JOINT STRIKE FIGHTER

Boeing X-32

Lockheed Martin X-35

http://www.thefighterenterprise.com/image_gallery/pr_photos/jsfpr_photos/jsf_1stflight/x350370d.html

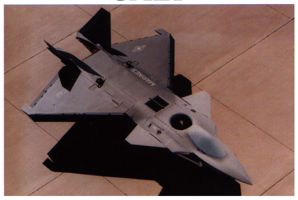
Geoffrey Buescher 23 April 2001

History

Harrier

http://www.boeing.com/defense-space/military/av8b/images/av8b03.htm

CALF

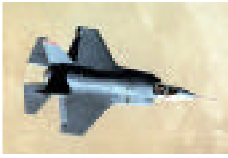


From Joint Strike Fighter, Bill Sweetman

JAST ⟶ JSF

http://www.robotgroup.org/lubbock/AircraftOfTheMonth/5-00.html

http://www.boeing.com/defense-space/military/jsf/images/X-32A_quote.jpg

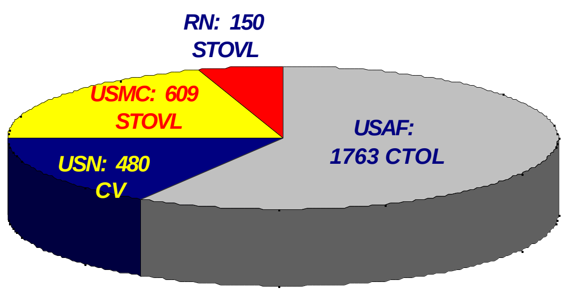


http://www.jast.mil

•The U.S. Marine Corps and Royal Navy, among several other navies, recognized the advantages of STOVL when they adopted the Harrier. A follow-on was a necessity, as the requirement for a STOVL aircraft has not disappeared since service entry of the Harrier. Some research into STOVL therefore continued through the 1980s, notably in the Advanced STOVL project begun by the U.S. and U.K. in 1986. DARPA had a hand in ASTOVL, and this agency in 1988 developed a requirement with the U.S. Navy and Marines for a STOVL aircraft weighing no more than 24 000 lb and occupying no more ground space than an F-18. Although the weight cap was intended to keep cost down, the DARPA requirement was also based on the GE F120 and Pratt & Whitney F119 engines. Design studies made against this requirement focused on reducing hot gas ingestion and improving stealth in up and away flight.

-The aging of front line aircraft—the F-14, F-16, F-18, and AV-8B—and the cancellation of programs intended to replace them, including the A-12, brought the possibility of combining the requirements to save cost. The Marines still needed a STOVL aircraft, while the Air Force needed a relatively lightweight and cheap fighter with fairly long range and good stealth characteristics. The Navy needed a stealthy long-range medium bomber. Despite the dissimilarities in the requirements, the Common Affordable Lightweight Fighter program awarded contracts for a multi-service aircraft to Lockheed Martin and McDonnell Douglas in 1993. Both aircraft used lift fans and internal weapons carriage. The lift fans simultaneously increased mass flow (for added thrust above that at which the gas generators were rated) and provided a cold flow of air shielding the engine inlets from hot-section exhaust at the tail.

Requirements



	CTOL	STOVL	CV
Cost	$28M	$35M	$38M
Empty weight	Mid-22000 lb	Mid-22000 lb	Mid-24000 lb
Max takeoff weight	50000 lb	50000 lb	50000 lb
Internal fuel	15000 lb	15000 lb	16000 lb
Payload	13000 lb	13000 lb	17000 lb
Range	600 nmi +	600 nmi +	600 nmi +

•U.S. Air Force: Increased stealth, reliability and range relative to F-16, but performance not necessarily better. Low-end fighter to complement F-22 (as F-16 for F-15); Air Force acquisition executive Arthur L. Money: “The F-22 is the force enabler; the JSF is the force” (Ref. 2). 1763 aircraft, replacing A-10 and F-16. (Ref. 2, 3)

•U.S. Navy: Stealthy “first day of the war” deep-strike medium bomber capable of eliminating high-priority installations and opening a path through air defense systems for F/A-18E/Fs to follow. In this sense, replaces A-6 in lieu of A-12. Must be able to carry two 2000-lb PGMs internally to 600 nmi. For Navy, JSF is high-end complement to F/A-18E/F. CVW mix: 36 F/A-18E/Fs, 14 JSFs. 480 aircraft, replacing F/A-18C/D. (Ref. 2,3,4)

•U.S. Marine Corps: STOVL strike aircraft for close air support. Quick response capability of AV-8B at increased reliability and speed. 609 aircraft, replacing AV-8B and F/A-18. (Ref. 2, 3, 4)

•Royal Navy: STOVL strike fighter. 150 aircraft, replacing Harrier. (Ref. 4)

•Total requirement: 3002 airframes

•Program office requirements for operational aircraft: as in chart. (Ref. 5) However, these are flexible to achieve the best-value solution. (Ref. 2) Note weights do not sum to max takeoff weight, and note that empty weights specified are less than actual weights of demonstrators (see slide 8)

Pratt & Whitney JSF119

http://www.allstar.fiu.edu/aerojava/P&WEngines04.html

http://www.thefighterenterprise.com/image_gallery/jsf/images/afterburner.jpg

Pratt & Whitney F119 is used as baseline engine for all JSF airframes from both manufacturers. However, General Electric hopes to present a derivative of its F120—which lost in the competition to power the ATF (F-22/F-23)—as competition after the initial block of aircraft. (Ref. 2)

Baseline F119 produces 35 000 lb of thrust—the JSF119 produces about 40 000 lb. (Ref. 6)

In X-35, JSF119 has produced 25 000 lb dry. (Ref. 7)

Above basic F119, JSF119 features:

Added prognostic health management system to sense impending failure. JSF119-614 for Boeing airplane, JSF119-611 on Lockheed Martin entry. Low pressure turbine increased from one to two stages, and fan scaled up 10-20%: allows increased airflow and power. (Ref. 8)

Competitors

LOCKHEED MARTIN

X-35

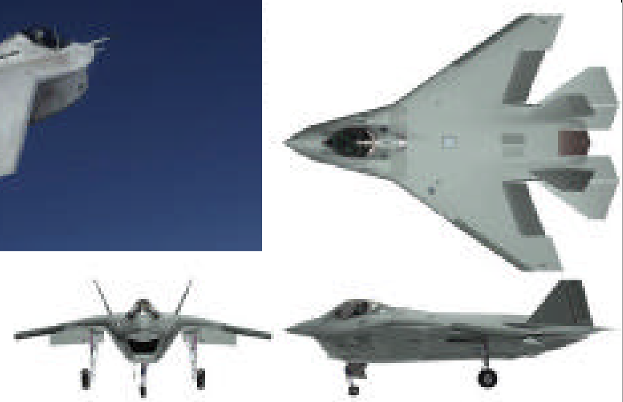
BOEING

X-32

http://www.fas.org/man/dod-101/sys/ac/jsf.htm

Boeing X-32

http://www.boeing.com/defense-space/military/jsf/images/dsc_0013.htm



http://www.boeing.com/defense-space/military/jsf/images/6-jsf_ctol_3vu.htm

•Original Boeing design retained high fuel-volume delta wing of Boeing CALF concept; mounted high to avoid suckdown from high-velocity exhaust moving along ground in STOVL mode (Ref. 1)

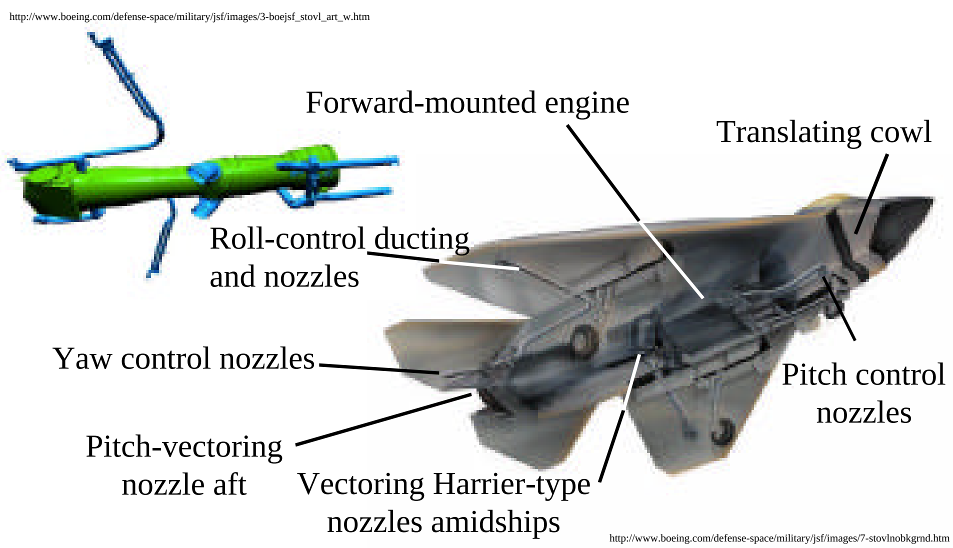
•Original design: CTOL and CV versions to have the same dimensions, with a leading-edge vortex flap on the leading edge of the Navy version (Ref. 8). 36 ft wingspan, 45 ft long. STOVL to have shorter, 30 ft wingspan. (Ref. 4) Forward-swept chin inlet.

•1998 design effort to improve control and maneuverability, reduce weight. Two parallel redesign efforts, one to rework original delta wing, one to try other options; cost of improvements was weighed in considering whether to implement changes. Demonstrator aircraft (X-32s) would not reflect these changes planned for the PWSC (preferred weapon system concept):

-Change inlet from forward to aft sweep, allowable because of nosegear redesign. Reduced weight of inlet structure, improved RCS and high-alpha inlet efficiency.

-To improve pitch control, wing needed to move aft, but this caused difficulties with balancing, imposing limits on fuel and payload capacities. By reducing wing area, lengthening aircraft by two feet, and adding horizontal tails, necessary pitching moment could be produced without affecting fuel fraction, range, weight, or balance. Trailing edge of wing has full-span flaperon on CTOL version, separate flaps and ailerons on CV version—also a leading edge flap forward of the aileron. (Ref. 9) Vertical tail redesigned also—same area, but reshaped.

Boeing STOVL 3-Post Direct Lift System

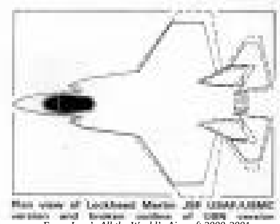


Boeing concept uses Harrier-type vectoring nozzles at center of gravity, vectoring main nozzle that can be directed downward. Auxiliary nozzles provide fine control of pitch, yaw, and roll. An additional nozzle forward of the swiveling nozzles provides a cold flow to screen the inlet from the hot exhaust gases aft. The cowl translates forward to increase area for higher airflow during high-thrust requirement STOVL operation. (Ref. 1, 2)

In up and away flight, midbody nozzles are covered with doors to improve observability. (Ref. 8)

Concept has been proven on Harrier, but still considered high-risk (Ref. 1, Ref. 2)—I don't entirely understand this. It is said that many things have to go right for it to work. Propbably this refers to the limited thrust capability of the concept, unaugmented by a lift fan.

Lockheed Martin X-35



From *Jane's All the World's Aircraft 2000-2001*,
Paul Jackson editor, p. 702

http://www.thefighterenterprise.com/image_gallery/jsf/jsf_2.htmlhttp://www.thefighterenterprise.com/image_gallery/pr_photos/jsfpr_photos/jsf_1stflight/jsf_1stflight88.html

•X-35 design reminiscent of F-22, but smaller and with only a single engine

•Notable feature: diverterless inlets with no moving parts: instead, a bump on the inlet wall splits the boundary layer apart and the sawtooth inlet captures clean airflow while the boundary layer slides around the upper and lower edges. Concept is a risk, but has flown at Mach 2 on a modified F-16. (Ref. 1, 11)

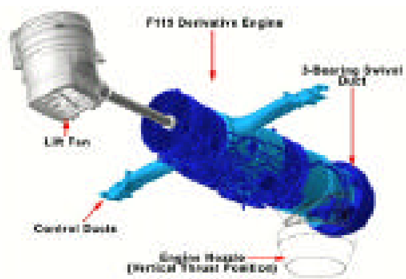
•CTOL and STOVL aircraft of the same dimensions, 35 ft wingspan, 50.5 ft length; CV aircraft larger, 43 ft wingspan, 50.8 ft length. (Ref. 2)

•Aircraft planned for production very similar to demonstrator aircraft. A higher-performance version with a larger wing was planned, but the extra capability was not needed, so the smaller, lighter, cheaper wing was selected for production. Wing area of the production CTOL version will be 412 ft^2 (compared to 450 ft^2 for the demonstrator), while the CV version will have 600 ft^2 of wing area (versus 540 ft^2 on the demonstrator). (Ref. 11, 12)

•CV version longer range (~100 nmi), lands slower (10 – 15 kt), but rolls and accelerates more slowly than the CTOL and STOVL versions. In the development of the production airplane, the high-lift devices and trim will be adjusted to produce similar performance in the carrier-based aircraft relative to the land-based ones; the extra effort will be reflected in extra cost for the carrier-based version. (Ref. 12) It is not clear to me how acceleration can be improved without uprating the engine or drastically reducing the drag—enough to require significant configuration changes.

•Weights: X-35A, 26 500 lb; X-35B, 30 697 lb; X-35C 30 618 lb (Ref. 4)

Lockheed Martin STOVL Lift Fan System



http://www.fas.org/man/dod-101/sys/ac/jsf.htm

- 60% thrust boost from increased bypass ratio
- Smaller inlets for supersonic flight

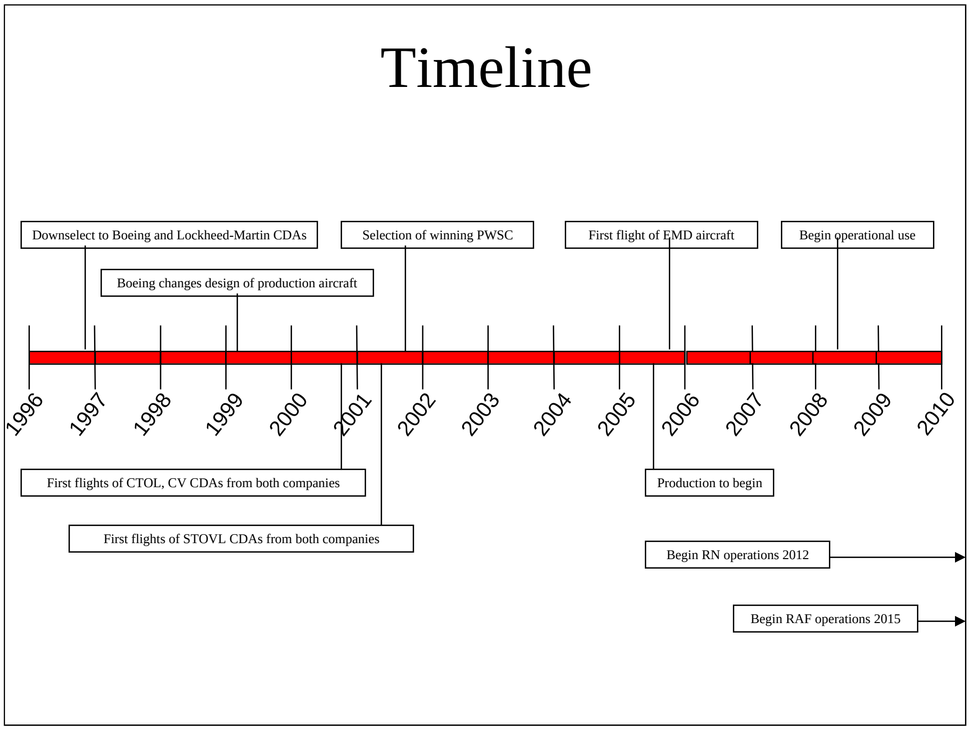
•Aft engine location better than forward for observability, supersonic concerns—three-bearing nozzle, as on Yak-141, rotates 90 deg from aft (cruise) position) to pointing down for vertical landing.

•Clutch at lift fan couples F119 low pressure shaft to lift fan. Lift fan has two stages, pressure ratio of 2. Uses 27 000 – 28 000 hp from 70 000 – 80 000 produced by turbine. (Ref. 7)

•Using lift fan instead of hot flow reduces flow velocity by 30%, lowers temperature by 250 deg F; lift fan produces about 18 000 lb thrust. (Ref. 8)

•Lift fan adds 4000 lb to airframe, but lifting capacity of STOVL is increased by much more—claims of 60% above direct thrust approach. For CTOL and CV versions, extra space otherwise used for lift fan is used for fuel and avionics. (Ref. 2)

•Cold flow from lift fan protects inlet from hot gas ingestion (Ref. 13)



•It is assumed that both aircraft will meet all requirements specified by the program office and that the winner will be the least-expensive of the two aircraft. The CDAs (concept demonstrator aircraft) are intended to *prove* that the concept is feasible (which may or may not present a problem for Boeing's design change). (Ref. 11)

•Design of each contractor's preferred weapons system concept (PWSC) is occurring concurrently with development of the CDAs. Proposals for an operational JSF will be submitted, and a winner selected in September of 2001. First flight will occur about four years later, and the engineering-manufacturing-development testing will proceed. (Ref. 14)

•Production is to begin in 2005 (note this is concurrent with EMD testing), for IOC in 2008. (Ref. 4)

•The U.K. anticipates replacing its RN Sea Harriers beginning in 2012, and its RAF Harrier GR.7s in 2015. (Ref. 15)

Flight Testing

http://www.boeing.com/defense-space/military/jsf/images/dsc_0010.htm

http://www.thefighterenterprise.com/image_gallery/pr_photos/jsfpr_photos/jsf_1stflight/jsf_1stflight51.html

Manufacturers break up differently between 2 airframes the flight testing of the three variants :

•Boeing is using a single airframe, the X-32A, for both the conventional and carrier landing versions. Both are to be tested at Edwards AFB. Boeing's STOVL version, the X-32B, has a smaller wingspan and is a separate airframe. (Ref. 4)

•Lockheed Martin originally flew the X-35A CTOL variant, then followed with the X-35C carrier version. The X-35B STOVL aircraft is being converted from the CTOL variant, while the larger X-35C is its own airframe. (Ref. 4)

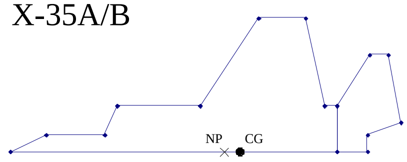
Boeing and Lockheed Martin's CTOL demonstrators had their first flights on September 16, 2000, and October 24, 2000, respectively (Ref. 4). Both companies' aircraft have flown supersonically. (Ref. 4, 16, 17)

Lockheed Martin's X-35C had its first flight 16 December 2000, flying from Palmdale, California to Edwards AFB. (Ref. 2) Two months later, the aircraft made a two-leg trip to Patuxent River NAS to take advantage of its sea level elevation (Edwards is at ~2300 ft) for field carrier landing trials. (Ref. 14)

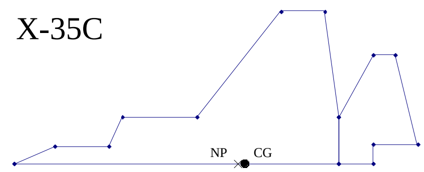
Boeing's X-32B STOVL demonstrator made its first flight on March 29, 2001. It will stay at Edwards for 6 weeks making conventional flights and will begin transitioning the vectoring nozzles at high altitude and 150 to 180 knots. Because of concerns about the aircraft's ability to land vertically at Edward's

VLM Analysis

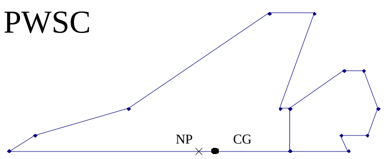
X-35A/B



X-35C



X-32 CTOL/CV
PWSC



Version	x_{np} (ft)	x_{cg} (ft)	MAC (ft)	Instability	E
X-32 CTOL/CV PWSC	24.3	26.3	17.8	11.1%	0.999
X-35A	28.9	31.0	16.0	13.0%	1.001
X-35C	30.1	31.0	17.3	5.1%	1.001

•VLM models were constructed and run with VLM4999, an increased panel capability version of VLM4997, adapted for PCs rather than Macintosh. Because of availability of geometric information, the Boeing production aircraft and Lockheed Martin demonstrator aircraft were modeled. No Boeing STOVL configuration definition could be found, so this aircraft was not modeled in VLM, skin friction, or P_S (later slides).

•8 horseshoe vortices were used chordwise, and 20 spanwise on each planform. Models were attempted both with and without vertical tails modelled. No problems occurred with the Boeing aircraft when the vertical tails were modeled, but the Lockheed Martin configuration produced induced drag coefficients of order 10^2, and the problem was traced to extraordinarily high C_P values on the vertical tail planform inboard of the forward fuselage streamwise line segment. For consistency, vertical tails were then left off all configurations.

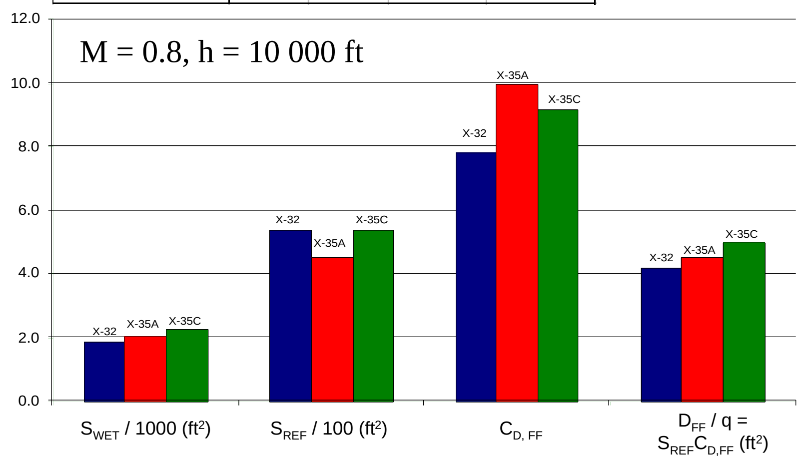
•Neutral point and Oswald efficiency data were extracted from the code output and are shown above. Centers of gravity were estimated by rotating the taildown angle 90 degrees forward and using a vertical position approximately equal to the wing height. Mean aerodynamic chords were estimated using trapezoidal reference wings drawn in to the centerline, with the MAC constructed geometrically.

•Using instability as an indicator, the X-35A/B appears to be the most agile. In reality, of course, many other factors affect maneuverability.

•Oswald efficiencies are quite high for these configurations—those for the X-35s are greater than 1.

Skin Friction / Form Drag Analysis

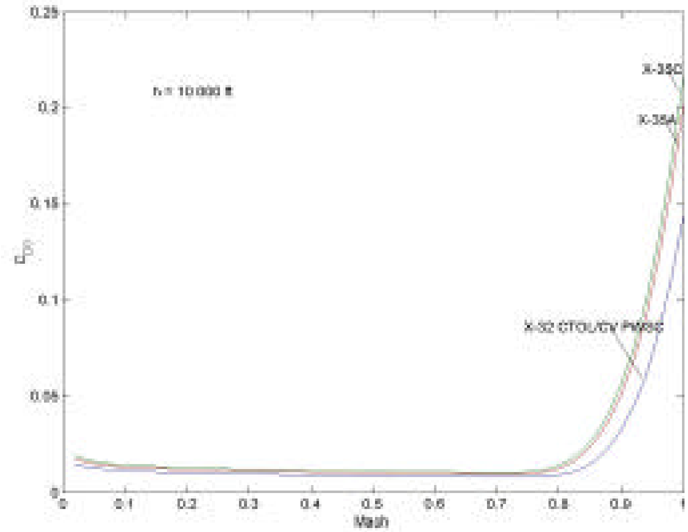
VERSION	S_{WET}(ft^2)	S_{REF} (ft^2)	$C_{D, FF}$	$D_{FF}/q = S_{REF}C_{D, FF}$ (ft^2)
X-32 CTOL/CV PWSC	1832	540	0.0078	4.212
X-35A	2043	450	0.0100	4.500
X-35C	2237	540	0.0092	4.968



•Wetted areas determined with AutoCAD on scanned three-views from Ref. 13

•Used validated MATLAB translation of friction.f to arrive at skin friction and form drag. Assumed fully turbulent flow.

Zero-Lift Drag Coefficient



Skin friction and form drag are already known. Wave drag is calculated below. Although the wing method is intended for high aspect-ratio wings, it at least provides some estimate of the increase in drag, preferable to a fully incompressible analysis.

Body drag divergent Mach number obtained from chart in Raymer (Ref. 22), based on nose fineness ratio:

X-32: 0.82

X-35: 0.865

Wing drag divergent Mach number calculated using Korn formula translated to 3-D, with sweep angle at 70% of the chord to represent shock line, airfoil technology factor assumed at 0.85 (not concerned with efficiency so much as a transport):

t/c

Sweep at 70% chord (deg) M_{DD} wing

X-32 0.10

34.3

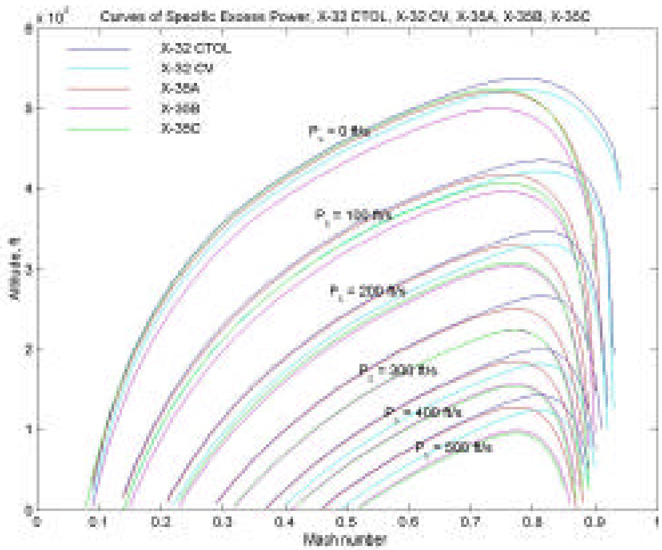
0.882

X-35A 0.0625

2.9

0.788

Specific Excess Power Contours



P_s contours give an indication of an aircraft's energy level—potential climbing or turning performance—at a certain flight condition. Overlaying the P_s curves will show which aircraft may have an energy advantage at different points in the envelopes, useful for ACM or missile evasion.

Weights used:

X-32 CTOL: Empty weight estimate plus half of 15 000 lb fuel, plus 2 x 2000lb JDAM: (26 500 + 0.5 * 15 000 + 2 * 2000) lb = 38 000 lb

X-32 CV: Empty weight estimate plus half of 15 000 lb fuel, plus 2 x 2000lb JDAM: (28 559 + 0.5 * 16 000 + 2 * 2000) lb = 40 559 lb

X-35A CTOL: Empty weight plus half of 15 000 lb fuel, plus 2 x 2000lb JDAM: (26 500 + 0.5 * 15 000 + 2 * 2000) lb = 38 000 lb

X-35B STOVL: Empty weight plus half of 15 000 lb fuel, plus 2 x 2000 lb JDAM: (30 697 + 0.5 * 15 000 + 2 * 2000) lb = 42 197 lb

X-35C CV: Empty weight plus half of 15 000 lb fuel, plus 2 x 2000lb JDAM: (30 618 + 0.5 * 16 000 + 2 * 2000) lb = 42 618 lb

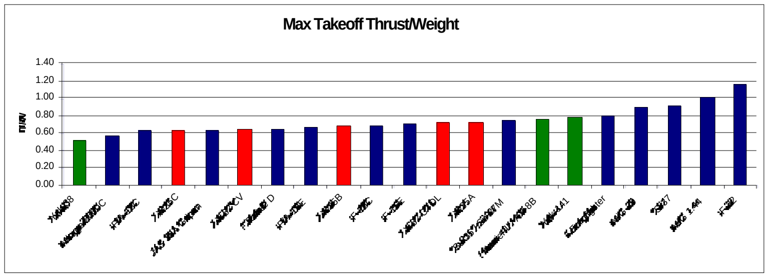
Drag model: $C_D(h, M, C_L) = C_{D,FF}(h, M) + C_{Dw}(M, C_L) + C_L^2 / (\text{pi AR E})$

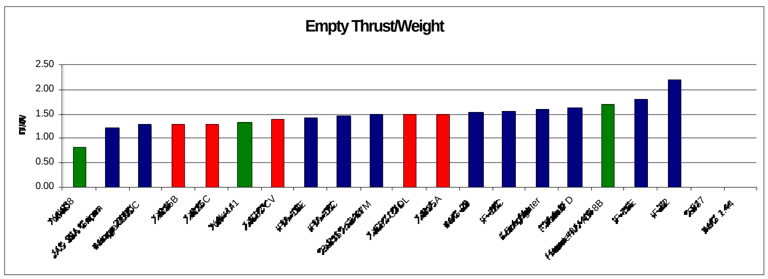
Used load factor n = 1 to determine $C_L = n W / (q S)$, and $q = 0.5\ \text{rho}^* (M a)^2$

Thrust model: $T_{SL} = 40\ 000$ lb, $T = T(h) = T_{SL} (\text{rho} / \text{rho}_{SL})$

- JSF intended to be primarily an air-to-ground airplane with an air-to-air capability
- JSF radar optimized for locating ground targets (Ref. 23)
- JDAM and AMRAAM are basic weapons intended for JSF (Ref. 24)
- X-32 designed to carry 2 air-to-air (lower bay) and 2 air-to-ground weapons (side bay) simultaneously. The lower door can open alone to fire a missile. The side bays for air to ground allow eye-level access for loading (although one might expect more difficulty loading a heavier weapon into a higher bay). (Ref. 9)
- X-32 planned to have 4 wing racks for missions when stealth is not so important (Ref. 10). X-35 plan unknown.
- USAF version will have internal cannon (Ref. 13)
- Other weapons in graphic above (from Boeing website) include JSOW, JASSM, SLAM-ER in addition to array of current widely-used weapons

Comparison—Thrust to Weight Ratio



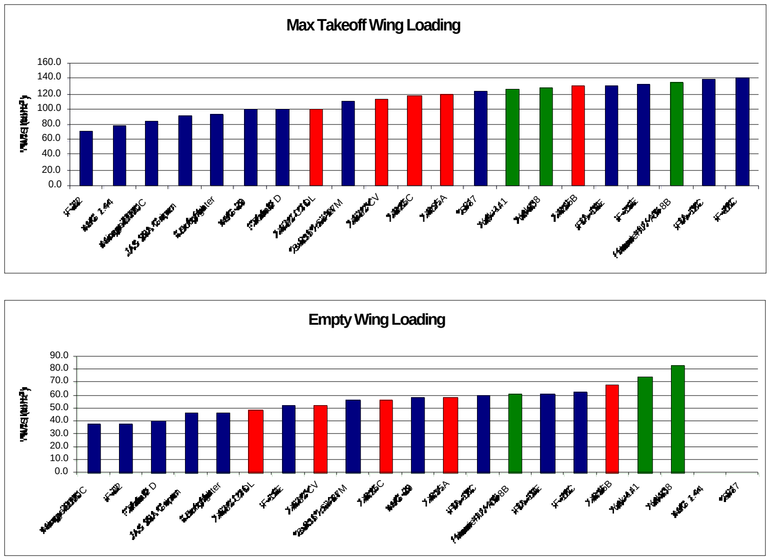


Data from Jane’s (Ref. 13, 25)—JSF data derived from program office requirements for payload and max fuel and assumes MTOW is empty plus max fuel plus max payload.

As expected, Air Force CTOL variant of JSF has highest T/W. JSF doesn’t outperform everything, but it is comparable to most the other aircraft. Yak-38, Yak-141, and X-35B numbers are in cruise; during STOVL operation, additional lift engine or fan operates and produces more thrust.

JSF’s advantage is in stealth.

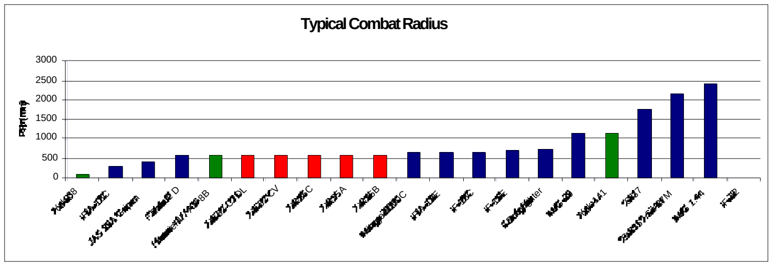
Comparison—Wing Loading

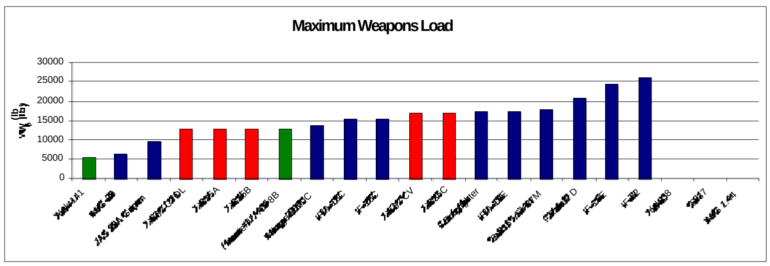


Data from Jane's (Ref. 13, 25)——JSF data derived from program office requirements for payload and max fuel and assumes MTOW is empty plus max fuel plus max payload.

JSF variants have higher wing loading than most recent and future fighter developments and demonstrators—implies poorer turn performance.

Comparison—Range, Payload





Data from Jane's (Ref. 13, 25)—JSF data from program office requirements.

As noted earlier, the X-35C has greater range than the X-35A by about 100 nmi, but this is assumed to be for the demonstrator with no weapons, and would not translate to 100 nmi greater range at combat weights. Since the equivalent combat radius difference is unknown, no difference is shown in the chart.

JSF variants carry same load to same range as Harrier: comparable to most combat aircraft

Outlook

- Cost drives the JSF program
- Assuming both demonstrators are successful in meeting performance goals—which they are expected to be—and there is no major difference in performance, the cheaper concept will be selected. But Boeing's demonstrator is dissimilar from production airplane!
- P_s curves indicate generally but marginally better performance for X-32, but the curves are known to be inaccurate with wave drag
- STOVL may become key issue. Lift fan concept produces greater thrust, offers MUCH more bringback capability unless Boeing can DRASTICALLY cut weight—and weight was already a problem for the Boeing STOVL variant
- Advantage: Lockheed-Martin

Air Force may want X-32, but Navy likely to opt for better performance of X-35C at lower regimes where P_s is most likely to be used—subsonic to transonic dogfights and maneuvering.

USMC almost assuredly will select better STOVL performance of X-35B over X-32.

Given marginal advantage of X-32A over X-35A, performance gains for Air Force will be insignificant, and X-35 will be selected.

HOWEVER, if the X-32 significantly outperforms the X-35, the services may attempt to choose different aircraft. Since the costs would be prohibitive, the services will have to settle for a single aircraft, or the program will be killed. Almost assuredly they will settle for a common aircraft.

References

- Sweetman, Bill. *Joint Strike Fighter*. MBI Publishing Company, Osceola, Wisconsin. 1999.
- Tirpak, John A. “Scoping Out the New Strike Fighter.” *Air Force Magazine*. October 1998, pp. 36-41.
- Tirpak, John A. “Strike Fighter.” *Air Force Magazine*. October 1996, pp. 22-28.
- Iannotta, Ben. “JSF Rivals Face Off.” *Aerospace America*, January 2001, pp. 34-40.
- http://www.jast.mil, Program→Overview. 15 April 2001.
- http://www.pratt-whitney.com/3a/html/products_f119.html. 22 April 2001.
- Dornheim, Michael A. “Lift Fan Installed In STOVL X-35B.” *Aviation Week & Space Technology*. 8 January 2001, p. 27.
- “Joint Strike Fighter: One Aircraft, Many Missions.” *Aviation Week & Space Technology*. 25 May 1998, pp. S3 – S18.
- Dornheim, Michael A. “X-32A Ends Test Series.” *Aviation Week & Space Technology*. 12 February 2001, p. 31.
- Fulghum, David A., and Paul Proctor. “Boeing Redesigns Its Joint Strike Fighter.” *Aviation Week & Space Technology*. 1 February 1999, pp. 28-32.
- Wall, Robert, and David Fulghum. “Lockheed Martin Sets JSF Design, Turns to Cost, Subsystem Work.” *Aviation Week & Space Technology*. 1 February 1999, pp. 33-34.
- Fulghum, David A. “Navy X-35C JSF Demonstrator Lands Slower, Flies Farther.” *Aviation Week & Space Technology*. 5 March 2001, pp. 32-33.
- Jackson, Paul, editor. *Jane’s All the World’s Aircraft, 2000-2001*. Jane’s Information Group, Incorporated. Alexandria, Virginia, 2000.
- Smith, Bruce A. “X-35C Begins Pax River Testing.” *Aviation Week & Space Technology*. 19 February 2001, p. 32.
- Morrocco, John D. “U.K. Antes Up $2.8 Billion for JSF.” *Aviation Week & Space Technology*. 22 January 2001, p.33.
- Warwick, Graham. “Hover pit testing begins for X-35C Joint Strike Fighter.” *Flight International*. 6-12 March 2001, p. 16.
- “Aircraft carrier version of JSF X-35 gets aloft.” *Flight International*. 2-8 January 2001, p. 16.
- “World News Roundup.” *Aviation Week & Space Technology*”. 1 January 2001, p. 18.

References (continued)

- “X-32B JSF Demonstrator Debuts in Conventional Mode.” *Aviation Week & Space Technology*. 2 April 2001, p.34.
- “Boeing and Lockheed Martin diverge on STOVL testing strategy.” *Flight International*. 20-26 March 2001, p. 20.
- http://www.boeing.com/news/releases/2001/q2/news_release_010416n.htm. 23 April 2001.
- Raymer, Daniel P. *Aircraft Design: A Conceptual Approach*, Third Edition. AIAA, Reston, Virginia: 1999.
- Fulghum, David A. “F-22, JSF Designed For Distinct Roles.” *Aviation Week & Space Technology*. 7 February 2001, pp. 52-54.
- Norris, Guy. “Boeing Predicts its Joint Strike Fighter will beat cost targets.” *Flight International*. 6-12 February 2001, p. 18.
- Lambert, Mark, editor. Jane’s *All the World’s Aircraft, 1993-1994*. Jane’s Information Group, Incorporated. Alexandria, Virginia, 1993.