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SPACE SHUTTLE SOLID ROCKET BOOSTER SEPARATION SYSTEM

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external Tank

Abstract

Separation of the Shuttle's solid rocket boosters (SRB) is accomplished by a method somewhat similar to that used for the Titan III. However, due primarily to the presence of the orbiter, the design of the SRB separation system has had to satisfy unique requirements. The supersonic staging of parallel boosters to clear a thrusting, winged, and manned vehicle is a new development complicated by asymmetrical SRB thrust and complex aerodynamics. The SRB separation system, the separation sequence, and flight control method are described. The approach taken to verify the separation system for flight is presented, and its performance on STS-1 and STS-2, the first times that the integrated separation system was tested under true flight conditions, is summarized.

I. Introduction

The Space Shuttle is the first manned launch vehicle to use solid propellant boosters. These solid rocket boosters (SRB's) are the most powerful of their kind ever designed, having the highest total impulse of any solid rocket built so far (294 x 10^6 lb-sec over an action time of 126.4 seconds). The SRB's are larger than an Atlas Centaur: about the same size as the European Space Agency's Ariane I launch vehicle. Each SRB is 149.13 feet long and 12.17 feet in diameter, and produces 2.65 million pounds of sea-level thrust at lift-off. At the time of separation, the weight of each SRB has decreased to 181,500 pounds from its lift-off weight of 1,286,600 pounds. In spite of the SRB's size, they are the first boosters designed to be reused.

The SRB's provide the primary propulsion during the first stage of a Space Shuttle launch. Together with the Space Shuttle main engines (SSME's), they provide thrust vector control (TVC) from lift-off to separation, using the largest movable nozzles ever employed (12-foot exit diameter).

The design, development, test, and integration of the SRB are under the direction of NASA's Marshall Space Flight Center (MSFC). The prime contractor is Thiokol Chemical Corporation.

II. Separation Requirements

The SRB separation system requirements were established to ensure that its design could provide for safe separation under all foreseeable conditions consistent with Shuttle groundrules. They are specified in Reference 1 and summarized in Tables 1 and 2. The system is required to provide for fail-safe capability and incorporates signal interlocks to prevent SRB release and ignition of the separation motors due to stray electrical signals.

Table 1 SRB/ET separation system requirements.

GENERAL
- Provide for SRB/ET separation without damage to, or recontact of, separating elements
  - Nominal separation modes (includes design disturbances)
  - Abort modes (recontact between SRB's and orbiter TPS lifetime degradation allowed)
- Provide for fail-safe capability, excluding primary structure and single BSM failures

SPECIFIC
- Automatic separation inhibit with manual override capability
- Provide 3-axis attitude hold for at least 4 seconds after separation command
- Initiate separation sequence when left and right SRM $P_c \leq 50$ psia
- Provide redundant P_c signals accurate to ±20 psia
- Backup separation sequence to be initiated on time
- Thrust of each SRB ≤ 60,000 lb at separation
- SRB nozzle actuators nulled and maintained at least 5 sec after separation command
  - 0° ± 1.0° pitch
  - 1° ± 0.6° yaw (thrust vector pointing away from ET)
- No damaging debris released
- Disconnect impulse torque per attachment ≤700 ft-lb-sec about each SRB c.g.
- Release of all structural attachments ≤ 30 msec from time separation command crosses pyrotechnic interface
- Design separation initial conditions:
  - $\bar{q}$ = 75 psf • P = ± 5°/sec
  - α = ± 15° • Q = ± 2°/sec
  - β = ± 15° • R = ± 2°/sec

III. Separation System

The SRB separation system consists of the following five elements:

1. Eight solid booster separation motors per SRB with ignition system
2. Four structural attachments per SRB
3. Four separation bolts per SRB with pyrotechnics

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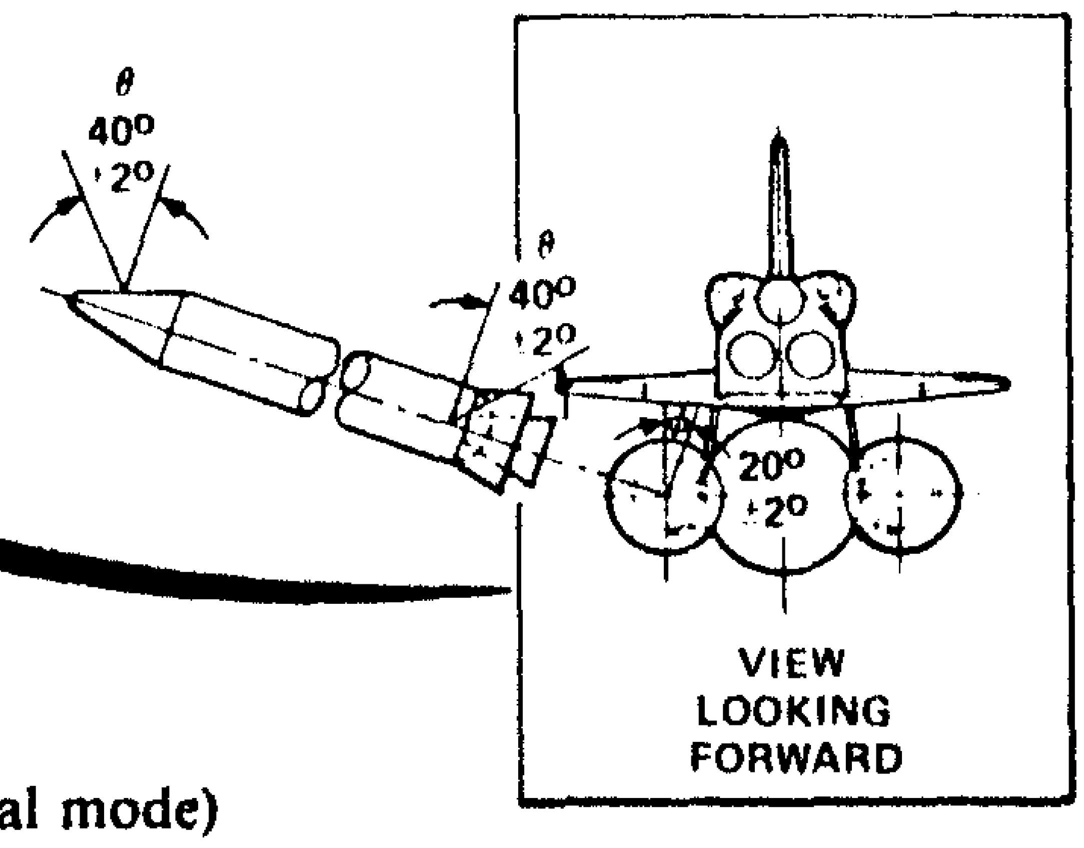
Table 2 BSM cluster requirements.

- F_{ave} ⩾74,000 lb (over web action time)
- F_{max} ⩽ 116,000 lb
- P_{EWAT} ⩽ 2,000 psia
- I_{WAT} ⩾56,000 lb-sec
- I_{AT} ⩾ 60,000 lb-sec
- Ignition interval: 30 to 100 msec
- WAT ⩽ 0.805 sec
- Total time (Ignition to ½ P_{EWAT}) ⩽ 1.05 sec
- Thrust vector orientation:
  - $\phi = 20° \pm 2°$
  - $\theta = 40° \pm 2°$
- Neutral or regressive thrust profile
- Stability additives (aluminum) ⩽ 2%
- Burn rate additives ⩽ 1%
- Operating temperature range: 30° F to 120° F
- No orbiter TPS damage from plume/debris (nominal mode)



4. Electronics to initiate separation

5. Sensors

Elements 2 and 3 constitute the release system which, along with the booster separation motors, is illustrated in Fig. 1.

Booster Separation Motor (BSM) System

To determine the best method for separating the SRB's from the external tank (ET), a tradeoff study was conducted by Rockwell International in 1973 and early 1974. The concepts that were considered, as shown in Table 3, included

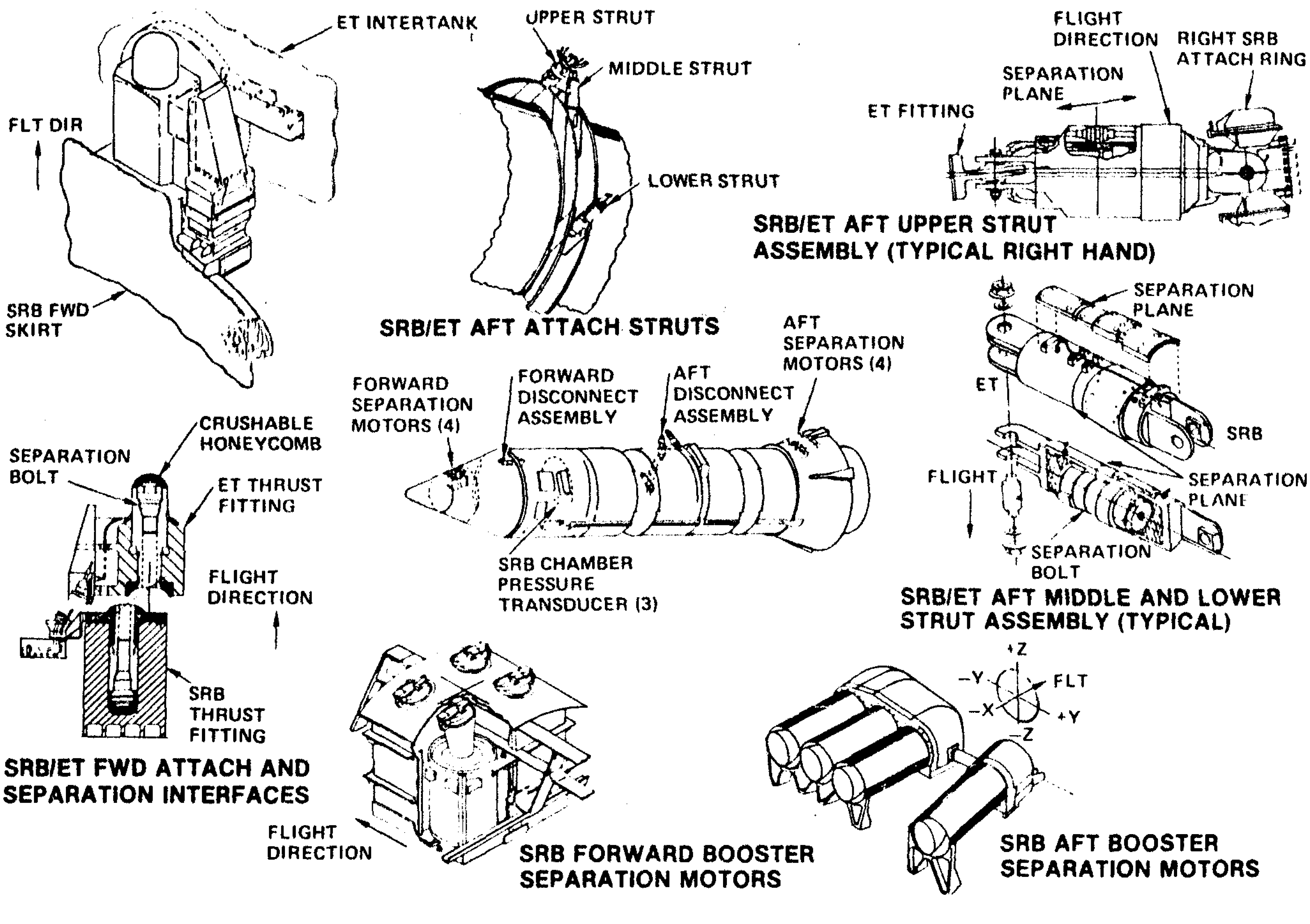


Fig. 1 SRB/ET separation system hardware.

Table 3. SRB separation methods evaluated

	Separation Method						
	1	2	3	4	5	6	7 ✓
Forward	Rails	2 fins*	2 fins*	60k lb piston	120k lb piston	120k lb piston	Rockets
Aft	Rails	2 fins*	Hinge	Hinge	190k lb piston	4x 14k lb to 27k lb rockets	Rockets
*250 ft²/fin							

		Final Concepts Considered	Selected Concept
•	Propellant	Liquid, solid	solid
•	No./SRB	8, 16	8
•	Thrust/Motor	9.2k lb → 25k lb	20k lb
•	Configuration		
	• Forward	In-line, tandem, orthogonal	Tandem
	• Aft	In-line, abreast, orthogonal	Abreast
•	Orientation		
	ϕ	0° & 90° (orthogonal), 20° → 30°	20°
	θ	20° → 40°	40°
•	Location		
	• Forward	Forward skirt, nose frustum	Nose frustum
	• Aft	Aft skirt	Aft skirt
•	Burn Time	0.75 sec → 2.0 sec	0.75 sec

rails, hinges, pistons, and rockets. By April 1974, it was concluded that separation rockets provided the best potential for producing the necessary clearances for safe separation within the expected ranges of staging conditions.

A parametric study was then conducted to decide between solid and liquid propellants and to determine the total impulse and burn time requirements of the BSM's as well as their locations and orientations. The study was completed by the end of 1974 and resulted in the present BSM configuration.

Solid propellant rockets were chosen over liquid propellant rockets primarily because of their relative simplicity and low cost. It was found that the most important factor in determining the burn time and location/orientation was impingement of the BSM exhaust plumes on the orbiter thermal protection system (TPS). Tests indicated that even short-term exposure of the TPS to the BSM exhaust would result in extensive damage to the TPS. This was due primarily to the presence in the BSM exhaust of high-velocity aluminum oxide particles of micron size, which are very abrasive.

This resulted in (1) the requirement that the BSM propellant have less than 2 percent aluminum as a stability additive, (2) relocation of the forward BSM's from the SRB forward skirt to the nose frustum, and (3) a reduced burn time requirement. These steps eliminated the exposure of the orbiter TPS to the BSM exhaust plume during nominal separation conditions.

There are eight BSM's per SRB: four in tandem in the forward SRB frustum and four abreast mounted externally on the aft skirt. Each BSM nominally provides 21,680 pounds of vacuum thrust and a total impulse of 14,760 lb-sec over a web action time (WAT) of 0.680 second at a propellant mean bulk temperature (PMBT) of 70°F. Nominal thrust-time traces are illustrated in Fig. 2.

The BSM's provide lateral and normal acceleration of the SRB's away from the orbiter/ET; the relative axial acceleration is achieved by the thrust from the orbiter's SSME's.

The BSM's are not reusable, since design and cost trade studies by NASA showed that there would be no cost advantage in designing the BSM's to be reused.

Release System

Each SRB has a release system consisting of four attachments, each with a frangible bolt. The forward attachment is a single thrust fitting located at the forward end of

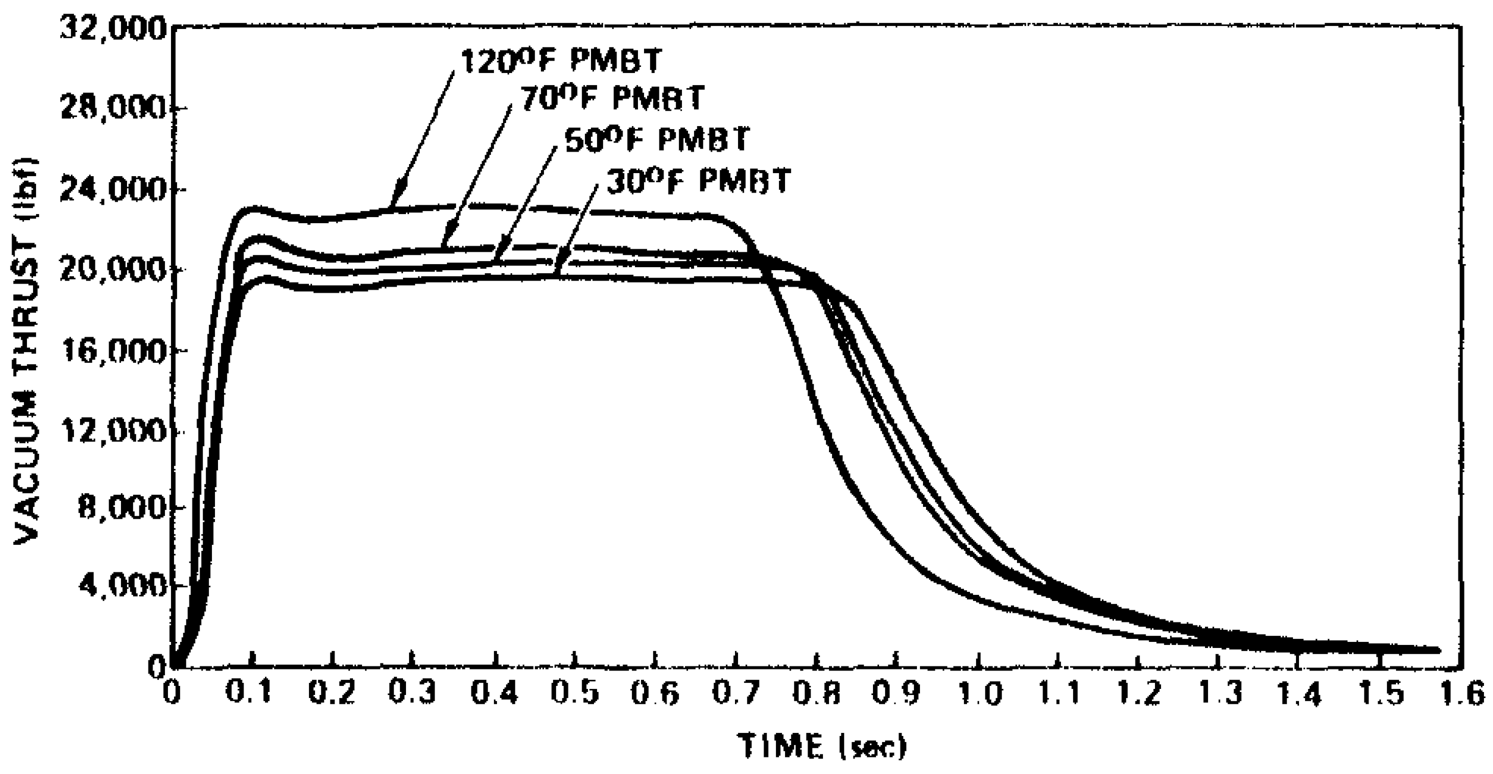


Fig. 2 BSM nominal vacuum thrust performance.

the forward SRB skirt. It is spherical and allows rotational movements of up to 1 degree between the SRB and ET before separation. It incorporates an aluminum honeycomb bolt catcher to minimize release of debris. Attaching each SRB to the ET are three aft struts that transfer lateral loads from the SRB to the ET during ascent—two lateral sway braces and a diagonal attachment. The upper strut has external flanges on each side of the separation plane to accommodate pullaway connectors on seven electrical cables arranged symmetrically around the strut.

The separation bolts are double-ended, tandem piston, pyrotechnically initiated bolts. For redundancy, there are two NASA standard initiator (NSI) pressure cartridges on each bolt (one on each bolt end); these are fired by electrical discharge from pyrotechnic initiator controller (PIC) capacitors. The bolts are notched to fracture in tension at the separation planes.

Avionics

The Space Shuttle is the first purely digital, fly-by-wire vehicle. Its avionics system, which is the most sophisticated equipment on board, is required to be two-fault tolerant (fail operational/fail safe) without compromising performance. To accomplish this, the GN&C system is quad-redundant.

The brain of the avionics system consists of a group of five general purpose computers (GPC's), four of which are programmed to operate as a unit and act in a redundant set to make guidance and navigation decisions and to control sequencing and engine gimbaling. All four receive the same inputs from sensors and the crew and issue simultaneous commands. The fifth GPC is programmed independently and is used as a backup.

Communication between the GPC's and avionics is provided via data buses and either master events controllers (MEC's) or multiplexer/demultiplexers (MDM's). There are two MEC's which perform the transfer and signal conditioning of control and measurement data between the GPC's and SRB pyrotechnic and control devices. The MDM's perform the following functions:

1. Conversion of analog and discreet subsystem data to digital serial data
2. Data buffering and format conversion between serial input/output channels
3. Conversion of serial data into analog and discreet data

Most of the separation system is channeled through the four aft MDM's and the two MEC's. The SRB manual separation switch, however, interfaces with the GPC's through three of the four forward MDM's.

The SRB electrical and instrumentation (E&I) subsystem provides an interface between the orbiter and the SRB separation subsystem which is powered by the orbiter's main buses until separation. The basic E&I components integrated into the SRB separation subsystem are the integrated electronic assemblies (IEA's) and PIC's.

Each SRB has two IEA's providing the primary electrical interface between the orbiter and SRB's: one forward and one aft. The IEA's pass commands and data to and from the SRB TVC actuators and auxiliary power units (APU's). The BSM's and separation bolts are controlled through the IEA's. The aft IEA provides signal conditioning, multiplexed functions, and distribution of the commands, data, and electrical power from the orbiter. Components located in the forward portion of each SRB are powered through the aft IEA to the forward IEA for distribution. All data from the SRB's to the orbiter are routed through the aft IEA.

The PIC's are single-channel capacitor discharge devices that require the ARM signal to be transmitted first to charge the capacitors. The FIRE 1 and FIRE 2 commands then discharge the stored electrical energy to detonate the separation pyrotechnics. The PIC's are activated through a set of dual redundant solid-state switches which receive their signals from the GPC's via the MEC's.

The SRB separation system block diagram is shown in Fig. 3.

Sensors

The candidates which were considered for primary cue to initiate SRB separation were time, longitudinal acceleration, and SRM chamber pressure measured by strain gauges or pressure transducers. It was determined that chamber pressure sensed by transducers was best. The transducers provide the necessary accuracy (the specified requirement is ± 2 percent full scale or ± 20 psia) to minimize performance penalty. In addition, they are very reliable; the type used in the SRM's have had 1,241 firings on the Minuteman program without a failure. To provide redundancy, three pressure transducers are mounted in the forward end of each solid rocket motor (SRM).

Development flight instrumentation (DFI) sensors have been provided to gather SRB separation data during the Shuttle test flights. These consist of separation cameras, separation instrumentation packages (SIP), and special SRM and BSM chamber pressure transducers.

The separation cameras are mounted in the ET propellant umbilical bays of the orbiter: a 10-mm camera and a 5-mm (wide angle lens) camera in the liquid hydrogen umbilical bay (left side) and a 10-mm camera for STS-1 in the liquid oxygen umbilical bay (right side). Each camera has

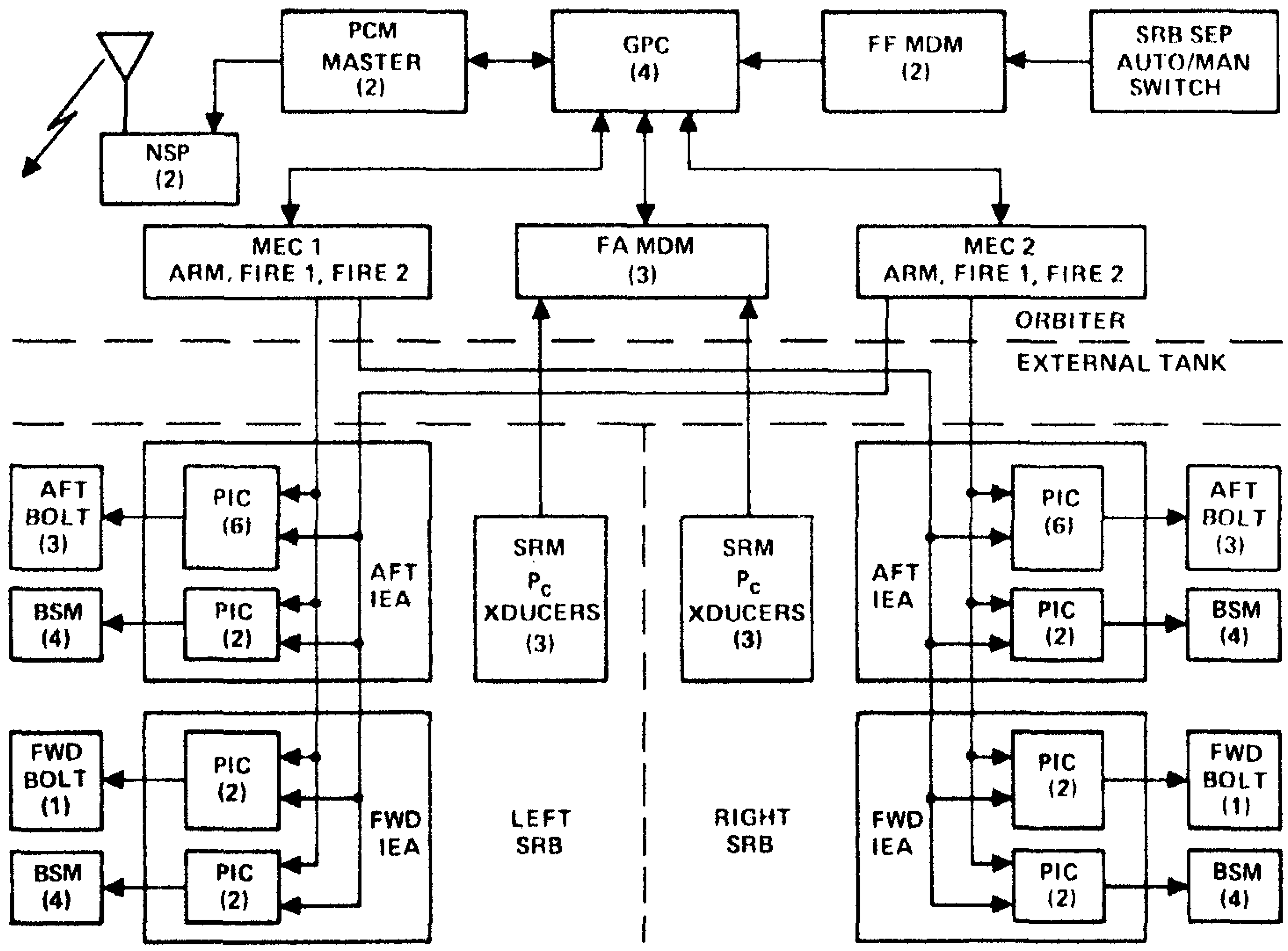


Fig. 3 SRB separation system block diagram.

a film speed of 240 frames per second and is turned on at Event 26, Separation Initiation, for ten seconds. The film from the wide angle camera is used to reconstruct the relative separation motion of the left SRB by the photo analysis lab at the Pacific Missile Test Center (PMTC).

One SIP is mounted in the forward skirt of each SRB. Each consists of a set of linear accelerometer and rate gyro triads. The accelerometers have a range of ± 1.0 g and a specified accuracy of ± 0.06 g. The rate gyros have a range of ± 20 deg/sec and a specified accuracy of ± 0.40 deg/sec.

IV. Separation Sequence

The SRB separation sequence is controlled by the orbiter through either the primary flight system (PFS) or the backup flight system (BFS) and performs the functions of monitoring the SRM thrust tail-off via chamber pressure measurements, controlling the separation process, and generating indicators for proper guidance, navigation, and control (GN&C) moding. The separation sequence is divided into three basic phases shown in Fig. 4:

1. Monitoring of the separation cues (Event 25)
2. Preparation of the orbiter and SRB systems for separation (Events 26 and 27)
3. Separation of the SRB's from the orbiter/ET (Event 28)

At Event 25, the selected left and right SRM chamber pressure measurements are monitored to determine if the primary cue, left and right SRM $P_C \leq 50$ psia, has been attained. To protect against multiple chamber pressure transducer failures on one SRB to the high state, mission elapsed time (MET) is used as a backup separation cue. This backup cue is reached when the MET exceeds the latest possible time at which $P_C = 50$ psia could occur. Protection against multiple transducer failures on one SRB to the low state requires marking the time at which the left and right SRM P_C measurements drop below 50 psia and computing the time differential. If this exceeds the predicted maximum differential, the backup separation cue is used. Once the separation cue is achieved (Event 26), the separation cameras are turned on, and the SRB range safety system (RSS) is safed and power terminated.

The PIC's are armed and the SRB nozzles are commanded to their null position at Event 27, 4.3 seconds after Event 26. The nozzles are "nulled" to reduce the possibility of recontact following separation due to residual thrust. Second-stage flight control is also initiated at this time.

Following a 1.7-second delay to allow the SRB nozzle actuators time to null and the SRM thrust time to decay to an acceptable level, the vehicle's dynamic state is compared with the auto-inhibit criteria. If the criteria are met, the FIRE 1 and FIRE 2 commands are sent automatically to separate the SRB's (Event 28). If the criteria are exceeded, separation is inhibited until they are either met or manually overridden. Four seconds after the FIRE 2 command is issued, the separation sequence is terminated (Event 29), and the separation cameras and SRB power are turned off.

V. Flight Control

During first stage, open-loop guidance computes body attitude commands from a predetermined attitude versus velocity profile. The Shuttle vehicle attitude is controlled by the ascent flight control system (FCS) using both the orbiter

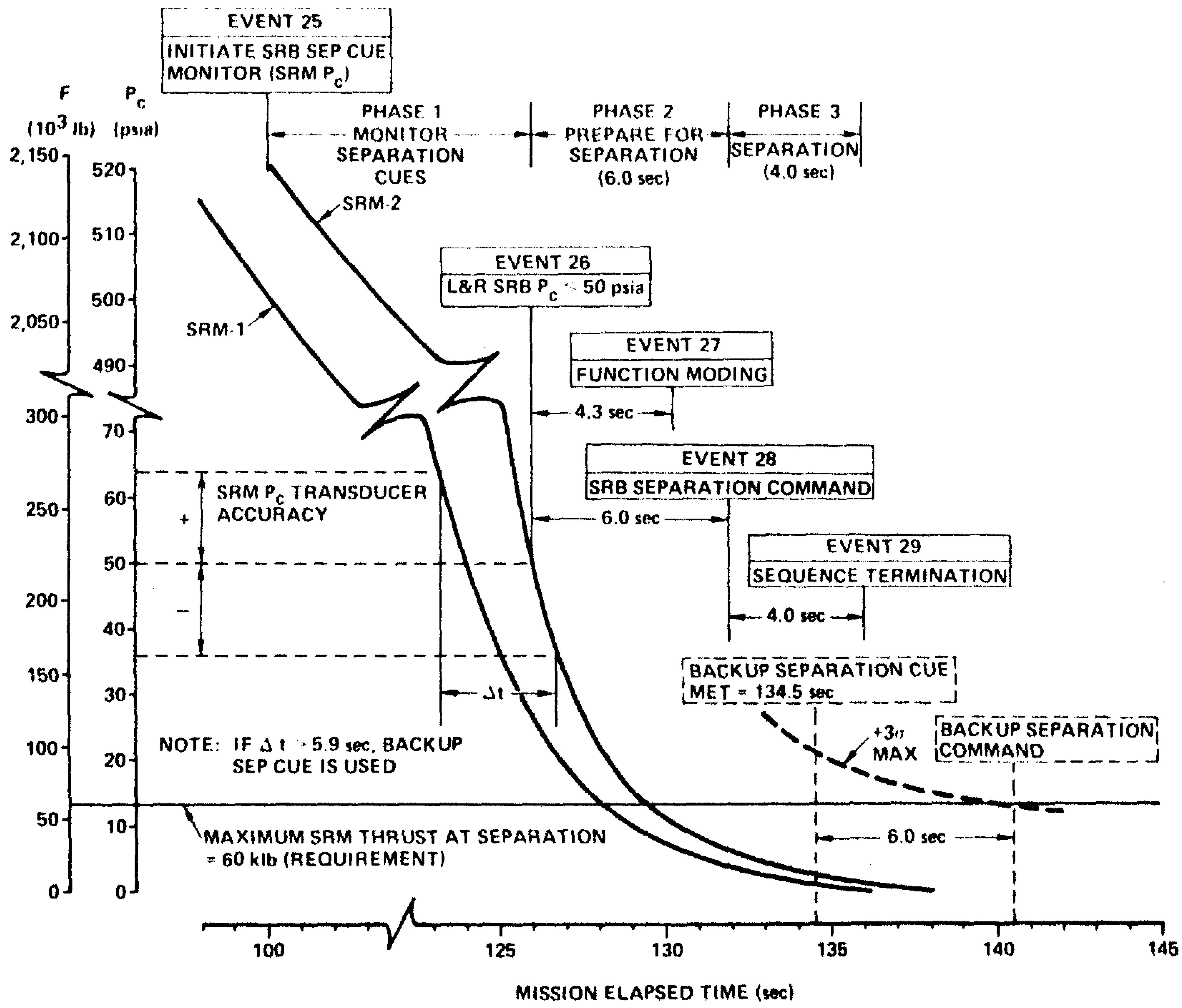


Fig. 4 SRB separation sequence.

and SRB TVC systems commanded from the orbiter. The GPC's formulate steering commands for the gimbal actuators. The SRB TVC system is a closed-loop hydraulic system with power provided by redundant APU's and hydraulic pumps. Each SRB nozzle has two servoactuators mounted 45 degrees to the body axes providing omniaxial gimbal capability of 6.65 degrees.

Steering is most demanding during SRB thrust tailoff when the thrust mismatch between the SRB's is greatest, producing dispersions primarily in roll. However, the control system has been designed to maintain control with any one of the SSME's failed.

At Event 27, the FCS provides attitude control with the orbiter TVC only. During separation, the FCS is reconfigured, as shown in Fig. 5, to preclude any attitude corrections. This is accomplished by a three-axis attitude hold which consists of the following two separate actions of the guidance and control module at separation command:

1. The "desired body" vehicle rates are set equal to zero causing the FCS to damp out any existing "actual body" vehicle rates
2. The "desired body" vehicle attitudes are set equal to the "actual body" vehicle attitudes

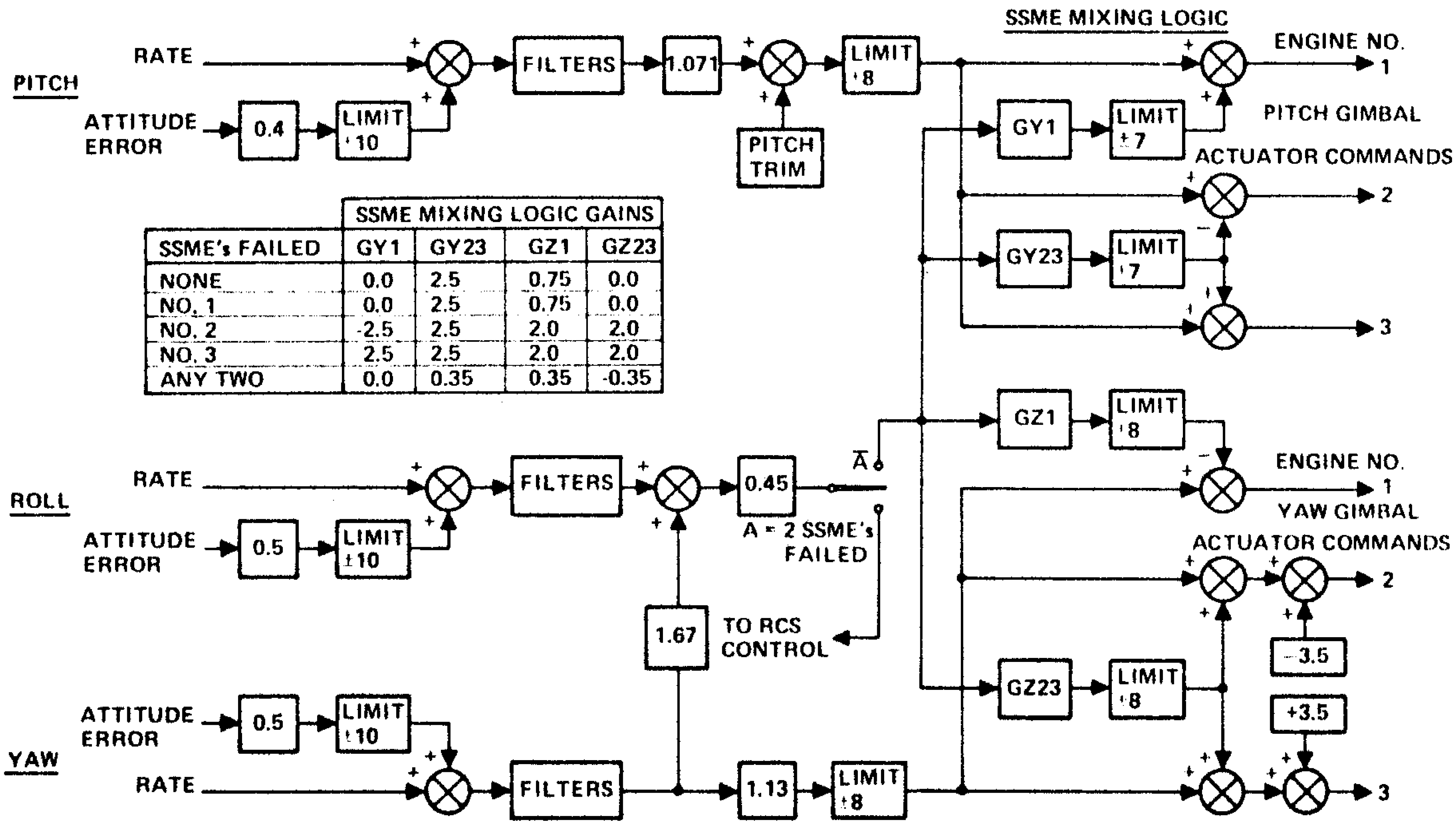
At separation, the FCS must perform an SSME pitch retrim to compensate for the abrupt shift of the vehicle's center of gravity forward and upward. This shift results in a tendency of the orbiter/ET to pitch nose-up, and the SSME nozzles must be commanded downward to counteract this. At SRB separation command, an I-loaded SSME pitch trim value is sent directly to the SSME command processor allowing the orbiter/ET to be trimmed in pitch sooner than it could be by normal flight control processing.

Automatic Separation Inhibit/Manual Override Capability

The design of the SRB separation system provides for an automatic inhibit of separation if the navigation-derived dynamic pressure or any one of the selected sensed body rates exceeds certain limits. This capability was provided to reduce any safety risk by ensuring that separation occurs only within design dynamic conditions.

The navigation-derived dynamic pressure, $\bar{q}_{nav}$, limit prevents staging from occurring at higher than the design staging dynamic pressure due to flight profile anomalies or atmospheric dispersions. The limit allows for up to a 20-psf error due to navigation errors (altitude and velocity) and environment factors, including winds and density.

The body rate limits prevent staging at high angular rates caused by stability anomalies. Originally, these limits were defined by a four-dimensional ellipsoid whose axes were selected body rates (P_{sel}, Q_{sel}, R_{sel}) which decreased with



SSME's FAILED	SSME MIXING LOGIC GAINS			
	GY1	GY23	GZ1	GZ23
NONE	0.0	2.5	0.75	0.0
NO. 1	0.0	2.5	0.75	0.0
NO. 2	-2.5	2.5	2.0	2.0
NO. 3	2.5	2.5	2.0	2.0
ANY TWO	0.0	0.35	0.35	-0.35

Fig. 5 FCS configuration during SRB separation.

increasing dynamic pressure. To economize on-board computations, the body rate inhibit region is now simply a rectangular box coinciding with the design staging body rates. Thus, separation is automatically inhibited when

$$\bar{q}_{nav} > 55 \text{ psf},$$
$$\text{or} \quad |P_{sel}| > 5 \text{ deg/sec}$$
$$\text{or} \quad |Q_{sel}| > 2 \text{ deg/sec}$$
$$\text{or} \quad |R_{sel}| > 2 \text{ deg/sec}$$

If an automatic separation inhibit should occur, it can be overriden by the crew by putting the SRB Auto-Auto/Manual SEP switch in the Auto/Manual position and then pushing the SEP pushbutton indicator (PBI) which activates the separation ordnance. The SRB Auto-Auto/Manual SEP switch is multiple contact, triple redundant, which enables or disables manual separation capability. According to current flight rules, the crew will override an inhibit (1) if the body rates are within limits and the "Go for SRB Sep" call has been given or (2) if, five seconds after the separation inhibit comes on, the body rates are diverging.

VI. Verification

The SRB separation subsystem underwent extensive tests and analyses to verify that it is in compliance with all relevant design, performance, and safety requirements defined in Reference 1.

As a result of analysis of the scope of the SRB separation test program to determine the most cost-effective approach, it was decided not to conduct full-scale all-element separation tests. Instead, a series of tests at the subsystem or component level was conducted. These tests, with wind tunnel tests, math model analyses, and use of mockups, were believed to be sufficient to ensure proper verification. The responsibilities of the various contractors and subcontractors for the primary tests and analyses of the separation are given in Table 4.

Hardware testing was performed by, or under the direction of, NASA/MSFC. Software/hardware integration testing was accomplished primarily by the NASA Johnson Space Center (JSC) Software Avionics Integration Laboratory (SAIL) with supplemental results obtained during dynamic integration tests (DIT) by NASA Kennedy Space Center (KSC). The primary and backup flight avionics software testing was accomplished by IBM and Intermetrics, respectively.

Verification of separation trajectories and clearance requirements was accomplished by non-real-time simulations using the Space Vehicle Dynamics Simulation (SVDS) computer program. It involved verification of the SVDS math models, demonstration of safe separation for all anticipated separation conditions, and verification of the separation inhibit limits.

SVDS simulates the six-degree-of-freedom rigid body dynamics of the orbiter/ET and each SRB simultaneously. The SRB equations of relative motion are integrated to obtain their trajectories with respect to the orbiter/ET. This program was originally created by NASA subcontractors for the Apollo program and has been modified for use on the Space Shuttle program. It has become the primary analytic tool for SRB separation system performance verification analyses.

For preflight verification, SVDS is initialized, to as great an extent as possible, by results obtained by first-stage simulations performed by the Rockwell/ST&SG First-Stage IGN&C Group. During postflight evaluation, these initial conditions are obtained from available preflight measurements and flight sensor measurements.

Table 4 SRB separation system verification responsibilities.

			NASA/MSFC	NASA/JSC	Rockwell/ST&SG	UTI/CSD	Thiokol	IBM	Intermetrics	MDTSCO	Hi-Shear Corp.
Test	Hardware	SRM thrust tailoff (4 DM + 3 QM static tests)	X								
		BSM cluster alignment at KSC	X								
		Attachments and connectors, fwd and aft	X								
		BSM qualification (18 tests)				X					
		• Dynamic thrust vector				X					
		• Performance				X					
		• Impingement/debris				X					
		• Timing				X					
		• BSM/pyrotechnic ignition system				X					
		BSM and release system pyro component qual				X					X
	Hardware/Software Integration	Shuttle Avionics Integration Laboratory (SAIL)			X						
		• STS - flight software integration			X						
		• GTS - GN&C hw/sw integration			X						
		• MMES		X							
		• SRB nozzle actuator null command		X							
		• SSME actuator response		X							
		Dynamic Integration Tests (DIT)			X						
		• Orbiter Integration Test (OIT)			X						
		• Hw/sw operation			X						
		• PFS to BFS switch ability			X						
		• Shuttle Integration Tests (SIT)			X						
		• Orbiter/SRB interfaces			X						
		• SRB systems functional operation			X						
		Software Development Laboratory (SDL)						X			
		• PASS software logic paths						X			
		• P_c transducer selection filter						X			
		Flight Simulation Laboratory (FSL): BFS Coding			X				X		
Analysis	H/W	SRM TVC system	X								
		SRM P_c transducer accuracy					X				
		Electrical stray signal			X						
	Performance	Non-real-time simulation	X		X					X	
		• Separation clearance/BSM plume impingement	X		X					X	
		• Component disconnect impulse torque	X		X					X	
		• SEP at inhibit limits, nominal and abort	X		X					X	
		• SRB/ET strut shear and loads	X		X					X	
		• 3-axis attitude hold/vehicle stability	X		X					X	

The plan used to verify the separation trajectories and clearances, diagrammed in Fig. 6, is in compliance with Reference 2. This worst-on-worst approach has two definite advantages. First, it is economical since it avoids the large number of simulations required in a Monte Carlo statistical approach. Second, it provides added confidence that the separation system is capable of producing safe separation since it is a very conservative approach. However, it has the disadvantage of requiring that the worst-on-worst combinations of separation system dispersions be determined. This was accomplished by parameter sensitivity studies.

Special math models have been implemented in SVDS to calculate indicators of clearances between the orbiter/ET and the SRB's and forward BSM exhaust plume damage boundary. These clearance indicators are described in Table 5 and Fig. 7. Analyses have shown that the most critical separation clearances are the ET lower strut stub-to-SRB clearance, C_{L4}, and the BSM plume damage boundary-to-orbiter nose clearance, C_{L8}. C_{L4} is sensitive to lateral-directional dispersions, whereas C_{L8} is sensitive to pitch-plane dispersions. Both are affected by aerodynamic uncertainties, staging dynamic pressure and body rates, and propulsion dispersions. Results of preflight clearance verification are summarized in Fig. 8.

Details of the results of the verification of the SRB separation system for STS-1 and STS-2 are documented in References 3 and 4, respectively.

VII. Post-Flight Analysis

Post-flight analysis during the Shuttle test flights supports verification of the separation system for Shuttle operations. The two main objectives are (1) to verify that the

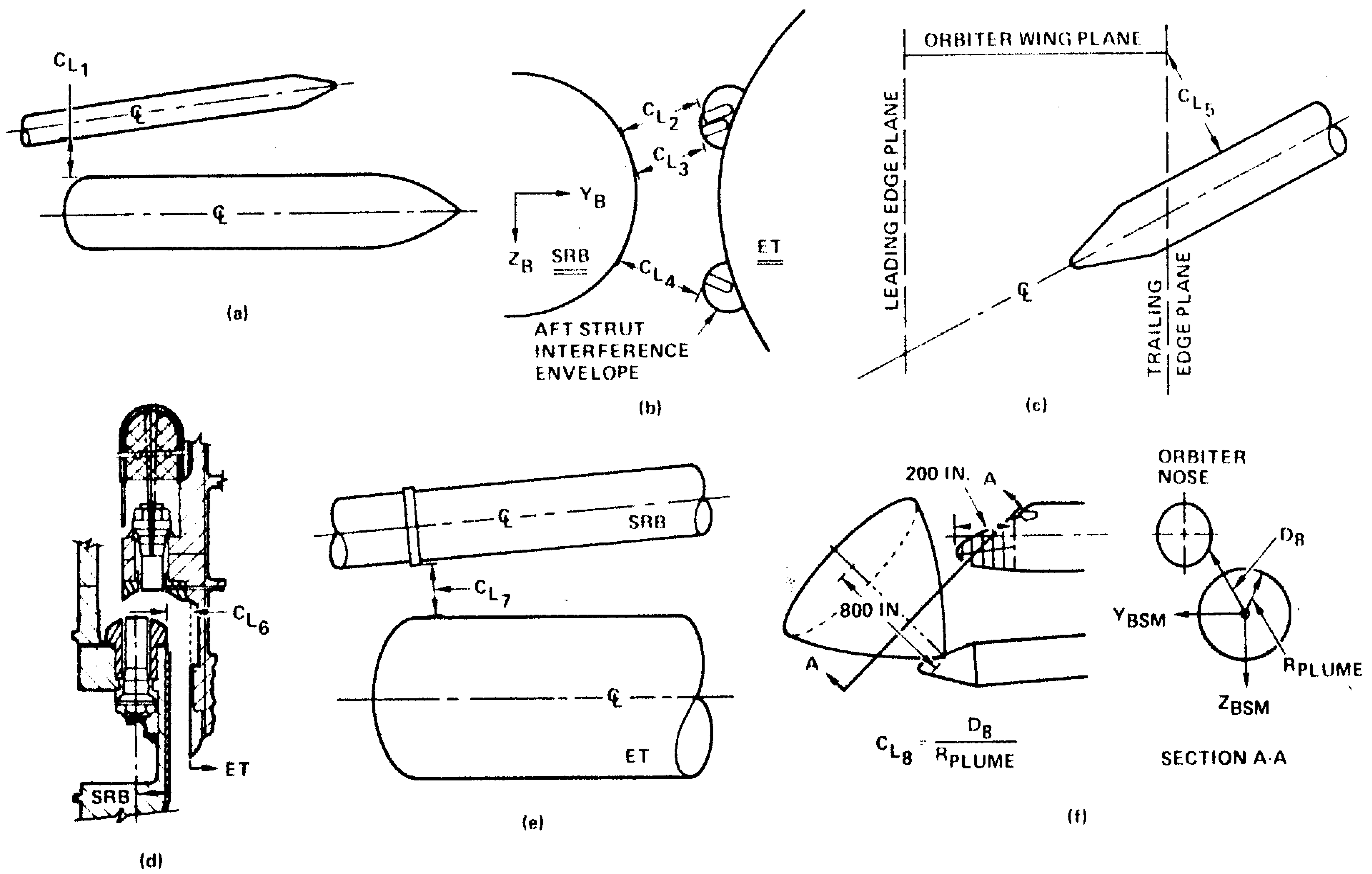


Fig. 7 Separation clearance indicators.

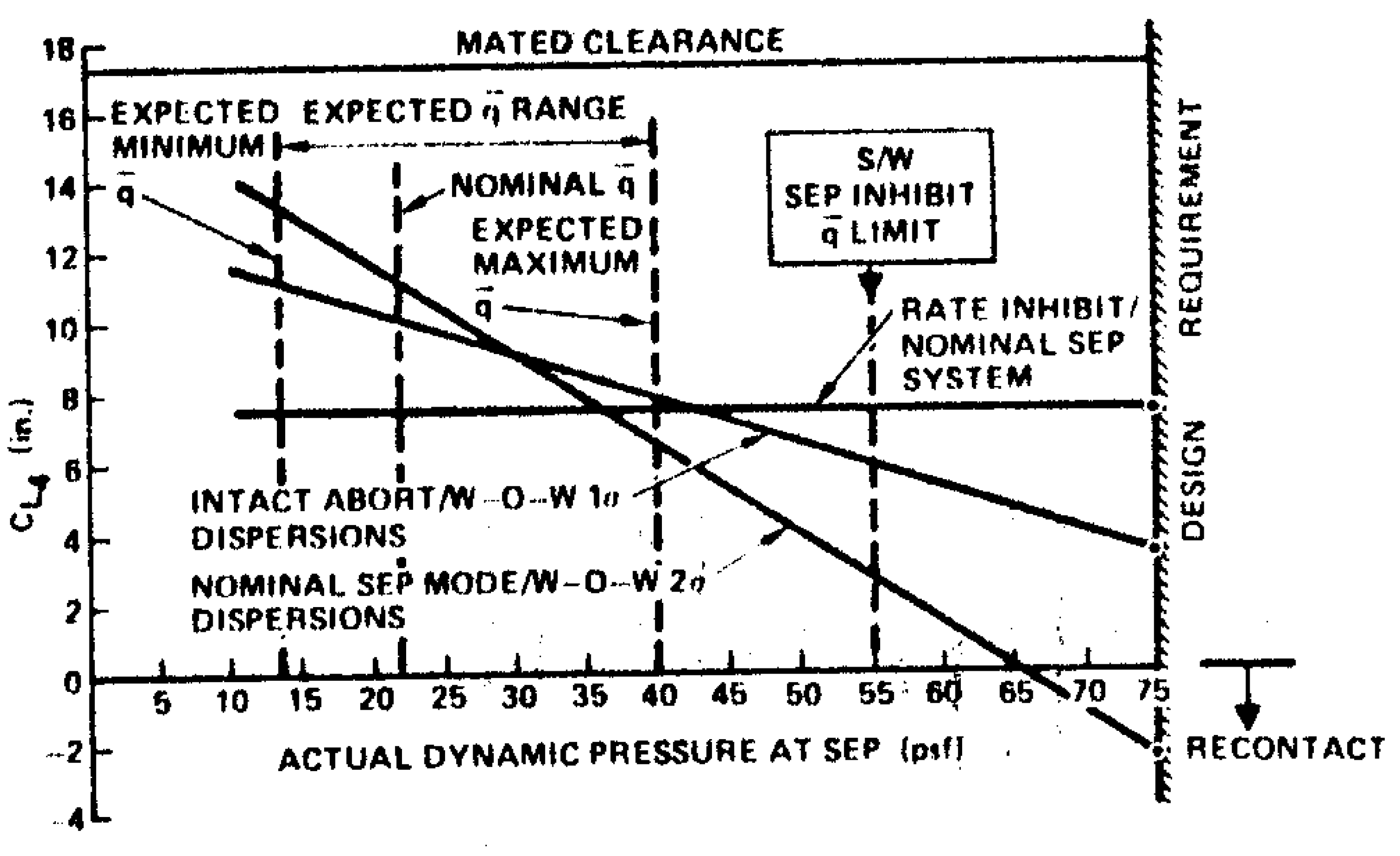


Fig. 8 SRB separation clearance versus dynamic pressure.

integrated separation subsystem functions under flight conditions as designed and (2) to verify the separation trajectories and clearance math models. To accomplish these objectives, the following tasks are undertaken during the postflight analysis:

1. Reconstruction of separation sequencing and timing
2. Determination of the vehicle state at separation
3. Reconstruction of the relative separation trajectories
4. Inspection of the recovered SRB's and orbiter
5. Comparison of reconstructed separation with requirements

As shown in the SRB separation reconstruction plan in Fig. 9, there are three independent methods used to obtain the relative SRB separation trajectories and clearances using flight measurements. The first is the SVDS program, which is a dynamics simulation that uses SRM, BSM, and SSME thrust histories, and the state vector at separation from flight data. The equations of motion are solved to obtain relative motion and clearances.

The second method is the CLEAR computer program developed by the Rockwell/ST&SG Separation Group. This is a kinematics simulation which reconstructs the SRB separation trajectories and clearances using only orbiter and SRB accelerometer and rate gyro measurements.

The third method uses the Photo Data Analysis System (PDAS) at the Pacific Missile Test Center's photo analysis lab to obtain relative motion data from separation camera film. This involves superposition of images from the separation film and a 1/50th-scale model of an SRB. Additional information on the PDAS is provided in Reference 5.

A good comparison of results from CLEAR and PDAS with results from SVDS provides the basis for the final verification of the SVDS math models. The detailed postflight evaluations of the STS-1 and STS-2 SRB separation system performance are documented in References 6 and 7, respectively.

Separation Initial Conditions

The best estimate of the STS-1 and STS-2 SRB staging conditions is provided in Table 6. The values of the parameters monitored for automatic separation inhibi

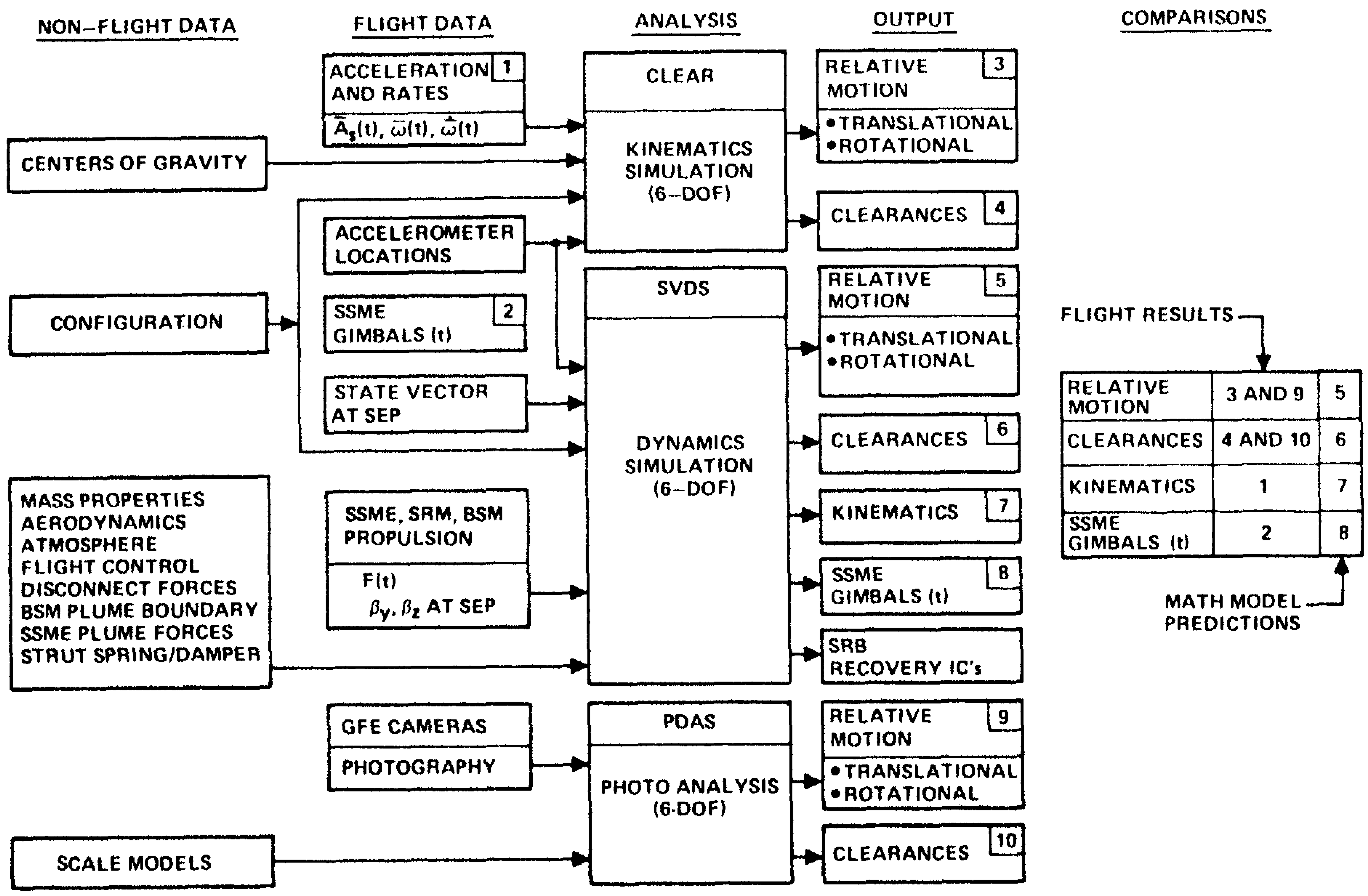


Fig. 9 SRB separation reconstruction plan.

Table 6 State vector at SRB separation.

			Requirement	STS-1	STS-2
MET	Mission elapsed time	sec		130.75	130.043
h	Altitude	ft		173,857	167,500
V_{air}	Wind relative velocity	ft/sec		4106	3964
V_E	Ground relative velocity	ft/sec		4112	4200
$\dot{h}$	Altitude rate	ft/sec		2473	2304
M	Mach number	—		3.877	3.767
$\bar{q}_{nav}$	Nav-derived dynamic pressure	lb/ft^2	≤ 55	12.0	16.7
$\bar{q}_{act}$	Actual dynamic pressure	lb/ft^2	≤ 75	12.83	13.19
α	Angle of attack	deg	−15/+15	3.00	3.93
β	Angle of sideslip	deg	−15/+15	0.75	0.68
P	Body roll rate	°/sec	−5/+5	−0.30	−0.36
Q	Body pitch rate	°/sec	−2/+2	0.40	0.28
R	Body yaw rate	°/sec	−2/+2	0.00	-0.08
γ	Flight path angle	deg		36.966	33.269
ψ	Heading angle	deg		58.37	61.96
ϕ	Bank angle	deg		179.35	179.40
$\ddot{x}$	Axial acceleration	g's		0.753	0.7535
$\ddot{y}$	Lateral acceleration	g's		−0.006	−0.0055
$\ddot{z}$	Normal acceleration	g's		0.200	0.198

(dynamic pressure and body rates) were all well within limits. The staging altitude and airspeed are shown graphically along with the predicted STS-1 staging corridor in Fig. 10. The separation altitude was higher than predicted for a strictly nominal ascent due to first-stage lofting caused by differences in aerodynamic pitching moment and normal force from predictions.

Performance

The performance of the four SRM's flown on STS-1 and STS-2 at separation is summarized in Table 7. All SRM's performed within specification without anomaly through separation.

The BSM's also performed within specifications without anomaly. The average STS-1 and STS-2 BSM cluster performances based on the performances of selected BSM's, one within each cluster, are provided in Table 8.

Separation Dynamics

The SIP-measured dynamics of the right SRB during the STS-1 separation are shown in Fig. 11. This graphically shows the effect of the impulse delivered by the BSM's as well as the effect of SSME plume impingement (starting about 2.75 seconds after separation) on SRB separation dynamics.

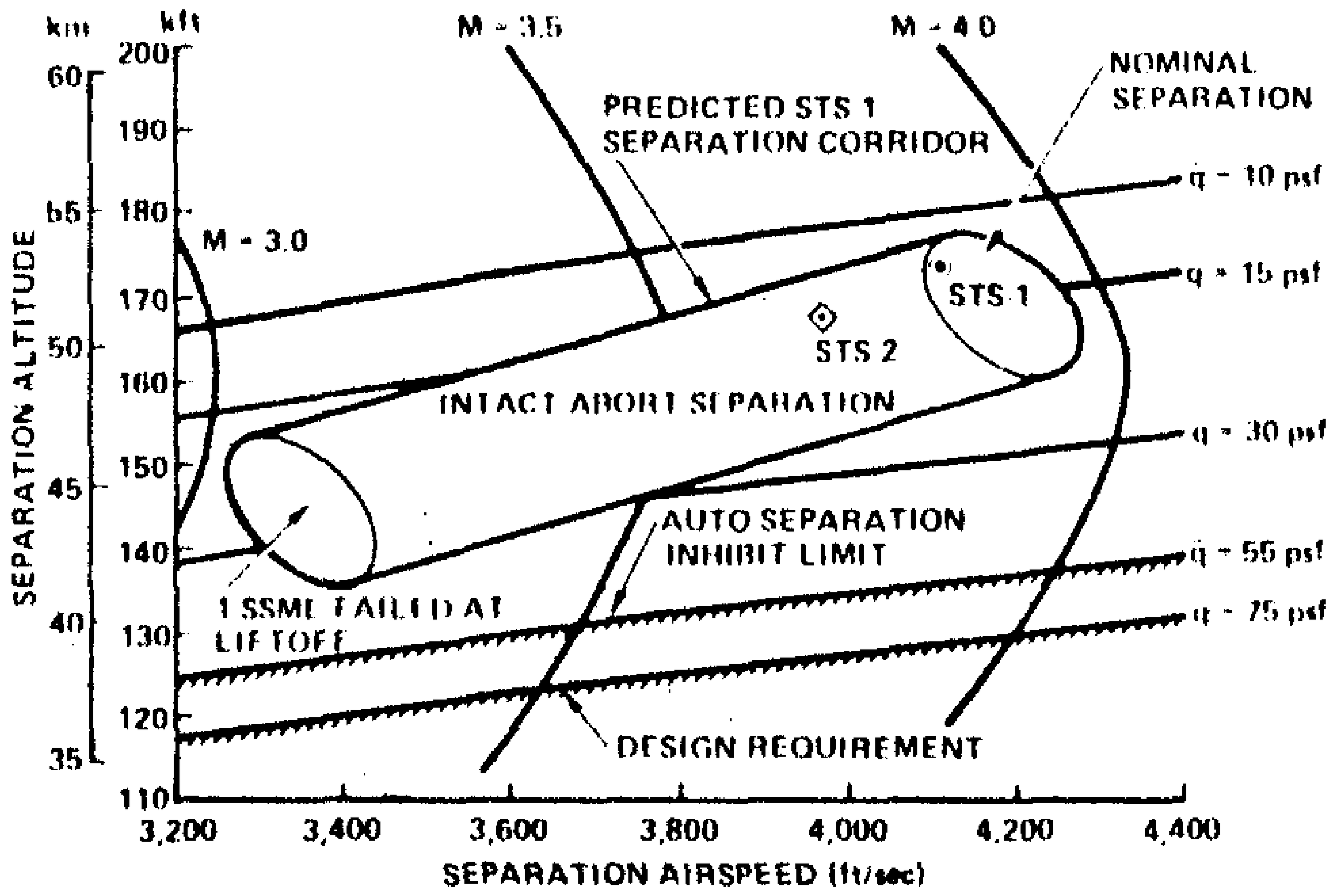


Fig. 10 SRB separation altitude versus airspeed.

Relative Motion and Clearances

Three-view strobe plots, showing the SVDS predicted relative motion of the SRB's with respect to the orbiter/ET

Table 7 SRM performance at separation.

				STS-1		STS-2	
			Requirement	Left	Right	Left	Right
PMBT	Propellant mean bulk temperature	°F	40 → 90	68	68	65	63
F	Thrust	lb	≤60,000	18,156.5	23,000.8	19,121.3	22,780.0
β_y	Pitch gimbal angle	deg	0 ± 1.0	0.042	0.064	0.0145	−0.0144
β_Z	Yaw gimbal angle	deg	1.0 ± 0.6	−0.679	0.672	−0.6898	0.7812
$\Delta t_{50/60}$	Δt (P_c = 50 psia → F = 60,000 lb)	sec	<6.0	3.312	4.035	3.215	3.885
$\Delta t_{P_c=50}$	Δt (P_{c_L} = 50 psia − P_{c_R} = 50 psia)	sec	<5.9	−0.135	−0.135	0.175	0.175
Δt_{null}	Time required to null nozzles	sec	<1.7	0.274	0.227	0.238	0.213

Table 8 Average BSM cluster performance.

			Requirement	STS-1	STS-2
$\Delta\phi$	Optical orientation error, roll	deg	±2.0	0.096	−.005
$\Delta\theta$	Optical orientation error, pitch	deg	±2.0	0.071	0.060
t_{ign}	Ignition interval (time to ¾ $P_{c_{max}}$)	sec	0.030 → 0.100	0.072	0.076
$t_{55.5k}$	Time to cluster F_{vac} = 55,500 lb	sec	0.030 → 0.135	0.053	0.059
WAT	Web action time	sec	≤ 0.805	0.685	0.661
t_{burn}	Total time (time to ½ P_{EWAT})	sec	≤ 1.05	0.884	0.895
AT	Action time	sec	—	1.235	1.241
P_{EWAT}	Chamber pressure at EWAT	psia	<2000	1801	1800
$P_{c_{max}}$	Maximum chamber pressure	psia	<2200	1845	1845
F_{ave}	Average thrust over WAT	lb	≥74,000	82,960	N/A
F_{max}	Maximum thrust	lb	≤116,000	90,826	91,950
I_{WAT}	Total impulse over WAT	lb-sec	≥56,000	61,906	N/A
I_{AT}	Total impulse over AT	lb-sec	≥60,000	77,552	N/A

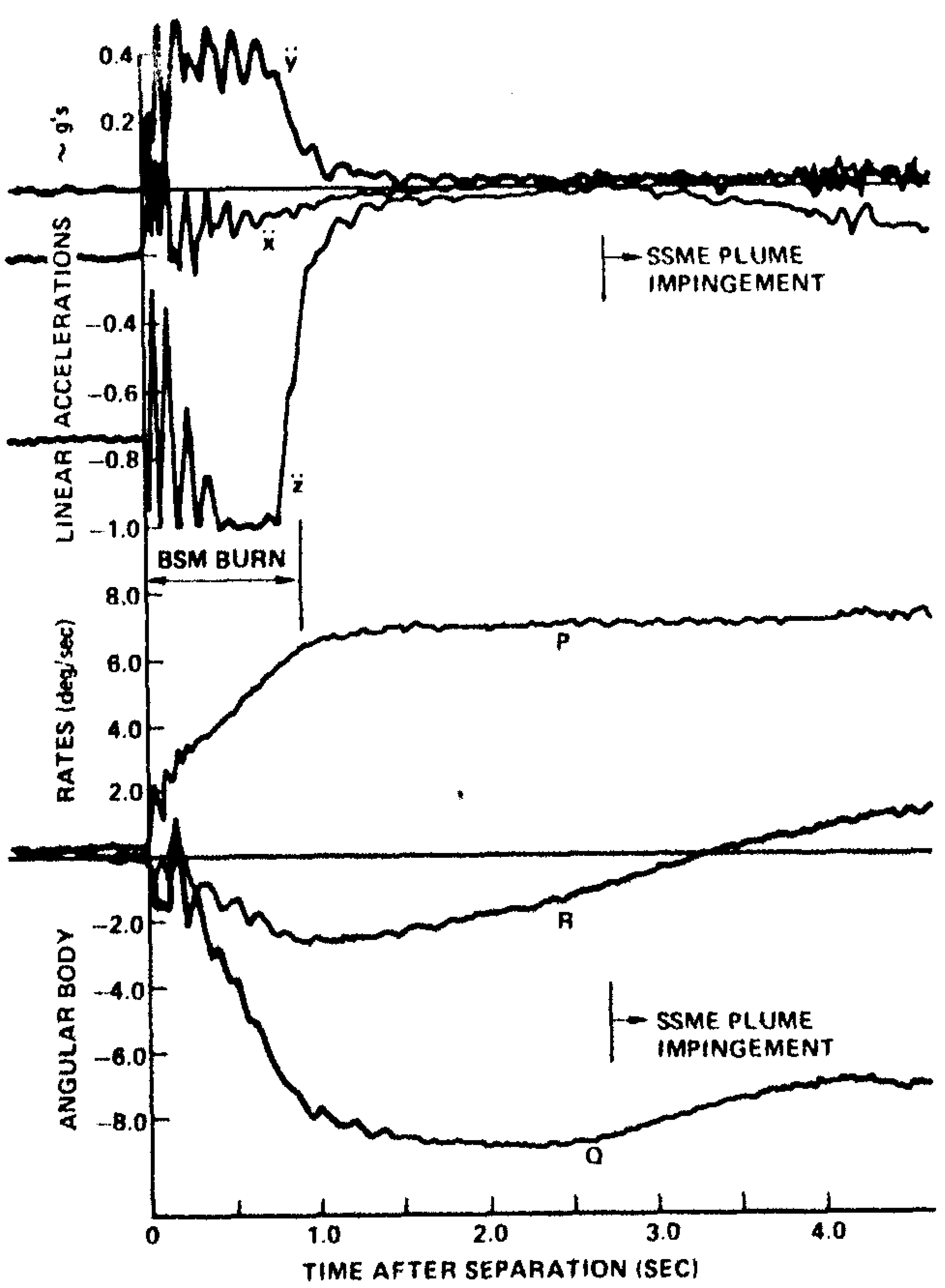


Fig. 11 SRB separation dynamics - right SRB/STS-1.

during the STS-1 separation, are shown in Fig. 12. A comparison of the axial, lateral, and normal displacements of the left SRB center of gravity relative to the orbiter/ET center of gravity obtained by SVDS, CLEAR, and PDAS for STS-1 is provided in Fig. 13. Although the comparison for the normal displacement is only fair, the trends are the same; and the overall agreement among the three methods is good. Discrepancies are accounted for primarily by the excitation of the SIP sensors at separation, accelerometer limits, and lack of SRB angular acceleration measurements. A comparison of the time histories of the clearance indicators obtained by the SVDS and CLEAR programs for the right SRB during the STS-2 separation is shown in Fig. 14. Again, overall agreement is good.

VIII. Conclusions

The unique requirements placed on the Shuttle SRB separation system as the result of the presence of the orbiter have been successfully satisfied by the design of the separation hardware, software, sequence, and flight control method. This has been verified by extensive tests and analyses and demonstrated by the excellent flight performance on STS-1 and STS-2. Data obtained from the test flights will enable the refinement of the analytic math models, the optimization of the separation sequence, and the improvement of the separation system for future versions of the SRB's.

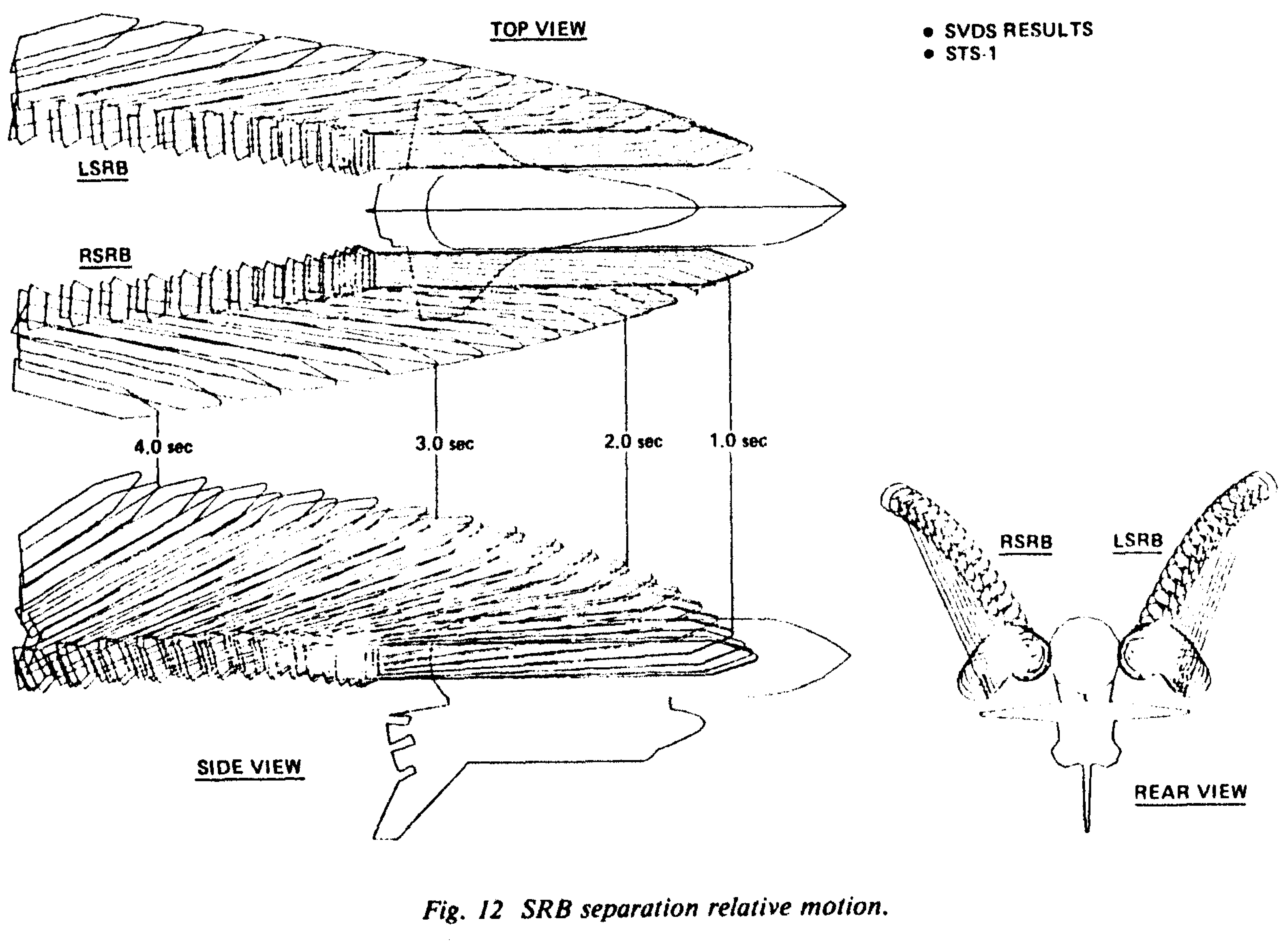


Fig. 12 SRB separation relative motion.

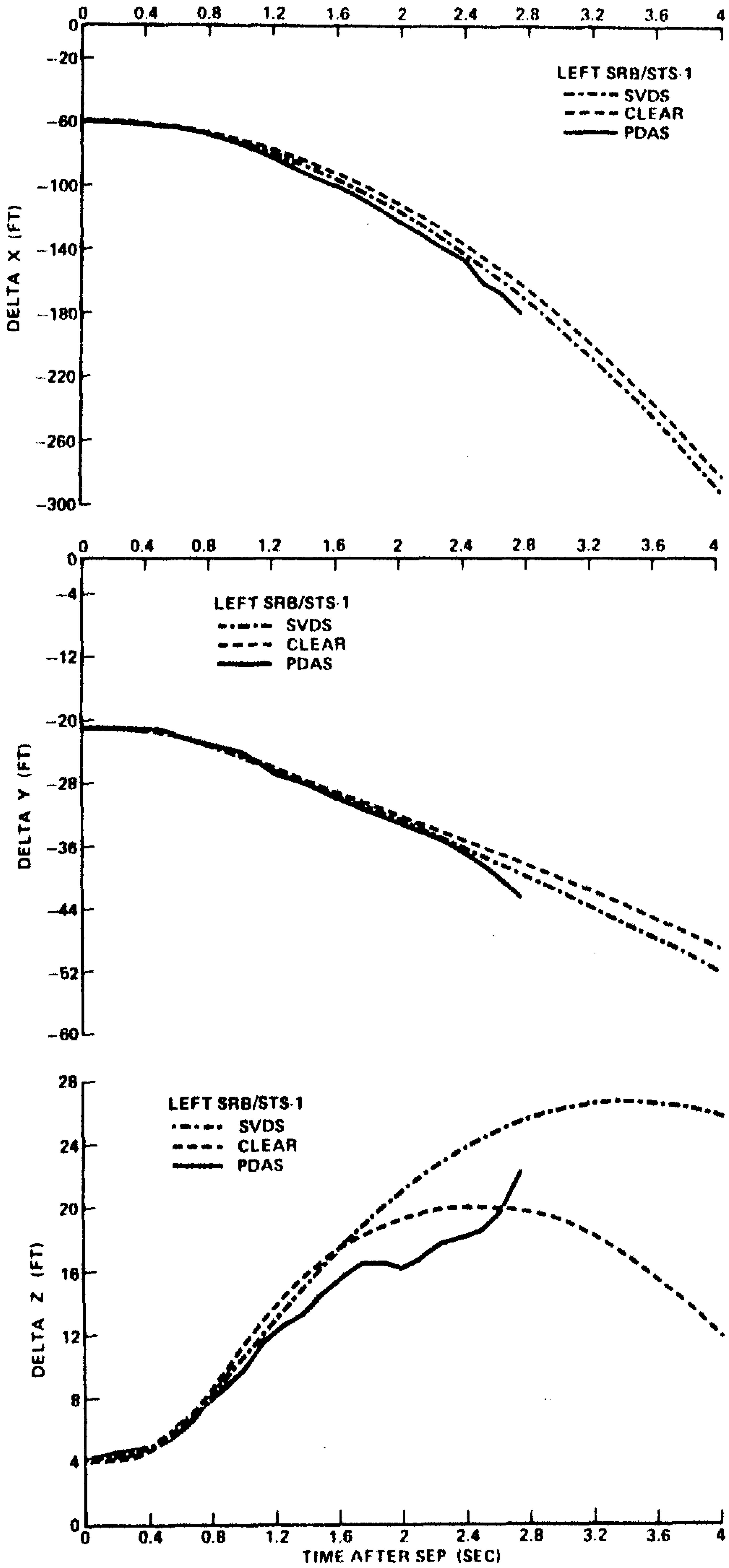
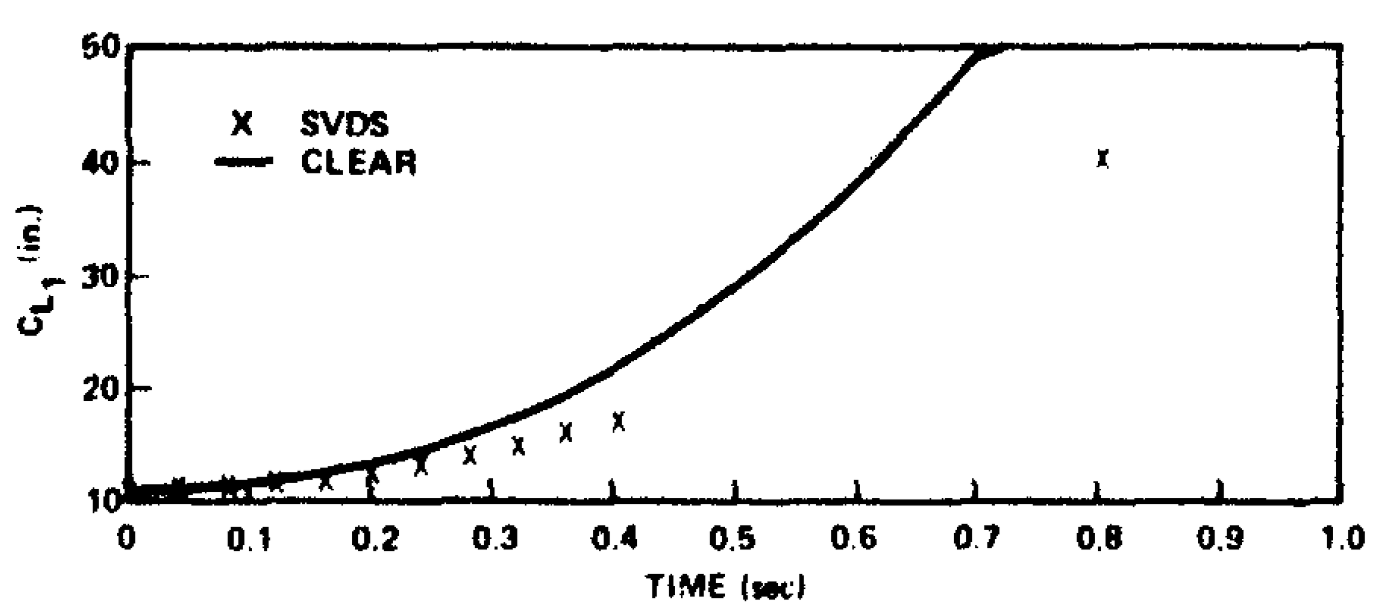


Fig. 13 C.g.-to-c.g. displacement – SRB relative to orbiter/ET.



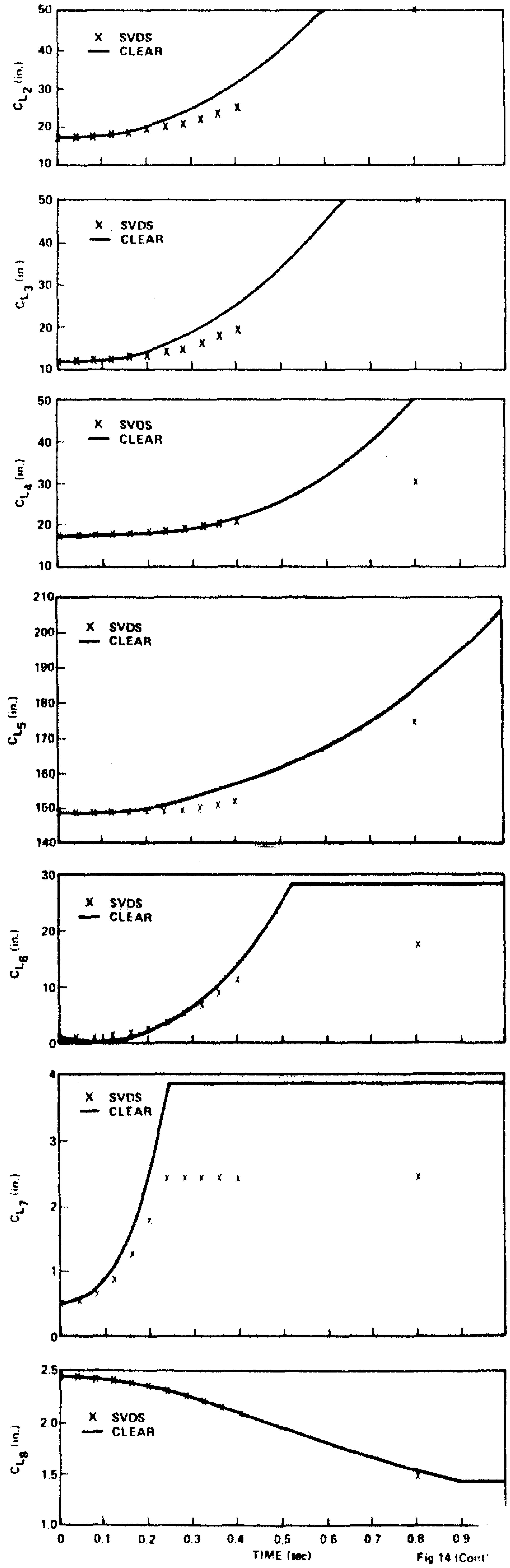


Fig. 14 Time histories of STS-2 right SRB clearance indicators.

Nomenclature

A	Translational acceleration
APU	Auxiliary power unit
AT	Action time
BFS	Backup flight system
BSM	Booster separation motor
c.g.	Center of gravity
C_L	Clearance indicator
℄	Centerline
DFI	Development flight instrumentation
DIT	Dynamic integration test
ET	External tank
E&I	Electrical and instrumentation
EWAT	End of web act time
F	Thrust
FA	Flight aft
FCS	Flight control system
FF	Flight forward
ft.	Feet
GFE	Government furnished equipment
GN&C	Guidance, navigation, and control
GPC	General purpose computer
I	Total impulse
IBM	International Business Machines
IC	Initial condition
IEA	Integrated electronics assembly
IGN&C	Integrated guidance, navigation, and control
I-Load	Initialization load
JSC	Lyndon B. Johnson Space Center
kft	Kilofeet
klb	Kilopounds
km	Kilometers
KSC	John F. Kennedy Space Center
lb	Pounds
M	Mach number
MDM	Multiplexer/demultiplexer
MDTSCO	McDonnell Douglas Technical Services Corporation
MEC	Master events controller
MET	Mission elapsed time
msec	Millisecond
MSFC	George C. Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NSI	NASA standard initiator
NSP	Network signal processor
P	Roll rate
P_c	Chamber pressure
P_{sel}	Selected roll rate
PBI	Push button indicator
PCM	Pulse code modulation
PDAS	Photo data analysis system
PFS	Primary flight system
PIC	Pyrotechnic initiator controller
PMBT	Propellant mean bulk temperature
PMTC	Pacific Missile Test Center
psf	Pounds per square foot
psia	Pounds per square inch, absolute
Q	Pitch rate
Q_{sel}	Selected pitch rate
$\bar{q}$	Dynamic pressure
$\bar{q}_{nav}$	Navigation-derived dynamic pressure
R	Yaw rate
R_{sel}	Selected yaw rate
RSS	Range safety system
SAIL	Shuttle Avionics Integration Laboratory
SIP	Separation instrumentation package
sec	Second
SRB	Solid rocket booster
SRM	Solid rocket motor
SSME	Space Shuttle main engine
STS	Space Transportation System
ST&SG	Space Transportation & Systems Group
SVDS	Space vehicle dynamics simulation
TPS	Thermal protection system
TVC	Thrust vector control
UTI/CSD	United Technologies Incorporated/Chemical Systems Division
WAT	Web action time
W-O-W	Worst-on-worst
$\ddot{x}$	Axial acceleration
$\ddot{y}$	Lateral acceleration
$\ddot{z}$	Normal acceleration
α	Angle of attack
β	Angle of sideslip
β_y	Pitch gimbal angle
β_z	Yaw gimbal angle
ϕ	Roll angle
σ	Standard deviation
θ	Pitch angle
ω	Rotational velocity
$\dot{\omega}$	Rotational acceleration

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