



AEROSPACE INFORMATION REPORT

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Reverse Thrust

RATIONALE

This SAE Aerospace Information Report is intended to provide a comprehensive reference on engine and airframe considerations pertaining to thrust reverser applications. In practice, reverse thrust is propulsion system specific since the thrust reverser is generally an engine component and operation of the reverser causes many engine/aircraft integration issues. This report offers technical insights on how reverse thrust can be applied to airplane configurations with minimal adverse effects on engine and airframe performance.

FOREWORD

Propulsion measurements and thrust methods presented in the current published versions of SAE AIR1703 and SAE AIR5450 place a primary focus on the engine reactionary force (thrust) acting to propel an aircraft in the forward direction. In contrast, this document addresses the use of the engine reactionary force in the opposite direction (reverse thrust) to supplement aircraft deceleration.

This document's application spans commercial and military transport turbofan engine applications for various engine and reverse thrust configurations. The discussion and examples primarily focus on separate flow exhaust turbofan engines. Piston and turboprop variable-pitch propeller blade applications are not covered. Although reverse thrust has been utilized for in-flight deceleration, primarily for short takeoff and landing aircraft and military fighter applications, this application of reverse thrust is only covered in a cursory manner.

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1. SCOPE

Propulsion measurements and thrust methods presented in the current published versions of AIR1703 and AIR5450 place a primary focus on the engine reactionary force (thrust) acting to propel an aircraft in the forward direction. In contrast, this document addresses the use of the engine reactionary force in the opposite direction (reverse thrust) to supplement aircraft deceleration.

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2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1703 In-Flight Thrust Determination

AIR5450 Advanced Ducted Propulsor In-Flight Thrust Determination

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 AGARD Publications

Available from <https://www.sto.nato.int/publications/>

AGARD-CP-91-71 Inlets and Nozzles for Aerospace Engines: Aerodynamics of Thrust Reverser Design

AGARD-CP-331 Essais en soufflerie de maquettes motorisées. Comparaison de deux méthodes de simulation de jets réacteurs

AGARD-CP-498 Aerodynamic Engine/Airframe Integration for High Performance Aircraft and Missiles

2.2.2 Air Force Aero-Propulsion Lab Publication

Available from National Technical Information Service, 5301 Shawnee Road, Alexandria, VA 22312, Tel: 1-888-584-8332 or 703-605-6050, www.ntis.gov.

AFAPL-TR-72-11 Thrust Reverser and Thrust Vectoring Literature Review

2.2.3 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, Tel: 703-264-7500, www.aiaa.org.

AIAA-70-513	Inflight Thrust Control for Fighter Aircraft
AIAA-70-699	Development of an In-Flight Thrust Reverser For Tactical/Attack Aircraft
AIAA-74-1170	Test and Evaluation of a Fighter Aircraft In-Flight Thrust Reverser
AIAA-74-1171	Performance of a Cascade Thrust Reverser for Short-Haul Applications
AIAA-79-1810	The Nonaxisymmetric Nozzle - It is for Real
AIAA-85-0381	Benefit and Costs of Powered Simulation at Low Speeds
AIAA-85-1779	Advanced Fighter Aircraft Metrics
AIAA-87-1922	F-15 SMTD Hot Gas Ingestion Wind Tunnel Test Results
AIAA-90-1906	Flight Test Results of the F-15 SMTD Thrust Vectoring/Thrust Reversing Exhaust Nozzle
AIAA-97-3153	Aerodynamic analysis of an installed thrust reverser
AIAA-2001-3747	Computational Procedures for Complex Three-Dimensional Geometries Including Thrust-Reverser Effluxes and APUs
AIAA-2003-0723	Aircraft Thrust Reverser Cascade Configuration Evaluation Through CFD
AIAA-2006-0056	Simulation of vortex flows for airplanes in ground operations

2.2.4 ASME Publication

Available from ASME, P.O. Box 2900, 22 Law Drive, Fairfield, NJ 07007-2900, Tel: 800-843-2763 (U.S./Canada), 001-800-843-2763 (Mexico), 973-882-1170 (outside North America), www.asme.org.

Anon. International Historic Engineering Landmark - Hamilton Standard Hydromatic Propeller

2.2.5 Boeing Publication

Available from http://www.boeing.com/news/frontiers/archive/2008/july/i_history.pdf

Lombardi, Michael Seventh heaven. Boeing Frontiers

2.2.6 Boeing Aero Magazine Publication

Available from http://www.boeing.com/commercial/aeromagazine/aero_11/

Nova, B. and Field, G. Rejected Takeoff Studies

2.2.7 Delft University Press Publication

Available from <http://www.iospress.nl/book/aerodynamic-design-of-transport-aircraft/>

Obert, Ed Aerodynamic Design of Transport Aircraft

2.2.8 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

FAA Advisory Circular No. 25-7C Flight Test Guide for Certification of Transport Category Airplanes

FAA Technical Report NTIS PB93-780013 Takeoff Safety Training Aid

2.2.9 Flight International Magazine Publications

Available from <http://www.flightglobal.com/pdfarchive/index.html>

Anon. Reversing the Flow

Anon. Too Many Overruns

Velupillai, DavidRB.211-535: Rolls-Royce's Boeing 757 Fan

2.2.10 Flight Magazine Publications

Available from <http://www.flightglobal.com/pdfarchive/index.html>

Anon. Aero Engines 1954 SNECMA

Anon. By Comet 4 to New York

Anon. Pierre Levasseur

Anon. Rolls Royce Reversers

Anon. The Aeroplane's Gear Box

Anon. The Gloster Aircraft Co., Ltd.

Anon. The Seventeenth S.B.A.C. Display - Rolls-Royce Reverse-thrust Hunter (XF 833)

Anon. Thrust to Drag - Boeing Reveal Details of their Thrust-reversal Research

2.2.11 International Congress of the Aeronautical Sciences

Available from <http://www.icas.org/>

Yao, H. et al The Aerodynamic Performance of a Reverser Cascade

2.2.12 NACA/NASA Publications

Available from NASA Center for AeroSpace Information (CASI), 7121 Standard Drive, Hanover, MD 21076-1320.

NACA RM L57J16 Effect of Target-Type Thrust Reverser on Transonic Aerodynamic Characteristics of a Single-Engine Fighter Model

NACA TN-3664 Summary of Scale-Model Thrust-Reverser Investigation

NACA TN-3975 Investigation of a Full-Scale Cascade-Type Thrust Reverser

NASA CR-144882 YF-17/ADEN System Study

NASA CR-145295	F-15 2-D Nozzle System Integration Study
NASA Memo 4-26-59A	Flight Measurements of the Effect of a Controllable Thrust Reverser on the Flight Characteristics of a Single-Engine Jet Airplane
NASA SP-3300	Flight Research at Ames - Fifty-Seven Years of Development and Validation of Aeronautical Technology
NASA TM-109158	Why Do Airlines Want and Use Thrust Reversers
NASA TM-110351	Investigation of Wing Upper Surface Flow-Field Disturbance Due to NASA DC-8-72 In-Flight Inboard Thrust Reverser Deployment
NASA TM-210300	Static Performance of Six Innovative Thrust Reverser Concepts for Subsonic Transport Applications
NASA TMX-3247	Effect on Fan Flow Characteristics of Length and Axial Location of a Cascade Thrust Reverser
NASA TN D-6460	Performance Characteristics of a Single-Engine Fighter Model Fitted with an In-Flight Thrust Reverser
NASA TP-2856	Thrust Reverser Flow Investigation on a Twin-engine Transport
NASA TT F-603	Systems for Deflection of the Jet Streams of Turbo-Jet Engines

2.2.13 Performance and Flight Operations Engineering Conference

Available from <http://www.scribd.com/doc/132880559/Performance-Margins>

Schmid, Paul Performance Margins

2.2.14 Popular Mechanics

Available from <http://books.google.com/books/serial/ISSN:00324558?view=1>

Anon. "Gear Shift" For Airplanes Seen in Adjustable Prop

2.2.15 Popular Science

Available from <http://books.google.com/books/serial/ISSN:01617370?view=1>

Boone, Andrew R. Boeing's Jet Stratoliner, July 1954

2.2.16 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Kehrer, W., "Development of In-Flight Modulating Type Thrust Reverser For Single Engine Aircraft," SAE Technical Paper 600381, 1960, <https://doi.org/10.4271/600381>.

Thompson, J., "Thrust Reverser Effectiveness on High Bypass Ratio Fan Powerplant Installations," SAE Technical Paper 660736, 1966, <https://doi.org/10.4271/660736>.

Pickerd, J. and Hinds, C., "Thrust Reversers for Business Jet Aircraft," SAE Technical Paper 670235, 1967, <https://doi.org/10.4271/670235>.

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Lennard, D., "Design Features of the CF6 Engine Thrust Reverser and Spoiler," SAE Technical Paper 690411, 1969, <https://doi.org/10.4271/690411>.

Caffier, E., "The SNECMA Thrust Reverser System of Concorde's Prototypes," SAE Technical Paper 690412, 1969, <https://doi.org/10.4271/690412>.

Colley, R. and Sutton, J., "Thrust Reversers for Civil STOL Aircraft," SAE Technical Paper 730358, 1973, <https://doi.org/10.4271/730358>.

Allen, A. and Wickline, R., "Design, Development and Flight Test of the Cessna Citation Thrust Reverser," SAE Technical Paper 760468, 1976, <https://doi.org/10.4271/760468>.

SAE Preprint 85C Practical Experience on Thrust Reversers

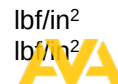
2.2.17 Springer Publication

Available from <http://www.springer.com/?SGWID=0-102-0-0-0>

Linke-Diesinger, A. Systems of Commercial Turbofan Engines: An Introduction to Systems Functions. Chapter 8: Thrust Reverser Systems

2.3 Symbols

		U.S. Customary	
Roman	Description	Units	SI Units
A	Area	ft ²	m ²
AE	Effective Area	ft ²	m ²
AM	Area Match	-	-
ART	Anti-Reingestion Tunnel	-	-
BOAC	British Overseas Airways Corporation	-	-
BPR	Bypass Ratio	-	-
C-D	Convergent Divergent Nozzle	-	-
CFR	Code of Federal Aviation Regulations	-	-
C _M	Pitching Moment	-	-
CS	Certification Standard	-	-
CV	Velocity Coefficient	-	-
EASA	European Aviation Safety Agency	-	-
F	Force or Absolute Stream Force	lbf	N
FAA	Federal Aviation Authority	-	-
F _G	Gross Thrust and Gauge Stream Force	lbf	N
F _G [*]	Modified Gross Thrust at Core or Bypass Nozzle Exit	lbf	N
FOD	Foreign Object Damage	-	-
KTS	Speed in Knots	knots	-
LH	Left Hand	-	-
M	Flight Mach Number	-	-
MGBP	Moving Ground Belt Plane	-	-
NASA	National Aeronautics and Space Administration	-	-
NLR	Dutch National Aerospace Laboratory	-	-
NPR	Nozzle Pressure Ratio	-	-
OEI	One Engine Inoperative	-	-
P	Pressure	lbf/in ²	N/m ²
Pamb	Ambient Pressure	lbf/in ²	N/m ²
P _s	Static Pressure	lbf/in ²	N/m ²



P _{SO}	Freestream Static Pressure	lbf/in ²	N/m ²
R	Gas Constant	ft lbf / lbmol °R	J/mol K
RH	Right Hand	-	-
RPM	Revolutions Per Minute	min ⁻¹	min ⁻¹
RTO	Rejected Takeoff	-	-
Q	Dynamic Pressure	lbf/in ²	N/m ²
STOL	Short Takeoff and Landing	-	-
T	Total Temperature	°R	K
TCS	Turbulence Control Structure	-	-
TPS	Turbine Powered Simulator	-	-
W	Mass Flow Rate	lbm/sec	kg/s
W _P	Primary Stream Mass Flow Rate	lbm/sec	kg/s
U ₀ (and V ₀)	Freestream Velocity	ft/s	m/s
V	Velocity	ft/s	m/s
V _{AC}	Aircraft Velocity	ft/s	m/s
V _r	Aircraft Rotation Speed	knots	knots
V ₁	Decision Speed	knots	knots

Greek	Description	U.S. Customary Units	SI Units
γ	Specific Heat Ratio		
Δ	Parameter Incremental Change	-	-
φ	Axial Gauge Force on a Body or Stream Tube Surface	lbf	N

Subscripts	Description
0,1,2, etc.	Station designations
A	Axial
a	Actual
CCAB	Core Cowl Afterbody
EXH	Exhaust
fan	Fan or Bypass Stream
i	Isentropic
id	Ideal
INL	Inlet
h _{rev}	Thrust Reverser Effectiveness
PLUG	Plug Surface Downstream of Primary Exhaust Exit
Pylon	Pylon Surface within Bypass Streamtube
REV	Reverser
Total	Combined Fan and Core Exhaust

2.4 Definitions

2.4.1 CUT-OFF SPEED

Minimum aircraft speed where power setting must be reduced from maximum reverse power, because of potential reverser exhaust gas reingestion, foreign object ingestion, or reverser plume impingement on aircraft surfaces.

2.4.2 STOPPING DISTANCE OR LANDING GROUND ROLL

Aircraft runway distance traveled from touchdown to achieving a complete stop.

2.4.3 REVERSE THRUST EFFECTIVENESS OR REVERSE THRUST COEFFICIENT

Ratio of the corrected axial force during reverse thrust operation to the total forward thrust that is produced at corresponding nozzle(s) pressure ratio(s).

3. BACKGROUND AND CONFIGURATIONS

3.1 Historical Background

Reverse thrust is defined as the intentional turning of the thrust force vector away from the nominal axial direction for the intended purpose of providing additional aircraft deceleration capability beyond other conventional mechanical systems such as dive brakes, spoilers, wheel brakes, etc. Figure 1 illustrates simple single stream forward thrust and reverse thrust configurations.

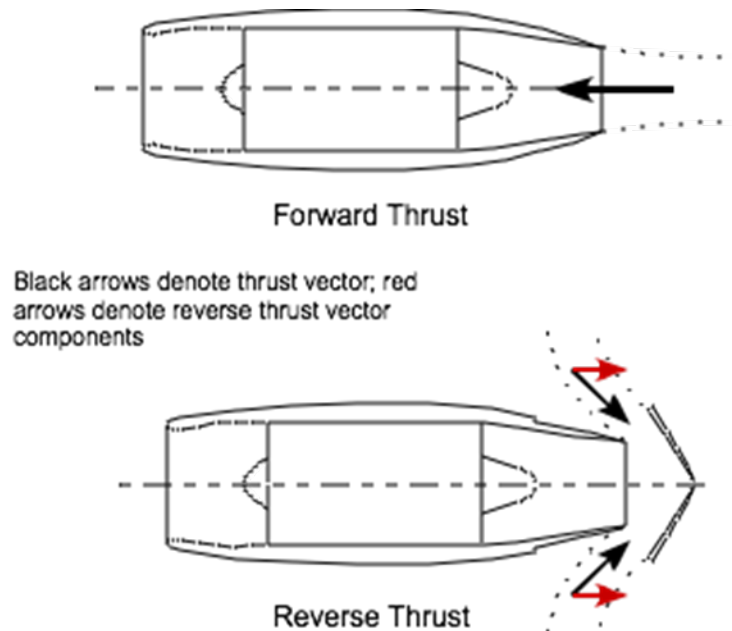


Figure 1 - Forward and reverse thrust configurations

During reverse thrust operation, the sum of all thrust vector components results in a total thrust vector acting in the negative thrust (drag) direction. Some thrust reverser designs have the capability to operate in partial reverse or thrust spoiler mode. In this mode, the sum of all thrust vector components results in a total thrust vector that still acts in the forward thrust direction but at a much lower magnitude than normal forward thrust.

Reverse thrust technology was first introduced on piston engine installations with variable pitch propellers capable of a reverse pitch setting. This reverse thrust technology grew from controllable, variable-pitch propeller blades that were first introduced in the period from 1921 to 1932 as a means for optimizing thrust over a range of flight conditions and thrust settings (References 1,2,3,4). The first practical, controllable pitch propeller (named the “Hydromatic”) was introduced in 1930 by Hamilton Standard; this innovation won the Collier Trophy in 1934 (Reference 5). The “Hydromatic” propeller was commercialized in 1937 and adapted by 21 airlines. Prominent aircraft that used the “Hydromatic” were the Douglas DC-2 and DC-3, Boeing 247, Stratoliner and Clipper, Sikorsky Flying Boat, Martin Clipper, and Lockheed 12, 14 and Lodestar. During World War II, the “Hydromatic” powered most U.S. military aircraft. After the war, as aircraft grew larger, designers had difficulty designing wheel brakes that would adequately stop the aircraft after landing. To meet this need, the “Hydromatic” was modified to allow the propeller blades to go into reverse or negative pitch. The first reversible “Hydromatic” propeller went in service on a United Airlines Douglas DC-6 in the fall of 1946 (Reference 5). This technology is still used on piston/turbojet commercial and short takeoff and landing (STOL) aircraft such as the Bombardier Dash 8 and de Havilland Canada DHC-3 Otter.

With the rising dominance of the jet engine in the 1940s, work turned toward developing thrust reversers for jet engines by utilizing deflected exhaust reaction forces. Most of the early thrust reverser development for jet engines was done for military aircraft. The first installation of a jet engine thrust reverser may have been on a Whittle engine mounted in the tail of a Wellington bomber in 1945, but this effort is not well documented (Reference 6). The first documented turbojet engine thrust reverser was built in the Soviet Union in 1948 and flight tested in 1949 (Reference 7). Two "shutters" were located aft of the nozzle exit that, when closed, deflected the exhaust in two directions and achieved a reverse thrust coefficient of 0.35 to 0.40. The Soviet Union thrust reverser development continued into 1949 by conducting research on a variety of thrust reverser concepts mounted on a RD-10 engine as shown in Figure 2. This work was conducted on round and rectangular nozzles.

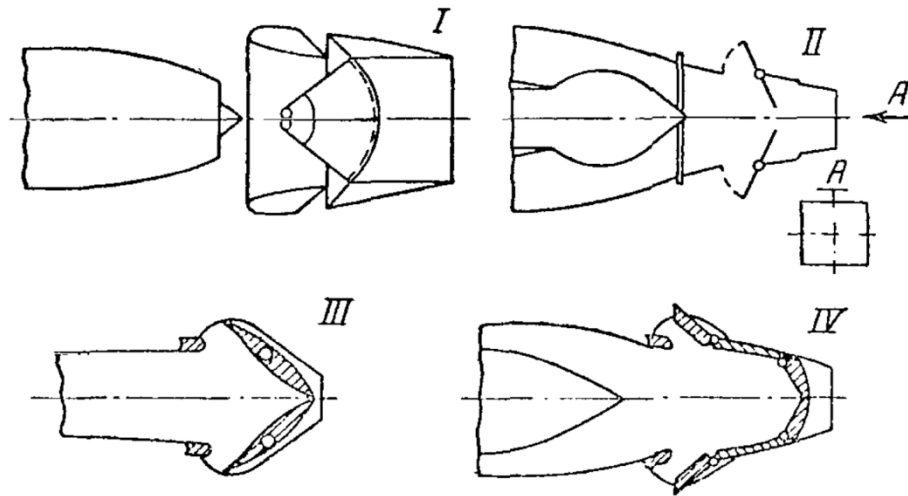


Figure 2 - Reversers investigated on the RD-10 engine (Reproduced from Reference 7)

SNECMA fitted a thrust reverser to a de Havilland Vampire aircraft with a Goblin engine in 1951 and was the first company to publish mechanical details of a jet engine thrust reverser in 1952 (Reference 6). This device was designed for in-flight use as a speed brake and was flight tested up to Mach 0.9. In 1953, SNECMA demonstrated thrust reverser operation at the LeBourget airport in Paris by traversing a Vampire aircraft backwards across the airport (Reference 7). By April 1954, SNECMA had developed a thrust reverser device that used a compressed air fluidic blocker to deflect the exhaust into a series of curved rings (cascades) to turn the exhaust about 130 degrees to provide a reverse thrust coefficient of about 0.25 (Reference 8). This device was flight tested 150 hours on five different aircraft.

In the 1950s, thrust reversers were being developed on both sides of the Atlantic Ocean for large jet-powered commercial aircraft being proposed by Boeing (707) and de Havilland (DH 106 Comet). Boeing, working with Pratt and Whitney, conducted research on a variety of reverser designs aimed at allowing an aircraft to land on a contaminated runway at maximum weight (Reference 6). One of the reversers studied was the target or clamshell design shown in Figure 3.

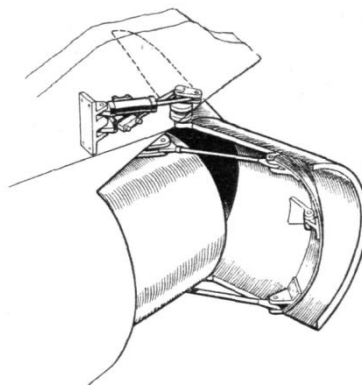


Figure 3 - Target reverser (Reproduced from Reference 6)

In 1954, Boeing initiated an extensive flight test program on various reverser designs installed on a B-47 and other aircraft and, in July, a clamshell reverser was flown on the Boeing 707 prototype (Boeing 367-80) (References 6 and 9). During the same period in Britain, Rolls Royce was developing thrust reversers under a contract to the Ministry of Supply. Their efforts were aimed at long range airliner applications (References 10 and 11). Flight tests were conducted on a reverser installed on a Hunter 6 aircraft with an Avon engine as shown in Figure 4 and Figure 5. The reverser concept included “eyelid” shutters (clamshells) to block and divert the jet exhaust through lateral exits with cascade vanes.

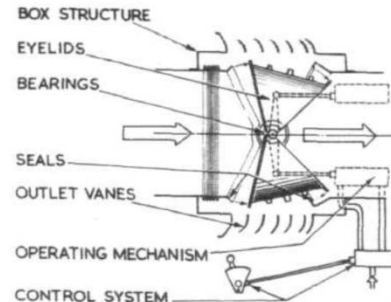


Figure 4 - Rolls Royce cascade thrust reverser concept (Reproduced from Reference 11)



Figure 5 - Thrust reverser installed on a Hunter 6 aircraft (Reproduced from Reference 10)

By 1959, Rolls Royce had completed over 5000 cycles during more than 1000 hours of running (including 150 hours of flight tests) on the thrust reverser designed for the new long-range commercial Comet aircraft, as depicted in Figure 6 (Reference 11).

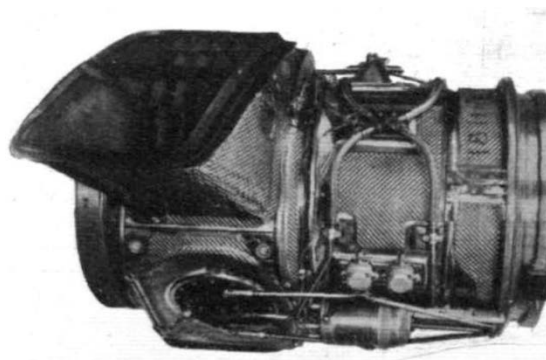


Figure 6 - Thrust reverser for Comet aircraft (Reproduced from Reference 11)

On October 4, 1958, a B.O.A.C. Comet 4 made the first jet passenger service flight across the Atlantic (Reference 12) and about three weeks later on October 26, Pan American initiated transatlantic jet service with the Boeing 707 (Reference 13); both aircraft utilized thrust reversers upon landing. Since these momentous events, almost every commercial jet aircraft built has utilized thrust reversers to shorten landing ground roll.

3.2 Benefits

Based upon thrust reverser utilization on current commercial airlines there is near unanimous agreement that the benefits of thrust reversers outweigh the disadvantages. The benefits that can be attributed to thrust reverser utilization are enumerated in this Section. A more detailed discussion of these benefits is provided in Section 5.

- Reduced Landing Distance (see References 6, 7, and 14 to 27)
- Shorter Ground-Roll On Rejected Takeoffs (see References 7, 16 to 18, 20, 23, 24, and 28 to 31)
- Reduced Brake/Tire Wear (see References 7, 15, 17, 18, 20, 22, 23, and 28)
- Power Back/Ground Maneuvering (see References 17, 18, 20, 23, 24, and 28)
- In-Flight Use
 - o Precision Landing (see References 7, 17, 20, 25, and 32 to 35)
 - o Rapid In-Flight Deceleration (see References 6, 7, 16 to 19, 22, 25, 28, 32, 33, and 36 to 38)
 - o Improved Thrust Response Time (see References 7, 9, 20, 22, 33, 34, and 39)
- Other (for military aircraft applications)
 - o Improved Combat Maneuverability (see References 22, 25, and 39 to 43)
 - o Improved Weapon Delivery Accuracy (see References 22, 25, 41 and 42)

3.3 Disadvantages and Issues

To obtain the benefits enumerated in 3.2, several disadvantages and issues must be addressed. The potential disadvantages and issues for thrust reverser installations are provided in the following sections. A more detailed discussion of these issues is provided in Section 5.

3.3.1 Disadvantages

Some penalties are unavoidable when thrust reversing capability is added to an aircraft design. A great deal of effort is required to minimize these penalties and since the thrust reverser is inherently an engine component, the burden of this effort often falls on the engine provider.

- Weight (see References 7, 15, 18, 20, and 24)
- Maintenance (see References 7, 15, 18, 20, 23, 24 and 36)
- Cost (see References 7, 18, and 24)

3.3.2 Issues

The decision to include thrust reverse capability on an aircraft presents many issues that must be addressed to ensure that the engine and airframe are successfully integrated with each other. Successful propulsion system integration requires cooperation between the engine and airframe manufacturers.

- Hot Gas and Foreign Object Ingestion (see References 7, 14, 16 to 20, 23, 24, 28, 36, and 45 to 47)
- Hot Gas Impingement (see References 7, 14, 18 to 20, and 28)
- Aerodynamic Interactions (see References 14, 18, 20, 22 to 25, 32, 34 to 37, 39, 41, 42, 44, 48, and 49)
- Engine Operability (see References 7, 14, 28, and 41)
- Thrust Reverser Effectiveness (see References 7, 16, 23, 28, and 41)
- Nozzle/Aircraft Cruise Performance (see References 7, 14, 18, 20, 21, 44, and 45)
- Noise (see References 20, 24, 44)
- Inadvertent In-Flight Deployment/Asymmetric Thrust (see References 7, 18, 20, and 45)

3.4 Configurations

Thrust reversers primarily consist of two different physical elements - an element that blocks exhaust flow (fan, primary or both) and an element that turns exhaust flow to a forward direction. Sometimes these two elements are combined into a single element serving both functions. During early development of reversers many options were studied. For example, Reference 7, published in 1968, categorizes thrust reversers into thirteen different types. As designs matured, thrust reverser concepts generally evolved into three recognized types - the pre-exit cascade thrust reverser, the pre-exit deflector or pivot door thrust reverser, and the post-exit target thrust reverser (References 18, 48, 50). A table showing the type of thrust reverser (unless noted, only fan exhaust flow is reversed) utilized on various aircraft is shown in Figure 7.

Figure 7 - Aircraft/thrust reverser combinations

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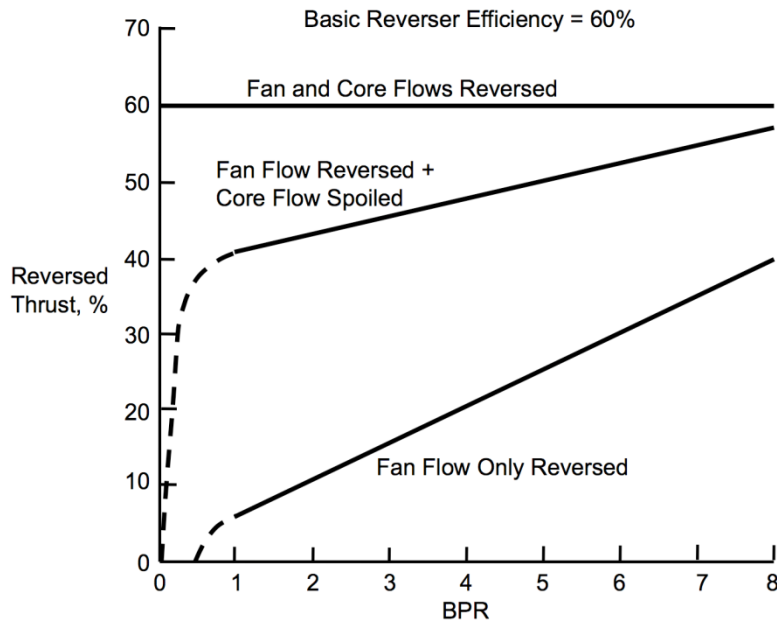


Figure 8 - Effect of engine BPR on available reverse thrust (Adapted from Reference 18)

References 16 and 18 indicate that for engine BPR less than 3, a core flow thrust reverser is required in addition to a fan flow thrust reverser; for engine BPR greater than 8, no core thrust reverser is required. For engine BPRs between 3 and 8, a core thrust spoiler (thrust = 0) may be required (References 16 and 18). Reference 23 indicates that a core thrust reverser is seldom used for engine BPR greater than 6. For engine BPRs (greater than 9, where the core stream only contributes about 5 to 10% of the total thrust, the design practice is to forego the use of a core stream reverser unless it is required to deflect the hot core exhaust gases for some other reason. For example, the C-17 deflects hot core flow to allow cargo/troop loading/unloading with engine running (Reference 28). The impact of BPR on reverser design is evident in Figure 7 where low BPR configurations (B-737, DC-8, DC-9, business jets) utilize target thrust reversers that reverse both fan and core flow; medium BPR configurations (DC-10, L-1011) utilize fan flow reversers and core flow thrust spoilers; and configurations with higher BPR (B-747, B-757, Airbus 340) utilize fan flow cascade or pivot door thrust reversers only.

A description of the three main types of thrust reversers listed in Figure 7 is provided in the following sections.

3.4.1 Target Thrust Reversers

The target thrust reverser converts the aft section of the engine cowl/nacelle into two reinforced target doors or buckets that are actuated by arms to swing together to a position aft of the nozzle exit (References 6, 7, 14, 17, 18, 23, 32, 45, 48, 50 and 55). This reverser type is sometimes called a “clamshell” or “bucket” reverser based on the shape of the target. The exhaust gas is deflected in a forward direction by these doors to produce reverse thrust. In the stowed mode, the doors form as smooth a nacelle contour as possible internally and externally to minimize losses. A sketch showing a target thrust reverser in the stowed and deployed mode is shown in Figure 9 and photographs showing typical target thrust reverser installations are shown in Figure 10 and Figure 11.

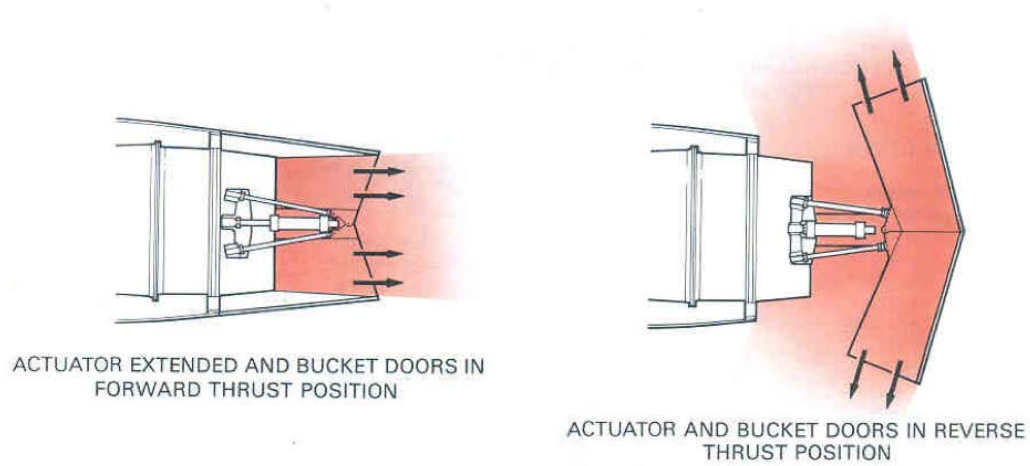


Figure 9 - Sketches showing a typical target thrust reverser



Figure 10 - Target thrust reverser installation on KLM FOKKER 70



Figure 11 - Target thrust reverser installed on Rolls-Royce RB199 engine (Photo by Remy Blot)

Some of the advantages of target thrust reversers are:

- The large aft facing surfaces cause increased drag when deployed and increase thrust reverser retarding force.
- They are relatively simple and have reduced maintainability concerns (References 14 and 48).
- All thrust reverser doors, actuators, hinges and seals are stored outside of the hot exhaust flow (Reference 48) and leakage can be less of a concern (Reference 18).
- Core and fan exhaust flow are reversed making them ideal for low BPR engines.

Some of the disadvantages of target thrust reversers are:

- For large, high BPR engines they become very large and unwieldy (Reference 14).
- They are subject to fluctuating and high operating loads downstream of the exhaust nozzle (Reference 14).
- They have less control (only two directions possible) over reversed exhaust flow direction than other thrust reverser types (Reference 23).

3.4.2 Cascade Thrust Reversers

Cascade thrust reverser types can be subdivided into two subsets based on the type of blocker used to block the exhaust flow.

One subset, which was developed first, utilizes an integral tailpipe assembly consisting of two large buckets and two radially opposed sets of curved vanes or cascades (see References 7, 10, 11, 14, 17, 18, 21, 23, 36, and 48). The buckets are like target thrust reversers discussed in 3.4.1 and generally called “blocker doors”, “clamshells” or “eyelids”. This assembly is inserted into the exhaust stream forward of the normal nozzle. In the forward thrust mode, the blocker doors are retracted and cover the cascade flow path providing a smooth normal flow path out the exhaust nozzle. In the reverse flow mode, the blocker doors are swung into the exhaust flow path, uncovering the cascades and blocking the exhaust flow. The blocked exhaust flow is redirected in a forward direction by the cascades, thus producing reverse thrust. Early design practice with this type of cascade thrust reverser was to leave the cascades exposed to the external nacelle flow field. This approach was probably selected to reduce weight and complexity of the thrust reverser assembly by eliminating the need for variable geometry nacelle doors. This thrust reverser subset is used primarily on low BPR engines where there is a need to reverse the core flow, or a mixed flow engine where the entire exhaust flow is reversed. Sketches and photographs of this type thrust reverser are shown in Figure 4, Figure 5, Figure 6, Figure 12 and Figure 13.

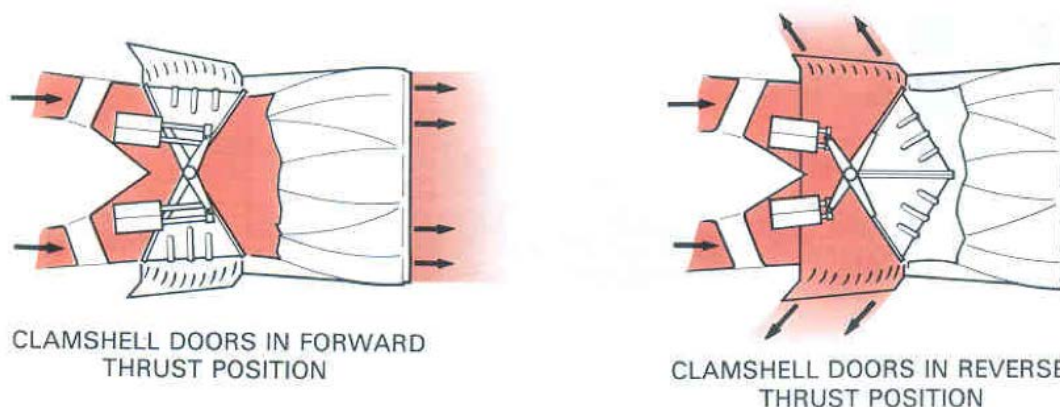


Figure 12 - Sketches showing a typical cascade thrust reverser with clamshell blocker

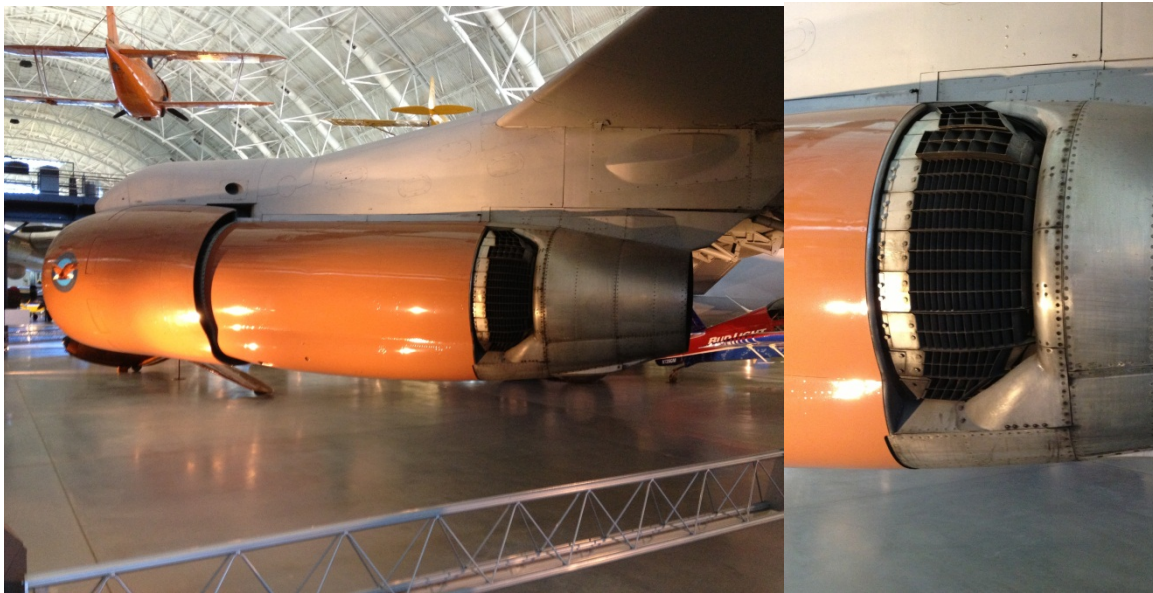


Figure 13 - Cascade thrust reverser with exposed cascades installed on the Boeing 367-80 (Boeing 707 prototype) (Photos by Bobby Berrier)

Probably because of the increasing diameter of aircraft engines, which can make the clamshell blocker doors large and unwieldy (similar to disadvantage noted for the target thrust reverser type (Reference 14) in 3.4.1), the second subset, that of the cascade thrust reverser, has become the design practice for today's commercial aircraft. This cascade thrust reverser subset utilizes a translating cowl to actuate multiple blocker doors to block the exhaust flow (References 15, 16, 23, 36, 44 and 52). The thrust reverser consists of a translating ring, as many as 16 blocker doors (Reference 44), and fixed cascades arranged around the periphery of the fan cowl. In forward thrust mode, the blocker doors are retracted and the cascades are covered, thus providing near smooth contours both internally and externally. In reverse thrust mode, the rear portion of the fan cowl is translated aft to uncover the cascades; simultaneously, the multiple blocker doors are forced to swing into the exhaust flow path by a force exerted by the translating fan cowl. Tracks and rollers provide stabilization of the translating cowl while simple pivot joints are used to control the movement of the blocker doors (Reference 16). This cascade thrust reverser subset is used primarily on high BPR engines where most of the engine thrust is provided by the fan flow, and there is little need to reverse the core or primary flow (see Figure 8). Sketches and photographs of this type thrust reverser are shown in Figure 14 and Figure 15, respectively.

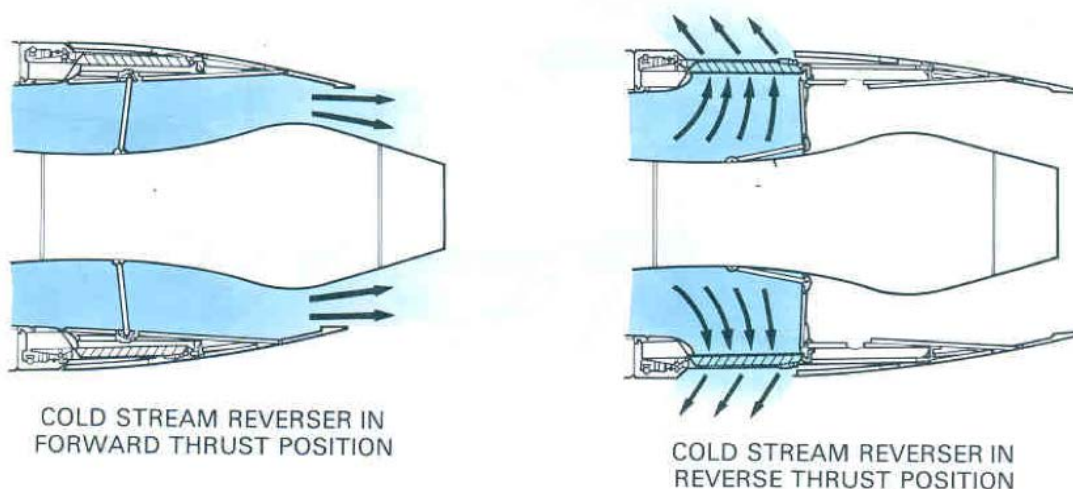


Figure 14 - Sketches showing a typical cascade thrust reverser with multiple blocker doors



**Figure 15 - Cascade thrust reverser with translating fan cowl installed on the C-17
(left photo by Alastair Bor)**

Some of the advantages of cascade thrust reversers are:

- A shorter axial length than target thrust reversers, especially with internal clamshell blocker (Reference 14)
- Cascade vanes provide the maximum control over reversed exhaust flow direction (References 23 and 48)
- Easily adapted for high BPR engines where only the fan flow is reversed

Some of the disadvantages of cascade thrust reversers are:

- Weight (References 14 and 23)
- Hot turbulent flow on the cascades (References 15 and 23) and blocker door complexity (Reference 48) can cause reliability issues (Reference 14)
- Increased concerns about exhaust gas leakage (cruise thrust loss) during forward thrust operating mode (Reference 18)
- For clamshell blocker thrust reverser designs, the blocker doors, hinges and seals are exposed to hot exhaust flow (Reference 48)
- For cascades exposed to external nacelle flow, an aircraft cruise drag penalty is incurred

3.4.3 Pivot Door Thrust Reversers

Pivot door thrust reversers work on the same principles as cascade thrust reversers. An internal set of blocker doors deploy into the exhaust flow and redirect the exhaust flow (usually cooler bypass flow air) radially through concurrently opened flow turning elements (see References 7, 18, 28, and 48 to 51). The main differences between cascade and pivot door thrust reversers are that the pivot door design does not require a translating cowl to actuate the internal blocker doors and the flow turning element has been changed from cascade vanes to pivot doors. One advancement in thrust reverser design is a pivot door thrust reverser that combines the separate flow blocking and flow turning design elements into a single design element performed by the pivot door (Reference 53). By moving the pivot point forward on the door, the aft portion of the pivot door pivots down into the fan bypass duct to block the airflow; simultaneously, the entire pivot door turns the fan airflow outward and forward to produce reverse thrust. This type of thrust reverser is used on many Airbus aircraft, such as the A320 family. Sketches showing pivot door thrust reverser designs are shown in Figure 16. The left side of Figure 16 shows an early design that has separate flow blocking (clamshells) and flow turning (pivot doors) mechanisms; this type thrust reverser was utilized on the Boeing 727. The right side of Figure 16 shows a design that utilizes the pivot doors for both functions; this type of thrust reverser design was utilized on the Airbus 319. Photographs showing typical pivot door thrust reverser installations are shown in Figure 17 and Figure 18.