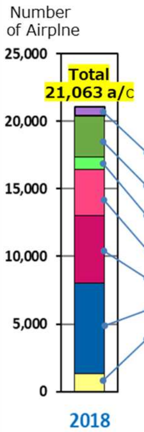
Figure 1 - Basic scenario for SSJP-1

2. Market Position

Figure 2 shows the market position of SSJP-1, which is targeted at the light/mid class of the overall business jet market. This class is the mainstay of the market so to speak, accounting for approximately 70% of the total number of subsonic business jet market. SSJP-1 is targeted this market with the key points of strategy as follows;

■ Distinctive speed, price and weight ■ Mainstay of Bizjet market





Business Jet Fleet @2018		
Category	Number	%
Airliners	678	3
Long Range	3,036	14
Large	886	4
S Midsize	3,458	16
Midsize	4,963	24
Light	6,723	32
VLJ	1,319	6
Total	21,063	100

72%

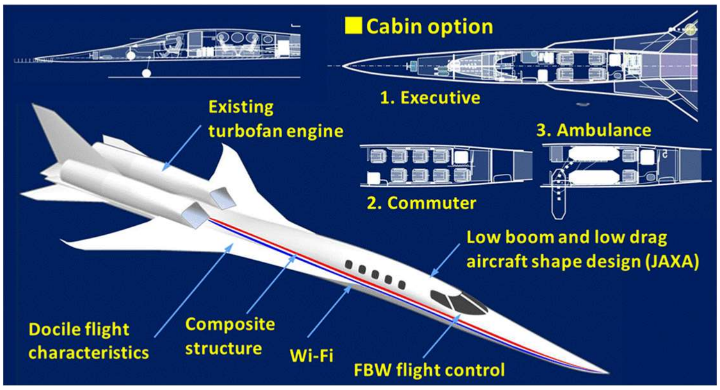
(a) Price vs max. take-off weight [1] (b) Number of aircraft [2]

Figure 2 - Position in the business jet market

SSJP-1 is an aircraft that is distinct from both existing subsonic bizjets and the currently planned supersonic airplanes in terms of cruise speed and price. Price target is around US$ 20-30M, that will be an affordable price for users, and delivery target is early 2030. The small size aircraft conforming to FAR part 23 will result a low development cost for relatively easy start-up. This is the principal philosophy of SSJP-1.

3. Design Objectives and Technology

Figure 3 and Table 1 show the objectives and system feature of SSJP-1, and the design technology features applied to SSJP-1 are described as follows;



Design objectives

- M1.4 Over-land Cruise speed
- 1 Pilot+5 Passengers (max;8)
- Price US$ 20-30m
- FAR Part23 aircraft (≤8.6ton)

Note;

- Single pilot operation is applicable only for Part 23 airplane.
- Part 23 Level 3 High speed category

(a) Design technology feature (b) Design objectives

Figure 3 - SSJP-1 design summary

- Low-boom design technology developed by JAXA [3] and small/light-weight and slender airframe for low boom, which are essential for the future supersonic over-land cruise.
- Existing turbo-fan engine for subsonic airplane expecting low airport noise and low emission.

- Small airplane in order to achieve these low emission, low cost and low risk requirements.
- Passenger cabin to be designed to provide the necessity comfort rather than luxury.
- Short take-off and landing capability to operate at small rural airfields.
- Systems for flight safety and low cost.
- Simple aerodynamic shape for low drag, docile stability for safe handling.

SSJP-1 is configured as FAR part 23 Normal Category aircraft. The cabin size is compact but good enough for a short trip, and aimed at practical comfort and functionality rather than luxury. Airplane geometry is designed also for easy access to the engine, equipment, refueling port, baggage, etc.

Table 1 Cabin arrangement and system feature of SSJP-1

Cabin arrangement	System feature
■ Executive (1 Pilot / 5 Passengers)	■ FBW, AI copilot (for Single Pilot operation)
■ Commuter (2 Pilots / 7-8 Passengers)	■ Emergency Auto Landing System
■ Ambulance (2 Pilots/2 Stretchers/2 Medics)	■ Wi-Fi office Equip, Galley, Vacuumed toilet
■ Express Cargo	■ Un-paved runway equipment (option)

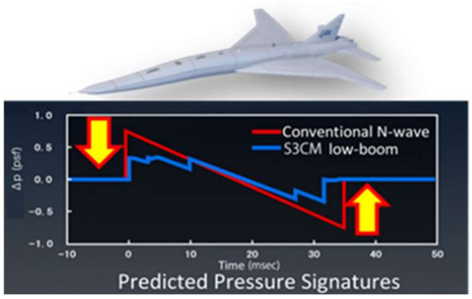
3.1 Low Boom Technology

As shown in Table 2, Over-land supersonic flight of Concorde was prohibited due to its large sonic boom observed as an N-shaped sound pressure waveform.

Table 2 Summary status of sonic boom

	Concorde	*SSJP-1 Target*	*Noise Rule*
Boom Intensity	*110 PLdB*	*80～85 PLdB*	*85 PLdB (undecided)*
Situation	*Prohibited over-land supersonic flight*	*Under trade-study with other design features*	*To be established by NASA flight test*
Actual Feeling	*Equivalent to a Nearby Lightning strike*	*Door knock*	

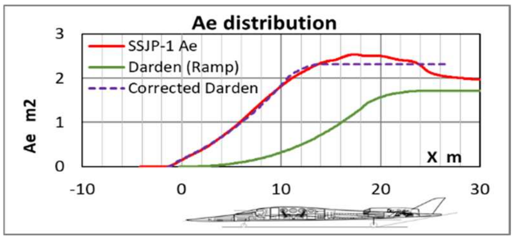
Figure 4 - DSEND project result



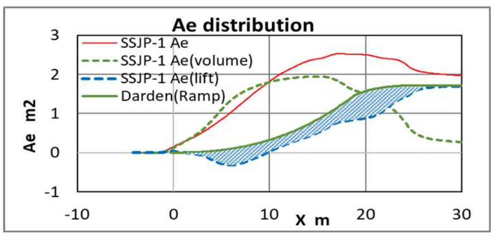
JAXA has conducted a research of the low boom design technologies [3], which was demonstrated in the D-SEND#2 flight test [4] shown in Figure 4, and JAXA patented the technologies. NASA is developing the X-59 low-boom demonstrator to establish the future sonic boom noise rule.

To realize the low boom characteristic, the equivalent area(Ae) distribution should be as close as possible to the theoretical Ae distribution derived by Darden [5]. Although it might be possible to meet exact Ae in case of experimental aircraft, but for actual operational aircraft, it might be difficult due to several design constraints such as cabin volume, pilot front view and CG envelope requirement, etc.

Therefore, as shown in Figure 5(a), the SSJP-1 Ae distribution is designed to meet the corrected Ae distribution which corresponds to heavier weight and shorter length (W:9.8ton, L:15m).



(a) Total Ae distribution



(b) Component Ae distribution

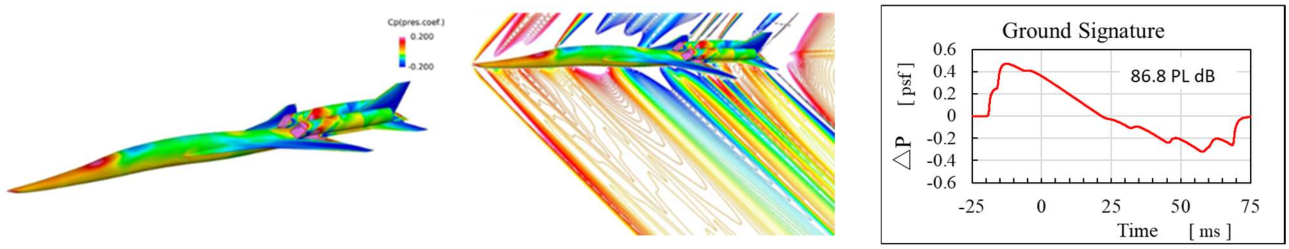
Figure 5 - Equivalent area(Ae) distribution

The comparison of Ae(lift), Ae(volume) and Ae(total)(=Ae(lift)+Ae(volume)), in Figure 5(b) shows that to keep Darden's Ae(total), Ae(volume); indicated by shaded area is very small and resulting fuselage diameter is less than 0.9 m against necessary diameter of 1.5m. Ae distribution of SSJP-1 is still discrepant a little from corrected Darden's Ae distribution, but estimated boom strength is 86.7 PLdB at 45,000ft/1.4 Mach and still 1PLdB larger than that of corrected Darden distribution (85.5 PLdB).

The signature of SSJP-1's theoretical Darden distribution (26m 7.3ton ramp-type) is 81 PLdB but the corresponding fuselage max. diameter is not satisfying the required diameter for cabin size. Consequently, the sonic boom of SSJP-1 will be louder than the theoretical Darden configuration by about 6 PLdB. That is, SSJP-1 is a low boom design but that is a result of a compromise of low boom theory and practical design requirements. It's necessary to optimize further to achieve the target boom strength of 80 to 85 PLdB and to be continued.

Figure 6(a),6(b) and 6(c) show pressure distribution and ground signature of SSJP-1 at 45,000ft 1.4Mach cruise estimated with Euler and Barger equations. The design point is that the front half geometry of the aircraft is configured with the corrected Darden's Ae distribution, and the rear half is configured with a wavy lower surface of the fuselage to repeat a series of small compression and expansion shock wave to prevent single large pressure recovery concentration at the tail end.

In case of X-59, by achieving theoretical Darden's Ae distribution, boom strength seems to be about 75PLdB at 50,000ft 1.4Mach cruise. Fuselage cross section is about1.2m width,1.6m height and applying SVS system, Ae distribution will be smooth enough to achieve theoretical Ae distribution.



(a) Surface Cp (b) Near field Cp (c) Ground signature

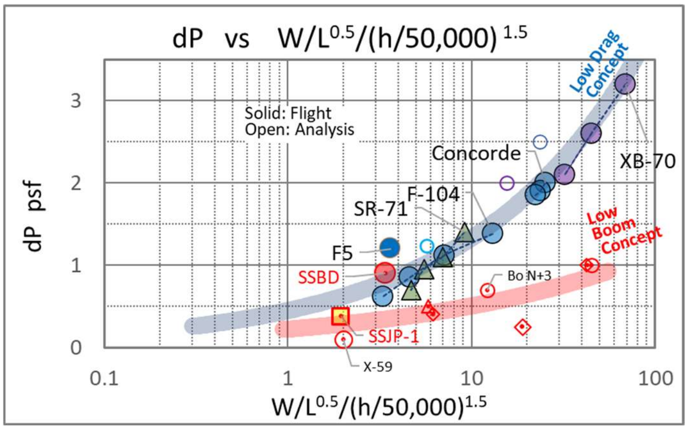
Figure 6 - Pressure distribution of SSJP-1 [6]

In addition to the Ae distribution optimization, SSJP-1 is designed as a light-weight aircraft to decrease boom strength. Generally, the boom strength is affected by aircraft weight, length, and altitude. In Figure 7 the flight test data of actual supersonic airplanes [7] is rearranged into the relation of measured boom strength data dP with airplane parameter;

$$W/L^{0.5}/(h/50{,}000)^{1.5} \tag{1}$$

where, W; aircraft weight(ton), L; length(m), h; flight altitude(ft).

As shown in Figure 7, light weight airplane itself is naturally a low boom airplane.

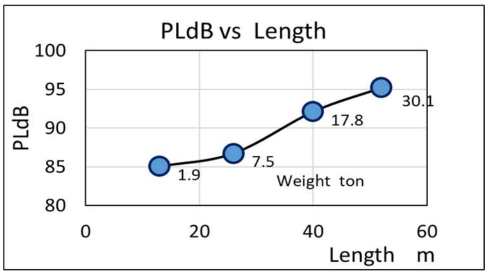


Note;

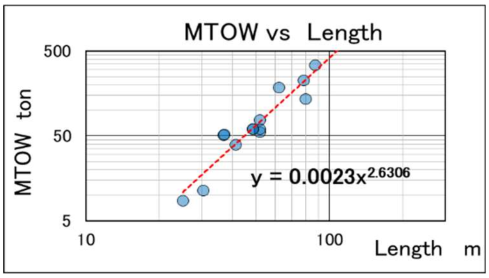
- Flight Data of XB-70,Concorde,F-104 and SR-71 are read from figure of reference [7].
- Flight data of F5 and SSBD from reference [8]
- Other data of analysis from ; AIAA-2010-4930, AIAA-7578-329, AIAA_2021-3030, NASA/TM-2003-212435, NASA/CR-2013-217820

Figure 7 - Boom strength vs $W/L^{0.5}/(h/50{,}000)^{1.5}$

Figure 8 shows the calculated result by CAPAS tools (panel and Thomas methods) [9] keeping similarity geometry and increasing weight proportional to $(length)^2$ to keep the same wing loading and cruise lift coefficient assuming the same relation of Ae(lift) and Ae(volume). The result showed a trend of longer the length of aircraft louder the boom. This result looks different from the theory of boom strength which will not be changed so much when keeping the same $W/L^{1.5}$ [10]. The assumption of Figure 8(a) resulted from the weight increasing further with L^2, and resulted in louder boom. The weight of various supersonic airplanes is roughly proportional with $L^{2.6}$ shown in Figure 8(b), therefore this tendency will become a little more evident. As shown in Figure 7, light weight itself is important for low boom airplane.



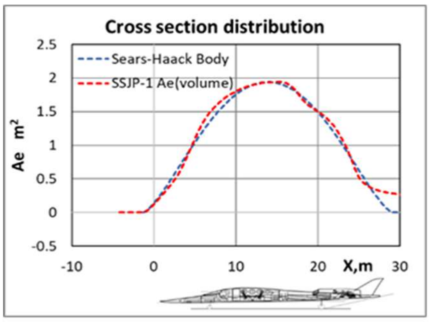
(a) Boom strength vs aircraft length



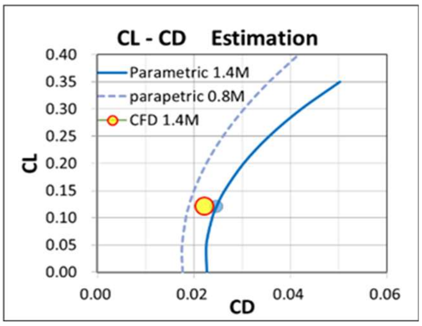
(b) MTOW vs length of supersonic airplane

Figure 8 - Size effect of sonic boom strength

Concerning the wave drag, as shown in Figure 9, the SSJP-1 cross section area distribution Ae(volume) is almost consistent with Seas-Haack body which represents the theoretical minimum wave drag geometry. Total drag estimation at cruise condition of 45,000ft, Mach1.4 by JAXA's CFD (RANS) code called "FaSTAR" compared with polar curve data used in parametric study in Figure 9(b) and show that parametric study has a little margin.



(a) Cross section area distribution



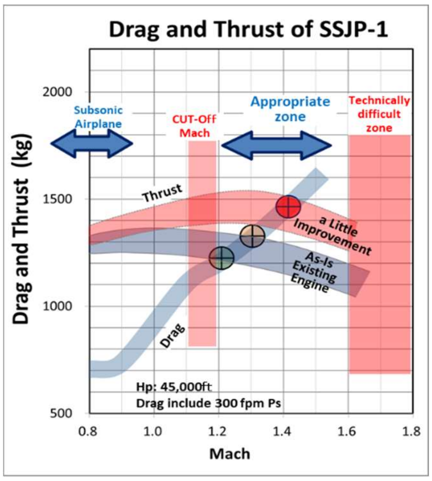
(b) Drag polar of SSJP-1

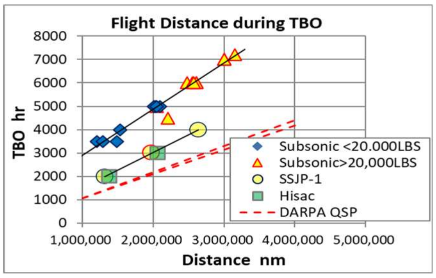
Figure 9 - Wave drag

3.2 Engine and Environment

Difficult point using the existing turbofan engine is the ram drag increase at supersonic flight condition, resulting in a little oversized engine becoming necessary, and consequently weight penalty should be accepted. Figure 10(a) shows the generalized Thrust and Drag relation of SSJP-1, and requires necessary small modification of nozzle design from the convergent nozzle to convergent-divergent nozzle for supersonic flight to meet the target performance. Also, a little amount of TIT (turbine inlet temperature) increase, which may accrue engine hot section life to decrease, but could be possible by sacrificing TBO (time between overhauls). The usual subsonic engine TBO is around 4,000 to 7,000hrs. The SSJP-1 is planned between 2,000 to 3,000 hrs TBO. As shown in Figure 10(b) supersonic aircraft will be considered acceptable assuming same total travel distance during TBO.

Examples of the existent engine will be 6000lbs class turbofan-engine such as Rolls-Royce AE3007, Pratt & Whitney PW-300, Honeywell HTF7000, etc., which are basically low noise and already compliant with the current LTO emission rule. The engines are certified for subsonic operation at this moment, therefore, even if no hardware modification is required, the amendment will be necessary by conducting an endurance test based on FAR part 33.87 rule for supersonic operation.





Note;
- Flight Distance= Cruise Speed × TBO
- Subsonic aircraft; estimated from Ref, [1]
- DARPA data: [11]

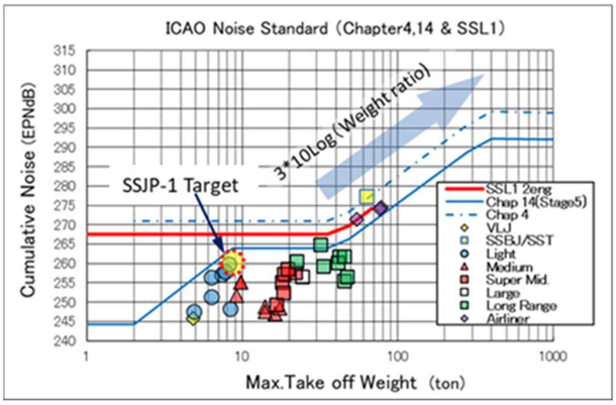
Figure 10 - Generalized thrust & drag relation and TBO

3.2.1 Noise

SSJP-1 will conform to the regulations of Noise and CO2 emission by utilizing of existing moderate bypass ratio subsonic turbofan engine.

Conforming to the Noise rule of Stage 5 (Chapter 14) for subsonic airplane, Figure 11 shows that many of the current medium class subsonic airplanes clear the stage 5 rule by about 5dB, therefor SSJP-1 will clear the rule easily with the use of "Derated takeoff thrust", which requires about 70% of the full thrust level to be sufficient for the normal take off. Moreover, the rule for the "Supersonic Level 1 (SSL1) noise regulation shown as the red line in Figure 11 is specified 4dB larger than Stage 5 rule, and SSJP-1 will be satisfied the SSL1 rule.

- Noise rule for SSL1 ; "Docket No.:FAA-2020-0316" Notice No.20-06 RIN 2120–AL29 [12]



Note;
Definition of Supersonic Level 1 (SSL1) airplane;
MTOW less than 60ton,
Cruise speed < 1.8Mach
Cumulative noise requirement;
<268 EPNdB at 35ton and lower
(SSJP-1; MTOW 8.6ton)

Figure 11 – Airport Noise regulation

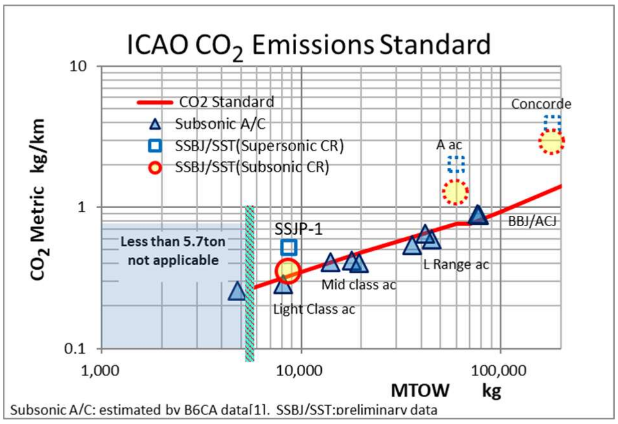
3.2.2 Emission

CO_2 emission rule for subsonic airplane is shown as the red line in Figure 12.

- Emission rule; "ICAO Airplane CO_2 Emission Standards Annex 16, Volume III, First Edition, July 2017 [13]" (no specific description for supersonic airplane is shown in the rule)

When the rule was applied to supersonic airplane, specific air range (SAR) will not be as good as of subsonic airplane even if using SAR condition of best subsonic speed, and RGF will be about a half of a subsonic airplane in similar weight. Therefore, it usually will be very difficult to clear the rule for supersonic airplane, but it may possible for SSJP-1 to barely satisfy the rule under best SAR condition.

Figure 12 shows the estimated results for several subsonic and supersonic airplanes. Also, a potential future regulation for supersonic airplane should be taken into account in the consideration.



Note;

Maximum allowable value of CO2 Metrics [14]

= 1/((SAR)x(RGF)$^{0.24}$): (red line in Figure 12)

where, SAR; specific air range in km/kg fuel for best cruise condition

RGF; Reference Geometric Factor relating to Airplane floor area in m^2

- Requirement;

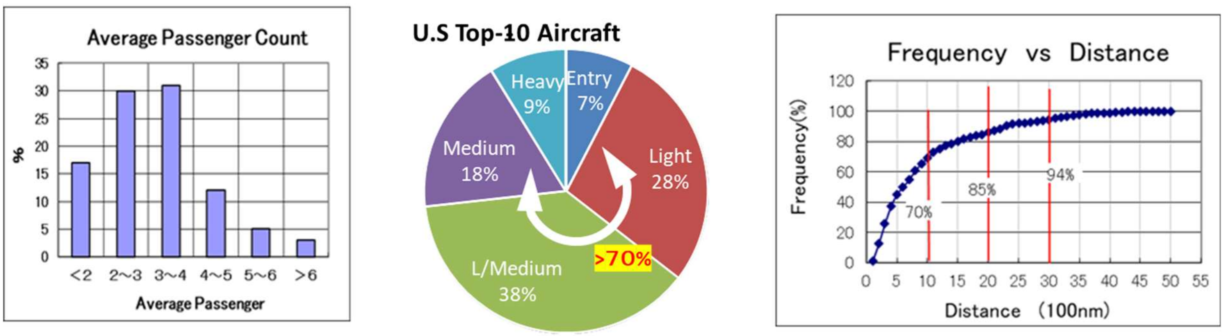
CO2 Metrix; < 0.269@5.7ton to <0.764@60ton (SSJP-1; MTOW 8.6ton)

Figure 12 – Cruise emission regulation

Sustainable Aviation Fuel (SAF) will be applied in accordance to the 'ICAO emission target for 2050'. The challenges are said to be the establishment of fuel specifications comparable to those of fossil fuel, price reduction, and production/supply systems. The price of SAF is said to be several times higher than that of jet fuel at present, and the future outlook is still difficult to predict. Assuming a price (12$/Gal) and 50% blending with jet fuel, it can be roughly estimate that the flight expenses shown in Table 3 (3.3.1) to increase by about 50%. The same is true for subsonic aircraft, and the increase is slightly larger for supersonic aircraft due to their higher proportion of fuel costs, but the relative comparison is not significantly different from Figure14. CO_2 emission by use of SAF is said to be reduced by up to 80%, and even assuming a 50% fuel mix, both sub and supersonic aircraft can reduce CO_2 emission by about 40%; thus, SAF is extremely effective in reducing ICAO emissions target.

3.3 Airplane Size, Performance, and Operability

SSJP-1 is designed 1 pilot / 5 passengers as basic configuration and 2 pilots / 8 passengers as a commuter arrangement by quick-change style, and those configurations will cover most of the operator's record of the average number of passengers shown in Figure 13(a). Also, more than 70% of Top-10 aircraft operation record in U.S. are by small size airplane shown in Figure 13(b). Ref. [17] says that 92% of operations of small jet is within 1000nm in distance, and 86% in the case of all jet. Even in case of large jet, 70% of the flight is less than 1000nm in distance as shown in Figure 13(c).



(a)Number of passengers [15] (b) Aircraft operation in U.S, [16] (c) Flight distance [18]

Figure 13 - Business jet operation statistics in U.S.

3.3.1 Competitive Analysis

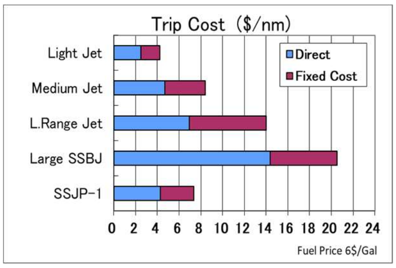
SSJP-1 focuses on middle range flight of less than 1000nm which is the most dominant business flights. Table 3 and Figure 14 show a comparison of SSJP-1 and the other Bizjets in the 1000 nm mission segment, reflecting the previous analysis, and clarifying the supersonic speed merit.

Table 3 Competitive Analysis @1000nm mission

		SSJP-1	Large SSBJ	Light Jet	Midsize Jet	Long. Range Jet
Price	M$	26	120	4.9	16.7	68.2
Cruise Mach	M	**1.40**	1.20	0.73	0.75	0.90
Passengers	-	4	8	4	4	8
Flight Time	h+m	1+34	1+44	2+40	2+25	2+10
Time Saving	min	**Ref.**	**-10**	**-66**	**-51**	**-36**
Fuel used	ton	1.9	6.6	0.8	1.8	2.7
CO2	ton	**5.9**	**20.6**	2.6	5.6	8.4
Trip cost	$/nm	7.3	20.5	4.2	8.4	14.0

Fuel price; 6$/gal

Figure 14 - Trip cost



The flight time can be reduced from approximately 2.5 hours to 1.5 hours. Time saving effect is -0.5 to -1 hour compared to subsonic airplane even in 1000nm range.

Fuel consumed is about the same as subsonic midsize jet, less than long range jet and well less than ongoing large size SSBJ. The necessary fuel for supersonic flight is usually higher than subsonic cruise, but comparison SSJP-1 with subsonic midsize jet is almost same. The reason can be cleared by specific range (S.R) comparison shown in Table 4.

Table 4 Specific range comparison * estimated

	Mach	W ton	L/D	SFC 1/hr.	F.F kg/hr.	S.R nm/kg
SSJP-1	1.4	7.3	6	0.9	1134	0.71
Subsonic Midsize jet	0.75	11.9	12*	0.6*	594	0.73
Ratio	1.87	0.61	0.48	1.5	1.91	0.98

$$SR = \frac{TAS}{Fuel\ Flow} \qquad Fuel\ Flow = \frac{W}{(L/D)} * SFC$$

Where; S.R; Specific range (nm/kg) TAS; Cruise speed= (575kt*Mach) F.F; fuel flow (kg /hr.)

CO2 emissions is comparable to a subsonic aircraft of the same class, and about 30% less than a large subsonic aircraft.

Trip cost is about 1/2 of a large subsonic aircraft, and about 1/3 of that of a large supersonic aircraft. Fixed cost of supersonic airplane is relatively small due to its short flight time (Figure 14). Large supersonic aircraft assumed to be restricted to operate within cut-off Mach number (1.1-1.2M) or lower due to the sonic boom, even if the aircraft is permitted to operate over-land at supersonic speeds. The market acceptance of SSJP-1 depends on whether the advantages of SSJP-1 shown in Table 3 are accepted even with its small cabin and shorter-range capability in consideration.

The price of SSJP-1 is higher than that of subsonic business jet, although, with its speed advantage, supersonic jet enables a shorter trip time, which leads to lower fixed cost than a subsonic jet, because the fixed cost is basically depend on the utilization hours.

Fractional Owner Ship will be the best solution to cover the higher price of SSJP-1. Table 5 shows the comparison for 5-years total cost of fractional ownership operation and shows that SSJP-1 will be more cost competitive over a subsonic airplane, and is suitable for fractional ownership system. With its speed advantage, a supersonic jet realizes a shorter trip time, which leads to more fractional owners per aircraft and consequently less acquisition cost than a subsonic jet, because the cost is basically dependent of the shared utilization hours. Thus, the expensive price of a supersonic aircraft will be compensated substantially by its speed advantage.

Table 5 Comparison of fractional ownership cost

		SSJP-1	Large SSBJ	Light Jet	Medium Jet	L. Range Jet
Price	M$	26	120	4.9	16.7	68.2
Flight Hours	hrs.	125	139	213	193	173
Fractional Ratio	-	1/6.4	1/5.8	1/3.8	1/4.2	1/4.6
Fractional Price	M$	4.1	20.7	1.9	4	14.8
Operating Cost	M$	2.9	8.2	1.7	3.4	5.6
5 years Cost	M$	6.5	25.5	3.3	6.8	18.0

Note;
- 80,000nm total trip distance; 20times round trip between (TEB-VAN)/year
- utilization (800hrs/year)
- Fractional owner ratio = (Flight hrs.)/800
- Residual value=(Fract.Price)/2

3.3.2 Range Capability

The range capability of SSJP-1 over 2100nm is good enough for US-domestic flight. Figure.15 shows one-day business trip from/to the East/West coast, enabled by the aircraft's low-boom supersonic over-land cruise capability, but a little more range capability will be necessary considering head-wind condition etc.

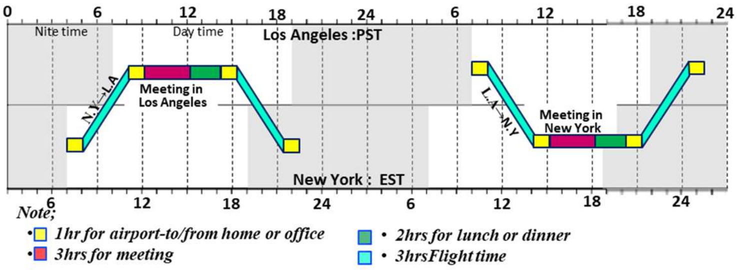
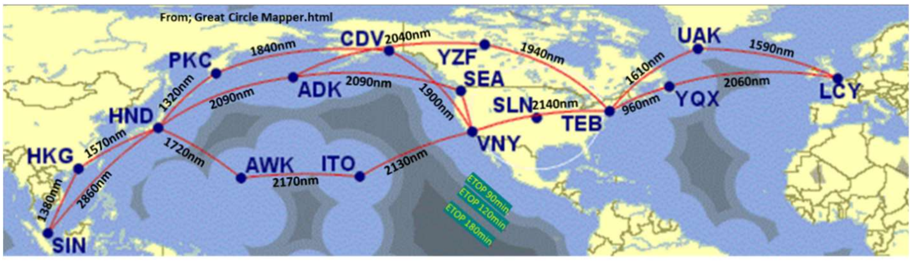


Figure 15 - Round trip east-west coast in U.S.

In the case of Long-haul flight, Figure 16 shows SSJP-1's one-stop Trans-Atlantic flight and two-stop Trans-Pacific flight capability as necessary, eventhough it will be a rare case.

A trans-Atlantic flight (New York-London; 3100nm) is possible with a range capability of about 2100 nm when refueling at Gander in Canada, or with 1700nm capability when refueled at Greenland.

In trans-Pacific flight (Tokyo-Los Angeles; 4750nm) refueling stops are necessary at Corboda (south of Anchorage) and the Aleutians or Kamchatka. The Current performance targets of 2100 nm (Figure 18 in Section 4) is a bit short considering the effect of wind. It will be necessary to improve in the future, but the last 30 minutes of the long-haul flight can be slowed down to subsonic, for example, 0.9M, extending the flight distance by about 200 nm with a time delay of about 20min. This characteristic will provide more leeway flight plan and secure a greater safety than subsonic aircraft.



Note;
- Figure 15 is made by using Great Circle Mapper [19]
- ETOP zone for 90, 120, 180min rule shown in the chart

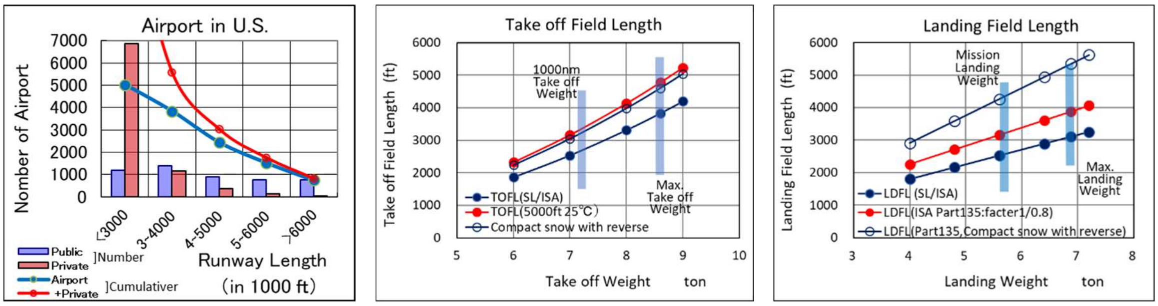
Figure 16 - Long-haul flight capability

3.3.3 Field length capability

About 80% of business jet operations take place at general-aviation airport in small cities not served by airlines [20]. There are approximately 4000 small airports with runways of around 3000-6000 ft in the US (Figure 17(a)), where it is important to be able to operate on such runways for business jet.

SSJP-1 can operate on a 4000ft runways under the standard sea-level condition, and on a 5000ft runways under adverse conditions such as take-offs from 5000ft elevation/hotday, or landings on contaminated runway covered with compact snow. In the case of 1000nm range flight, SSJP-1 can also takeoff from a 3000ft runway while decreasing take off weight as shown in Figure 17.

From a longer enough runways, SSJP-1 offers choices for the pilots to select more quieter takeoff with lower engine thrust (less than 70%) for neighbors or stringent nighttime curfews

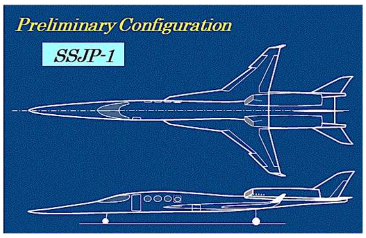


(a) US airport statictics [21] (b) Take off field Length (c) Landing field Length

Figure 17 - US airport statistics and Take-off and landing perforemance of SSJP-1

4. Airplane Feature

Figure 18 shows the preliminary configuration and specification/objectives of the SSJP-1. Those data need further investgation to finalize as the conceptional design result.



Specification		Objectives	
Max.TO Weight	8.6 ton	Max.Cruise Speed	1.4M
Crew+Passengers	1+5(max. 8)	Range (Supersonic)	2100nm
Length	26 m	Range (Subsonic)	2800nm
Span	10 m	Takeoff Field Length	4000ft
Wing Area	28 m^2	Landing Distance	3500ft
Cabin Size (W/H)	1.4m /1.4m	Max.Altitude	51000ft

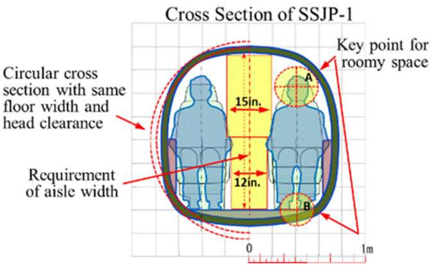
Figure 18 - Preliminary configuration of the SSJP-1 and specification and objectives

4.1 Basic Design

During the conceptual design phase, usually the initial wing loading and thrust-to-weight ratio (T/W) are analyzed based on various performance requirements, but in the case of SSJP-1, requirement for supersonic cruise using existing engine is the distinctive issue. And therefore the degree of freedom is very limited, and it tends restrictive.The T/W is out of the realm of business jets and more like a military trainer. The larger engine tends to increase empty weight, i.e. the payload penalty is unavoidable. On the other hand, there is more room for take-off and climb thrust. The FAR climb requirements to be satisfied would become more leeway. The problem is the challenge how to match the tendency of underthrust at supersonic speeds and the engine weight penalty to other items.

4.2 Cabin Size

In addition to achieving low boom characteristics, to realize supersonic cruise performance and economy, the airplane size should be as small as possible in order to help utilizing the existing



Note;
- Example of Oval section; King Air, FA300/Rockwell700, MU300/Nextant400 (Those airplane were well received)
- Example of Circular section; HondaJet, Citation, other Light Jet
- Floor width is very important for Cabin design

	Light Jet	Midsize Jet	SSJP-1
Floor Width (m)	0.9~1.2m	1.2~1.9m	1.1m

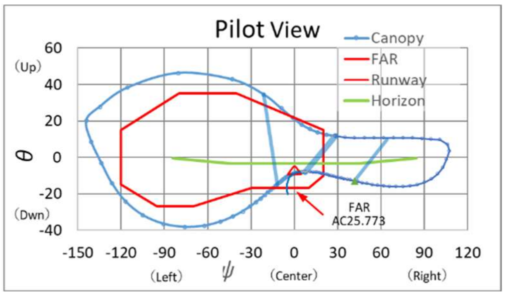
Figure 19 - Cabin cross section configuration

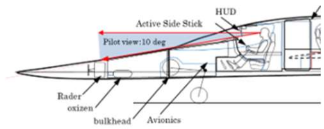
turbofan engine. However, in order not to impair the cabin comfort, oval(egg-shaped) cross section is seleced instead of circular one. This creates more headroom and legroom for passengers as shown Figure.19.

4.3 Safety Issue

4.3.1 Pilot View

The cockpit is arranged in referrence to subsonic light-class business jet. The challenge is to ensure an adequate forward visibility for the pilot, while achieving the low boom characteristics with a long nose. Figure 20 shows a comparison with the FAA's recommended visibility (AC25.773 Optimum for collision avoidance), which will not be strictly required even on part 25 airplane.





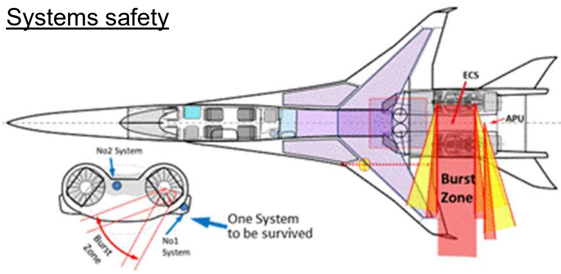
Pilot View of part 23 airplane			
Airplane	Light Jet	Single engine Turboprop	SSJP-1
Pilot front view (deg.)	-10~ -11	-7~ -10	-9

Figure 20 - Pilot front view

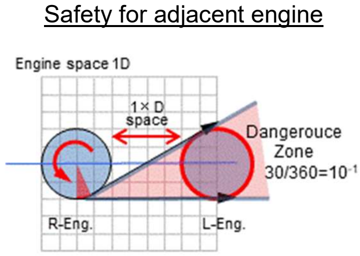
The pilot front view is slightly less than the recommendation on the centreline direction, which may be an issue, but is considered acceptable as it is almost as good as a single-engined turboprop aircraft, which also has a long nose for engine installation .

4.3.2 Engine Arrangement

Engine reliability is one of the most important issus for safety, and it is essential to select an existing engine which already accumulated plenty of safety record. Safety analysis should be considered for redundancy of the entire system in the event of an engine explosion, therefore engines should be separated as far as possible to minimize damage to the remaining engines at initial study phase. Probability of uncontained burst will be around 10^{-7} to 10^{-8} statistically, then, it’s good to apart engines at least one engine diameter shown Figure 21 to achieve 10^{-9} ”extremely improbable occurrence”.



Note; ▪FAR25.963(fuel tank), 25.1309 etc (equipment,systems and installations)



Note; ▪ FAR25.901,903(installation,engines), AC 20-128A(uncontained failure) etc

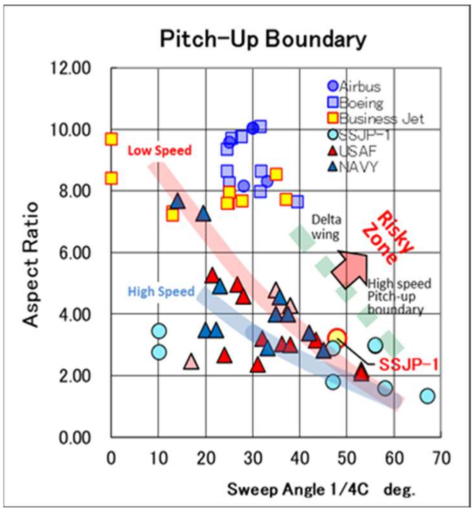
Figure 21 - Engine spacing to improve reliability at uncontained engine failure

The flght control, electrical, hydraulic systems should be separated into two systems, to survive at least one in case of engine burst etc, as regulations require. The basic configuration need to be arranged for survivability from the configuration design stage.

4.3.3. Flight Characteristics

While supersonic aircraft have the advantage of being able to fly at high speeds, they may tend to be more difficult to maneuver and may cause anxiety among pilots and passengers in the general aviation community. Therefore, to ensure flight safety, it is important to select a configuration that provides gentle and docile aerodynamic characteristics from the beginnings. The aerodynamic shape of SSJP-1 must be designed to give priority to low boom characteristics, but flight safety is the highest priority in aircraft design.

In particular, supersonic airplane like SSJP-1 may enter cautional transonic speed zone, that is, a risk of high speed instabilities such as pitch-up and coupling due to unintended control inputs, system malfunction, or encountering sudden turbulence must be carefully investigated. Since this will affect the airframe configuration, including wing shape, tail position and size, the initial configuration should be selected refer to histrical experience and data to minimize the need for future modifications to the basic configuration.



- wing planform should be select within the low-speed limit line.
- devices to improve stall characteristics is also considered necessary.
- wing plan for should be considered for low speed and high speed pitch-up
- Shifting of center of lift from subsonic to supersonic speed to be investigated
- Empennages configuration also important

Figure 22 - Wing planform for stable flight characteristics

<u>The wing planform</u> should be selected within the low speed limit line shown in Figure 22, or not be greatly exceeded, and the addition of stall prevention devices are also considered necessary.
It is important to reflecte the hard experiences that have been gained during 1960s in the 1st. generation supersonic fighter development, because SSJP-1 will be the very first supersonic airplane to fly by business aviation pilots not by the top notch test pilots nor the experienced fighter pilots. Also, It is difficult to avoid the phenomenon of gradually losing the longitudinal static stability toward stall angle, and the aerodynamic center moving backward at supersonic speeds.
<u>The FBW system</u> should be designed reflecting those issues and exclude operational errors related to conflicts between the computer system and pilot intension. It is important to prevent erroneous operations by simplifying the FBW control system architecture to be aligned with the pilot's normal operations.

For minimizing the effects of system failures, it is necessary to multiplex system to increase safety. The system should be based on a quadruple system, but based on a slightly older type such as the F-16 with hydraulic control system, considering general aviation maintenance capability, and should be considered for modernization by adding independent 5th electronic circuits in place of mechanical backup, active side sticks, and multiple layer sensor systems.
<u>Other safety equipment</u> should be incorporated. As one measure for flight safety, an emergency automatic landing system [22] will be installed as astandard equipment to support single-pilot operation. This system fully automates the flight to thenearest airport and landing after a passenger touches the button in the case of an emergency of pilot incapacitant. In addition, AI technology (Virtual Co-Pilot function) to facilitate flight operations, and usual safety equipment should be considered to eliminate CFIT(Controlled Flight Into Terrain) and LOC(loss of control), which are the causes of many accidents.

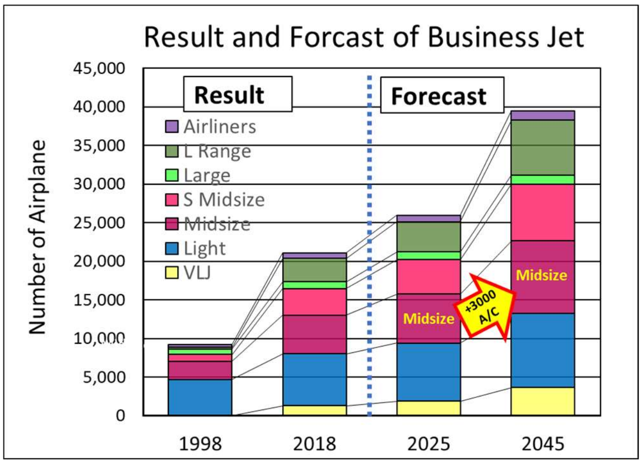
4.3.4. Regulations and histrical Safety Analysis

About the certification for supersonic airplane, currently, the corresponding regulations seems not to be established enough except for that of the airport noise rule for SSL1(section 3.2.1), the supersonic engine certification requirement specified in FAR part33.87, and on-going sonic boom rule based on NASA X-59 aircraft flight test. In case of SSJP-1, the applicable regulation is new FAR part 23 revised heavily in 2017 and corresponding ASTM (American Society for Testing and Materials) standard as MOC (Means of Compliance)[23]. But SSJP-1 will be the first case of the part 23 supersonic aircraft application, the historical FAR rule " Tentative Airworthiness Standards for Supersonic Transports" published 1965 [24] will be referenced. Therefore, it will be necessary to consult and collaborate frequently and intensively with the regulatory agency before and during the development.

Also, it is important to investigate the statistical records and analysis of accidents and incidents, and reflect a lesson learned on the configuration and system planning [25].

5. Market and Finance

Figure. 23 shows the market demand (1998 and 2018) [2] and demand forecast (2025, 2045) for all business jets. Demand for midsize class is projected to increase by 3,060 aircraft during 20 years.



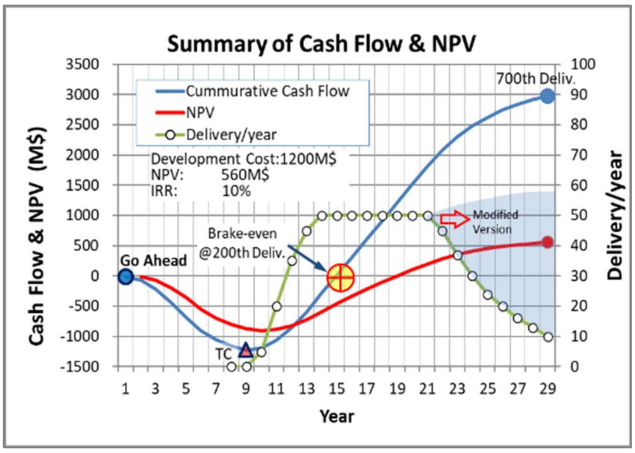
Note;

- The forecast for 2025 and 2045 ; based on the data of 1998 and 2018, and the forecast in GDP change..
- Increase of midsize Business jet from 2025 to 2045 is estimated 3060 aircraft.
- Target market shear assumed 24% of Midsize aircraft.

Figure 23 - Market demand and forecast

The market share of largest selling model of existing subsonic midsize business jets (24% of midsize aircraft) is assumed for the SSJP-1, Then the prospected amount of delivery is set to be 700 aircraft / 20years.

Figure 24 shows the preliminary financial prospect during 30years program period.



Note;

- Price; US$ 26M, Cost; US$ 20 M
- Development Cost; US$ 1.2 B
- NPV; US$ 500M, 10%IRR
- First flight of POC from Go-ahead; 5 years
  Certification from first flight; 4 years
- Production Objective: 700 aircraft /20year
- Break-even point will be approximately 200th aircraft, and 16th years from go-ahead.

Figure 24 – Preliminary Financial prospect

This section shows a simplified summary of market and finance study of the SSJP-1. The program is estimated to be $1.2 B development cost, $26 M airplane price based on the statistical method developed internally.

6. Conclusions & Outlook

This paper outlined the preliminary study results for the low-boom supersonic business jet 'SSJP-1'. The data is compiled the results of the study by the "Supersonic Aircraft Research Group" Design Meeting and Market Subcommittee as shown in Figure 25 .

Our concern is; there will be concerns about the social acceptance of supersonic aircraft, especially due to environmental and economic issues and their uniquely high price. However, the SSJP-1 concept is the right direction for social acceptance in the near future we believed. In this paper, we have demonstrated the potential of a low boom supersonic airplane using low boom technology, existing engine performance and existing technology. Hoever, it is clear that further research must be done as follows;

- Supersonic over land flight is the essential requirement for SSJP-1. Therefore, to pursue that the target of the boom strength of 80-85PLdB is good enough for the future regulation or not, and certainly achievable by shaping the geometry of SSJP-1,must be confirmed.
- Optimization of low boom shape including aircraft operating conditions, fuselage nose and tail shape Improvement, wing and empennage configuration and higher cruising altitude according to engine performance capability.
- Detailed study of engine performance and operability.
- Weight and CG estimation update and corresponding trim condition adjustment.
- Prospect of future regulations for supersonic airplane.
- Detailed study for aero, structure, equipment.
- Market analysis especially acceptance of small cabin but supersonic cruise capability, cost and environmental sales points.
- Financial planning and candidate of OEM.

This paper showed the first call out of the possibility of the SSJP-1 for its distinctive characteristics of the aircraft capabilities and benefits in the business jet market.

Acknowledgements

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- University of Tokyo
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- Kawasaki Heavy Industries Ltd.
- Japan Airlines Co., Ltd.
- MOOG JAPAN LTD.
- Sky Aerospace Institute
- Suwa University of Science
- Electronic Navigation Research Institute
- SUBARU Corporation
- KYB Corporation
- Tokyo Fluid Research Co., Ltd
- SuperSonic Jet Planning Inc.

Figure 25 – Member of Supersonic Aircraft Research Group

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