AIAA 81-1511R

Space Shuttle Orbit Maneuvering Subsystem Performance Status Report

D.D. Anglim*
McDonnell Douglas Astronautics Company, St. Louis, Missouri

On April 12, 1981, the launch of the Orbiter Columbia marked the beginning of the Shuttle era. During this first mission, the aft propulsion subsystem successfully demonstrated its capability to provide Shuttle orbit maneuvering and attitude control. This paper presents an overview of the orbit maneuvering subsystem and describes the performance results for the first Shuttle flight. Description of the aft reaction control subsystem design and performance is included as it pertains to orbit maneuvering subsystem operation.

Introduction

THE Shuttle aft propulsion subsystem (APS) is a modularized propulsion system which uses Earth storable hypergolic bipropellants, nitrogen tetroxide and monomethylhydrazine, to provide propulsive thrust for Shuttle orbit maneuvering and attitude control. The system is fully reusable, with a life requirement of 100 missions over ten years.

The APS is housed in two pods located on each side of the Shuttle's aft fuselage, as shown in Fig. 1. Each pod weighs approximately 4000 lbm (dry) and holds up to 15,000 lbm of propellant in two propulsion units: an orbit maneuvering subsystem (OMS) and an aft reaction control subsystem (ARCS). The OMS performs the orbit insertion, orbit transfer, and deorbit functions, while the ARCS provides on-orbit translation and attitude control both on-orbit and during entry. In addition, the OMS has the capability to provide propellants to ARCS thrusters for all on-orbit translation and attitude control operations. Table 1 summarizes the key subsystem design requirements.

The APS pods are interconnected by propellant crossfeed lines located within the orbiter aft fuselage. The crossfeed lines provide the capability to distribute propellants from one pod to the engine/thrusters in the opposite pod. The crossfeed lines will also allow interconnection of the pods to auxiliary tankage located in the orbiter payload bay for missions requiring greater propellant capacity.

Design Description

The functional and performance requirements imposed on the APS led to the subsystem configuration schematically depicted in Fig. 2. The OMS and ARCS use dedicated pressurization and propellant tankage systems but have interconnected feed systems to allow OMS-to-ARCS propellant transfer.

Each subsystem employs a regulated pressurization system. The helium pressurant is stored in high pressure bottles located in the pod aft bay. These filament-wound titanium bottles provide a leak-before-burst failure mode. The OMS bottle operates over the pressure range 4800-460 psia.

Near-continuous mission demands on the ARCS necessitate dedicated fuel and oxidizer pressurization systems to preclude propellant vapor mixing within the pressurization system. However, OMS burns are predictable and far fewer in number. As a result, a common pressurant supply control panel is used for OMS fuel and oxidizer pressurization, providing accurate mixture ratio control. Normally closed solenoid valves in the OMS oxidizer pressurization system provide a reliable means of isolating the two propellant circuits against possible propellant vapor mixing during inactive periods. Parallel redundant regulation legs, each having a series redundant dual regulator, provide for system operation with up to two failures. The pressurization system controls OMS tank pressures to 252 ± 5 psia. When the OMS-to-ARCS flow mode is employed, the OMS tankage is operated in the blowdown mode over the pressure range 266 (regulator lock-up) through 238 psia.

The ARCS and OMS propellant tanks are tandem-mounted in the lightweight graphite-epoxy structure, with the smaller, spherical ARCS tanks located forward. A single gimballed, regeneratively cooled 6000-lbf-thrust orbit maneuvering engine (OME) is used in each pod. All ARCS thrusters are contained in a structural housing that is located outboard of the OME. Each pod contains twelve 870-lbf primary thrusters and two 25-lbf vernier thrusters.

Both the OMS and ARCS employ passive surface tension propellant acquisition systems. Together they represent the first manned spacecraft application in which propellant management is fully dependent on surface tension devices. The OMS system, shown in Fig. 3, consists of a bulkhead communication screen and a gallery/collector manifold assembly. The bulkhead screen divides the tank into a forward compartment and an aft trap reservoir. The bulkhead

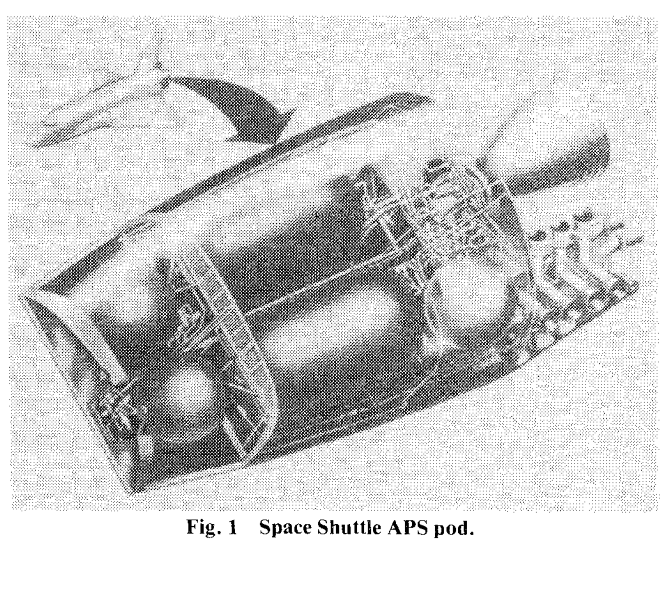

Fig. 1 Space Shuttle APS pod.

Presented as Paper 81-1511 at the AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colo., July 27-29, 1981; submitted Aug. 12, 1981; revision received Feb. 25, 1982.

*Unit Chief, Technology. Member AIAA.

Table 1 APS design requirements

OMS
Provide 1000-ft/s velocity increment (two pods)
Capability to launch with off-loaded tanks (5400 lbm/pod minimum)
Engine start without propellant settling maneuvers
Capability for at least ten starts
Provide up to 1000-lbm propellant per pod to the ARCS thrusters
System operation with up to two failures
Capability to expend usable propellants within 300 s (abort)
ARCS
Provide attitude control and three-axis translation
Operation down to 45,000 ft
Provide roll control during single OMS engine operation
System operation with up to two failures

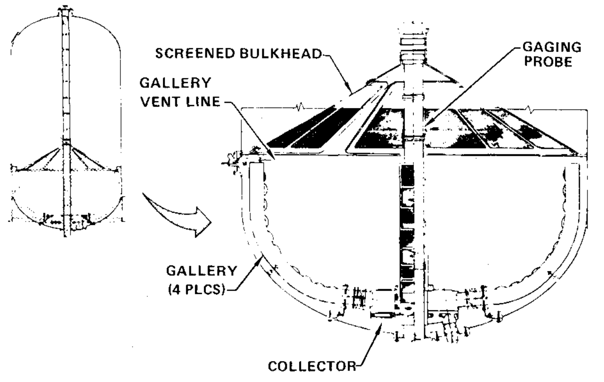

Fig. 3 OMS propellant tank.

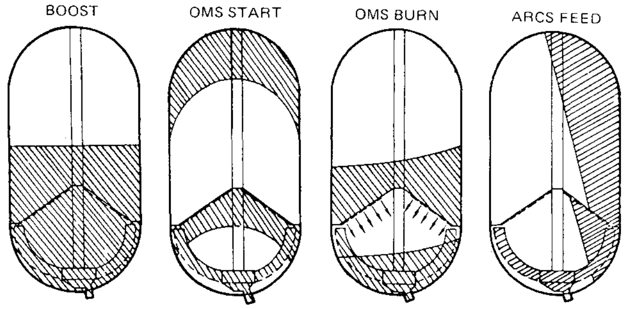

Fig. 4 OMS acquisition assembly operating modes.

retains propellant within the trap reservoir during all vehicle adverse maneuvers on orbit but allows propellant to flow into the trap reservoir when propellants are settled during OMS or OMS-to-ARCS burns, as depicted in Fig. 4. Inside the trap reservoir are four gallery legs which contact wallbound propellant. Propellant flow is through screen windows located on the outer surface of each gallery leg. The gallery legs tie into a collector manifold at the bottom of the tank, which supplies propellant to the tank outlet. Maintainability is provided for by incorporating sense lines at the forward ends of the gallery legs and immediately beneath the bulkhead screen to allow in-tank checkout of system integrity. Additionally, a tank access cover allows for removal and replacement of all internal acquisition hardware.

APS fluid system instrumentation consists of 40 operational pressure measurements located at the pressurant bottles, propellant tanks, thruster manifolds and OME inlet, and ARCS thruster and OME combustion chambers. Forty operational temperature measurements are located at the pressurant bottles, propellant tanks, feed lines, and thruster and OME injectors. The OMS propellant gaging function is performed by capacitance-type concentric tube probes installed in both the tank forward and aft compartments. The fuel and oxidizer gaging systems are similar in principle, although the measurement methods differ because the oxidizer is dielectric while the fuel is conductive. Drain ports at the bottom of the probes allow the fluid between the tubes to seek the level of the bulk fluid in the tank. As fluid is depleted the capacitance between the tubes changes, thereby providing an indication of quantity remaining. The probes are only operational during OME firings, when there is a sufficient acceleration level (0.06g) to predictably orient the propellants. A 14-s delay in probe activation following engine startup is incorporated to avoid erratic data during propellant reorientation and settling at the start of each firing. Propellant quantity during this phase, as well as during the period when the bulk fluid level is between the forward and aft probes, is based on OME burn time flow-rate integration.

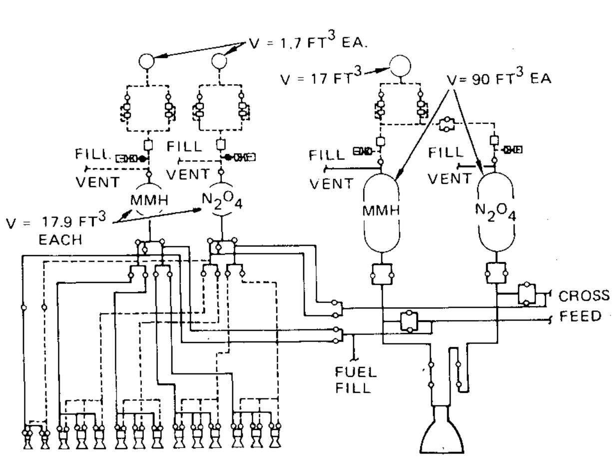

Fig. 2 Simplified APS schematic (left pod).

Over 700 welds join the majority of 290 fluid line assemblies and 470 propulsion components in each pod. The only significant exceptions to the use of welded joints are the pressure transducer installations (heat sensitive and fairly high failure rate components) and tank/engine interfaces (final assembly joints that provide for end-to-end purge or flush of completed assemblies). Mechanical joints with redundant seals are used at these locations.

Table 2 summarizes operating time and cycle life requirements for a sampling of OMS components. While most of the components were based on previous hardware designs, the Shuttle 100 mission reuse life represented an entirely new requirement for spacecraft components, and the primary component design challenge was to eliminate life limiting features. Material selections considered not only compatibility with the propellants, but also with system flush fluids and tertiary products that might be formed by reaction of the propellants with moisture and/or atmospheric constituents. Teflon was the only well-characterized nonmetal offering full compatibility with these fluids, and it is used extensively in the APS for pressure sealing. A detailed description of the APS approach to design for reuse capability is presented in Ref. 1.

STS-1 Performance

APS operation during the first flight (STS-1) satisfied all requirements and performance agreed closely with analytical predictions. A total of five OMS burns were performed, as detailed in Table 3. As shown, the operational modes demonstrated included both single and dual engine firings, and normal pod and crossfeed propellant supply modes. In addition, the OMS-to-ARCS feed mode was employed for three periods entailing roughly 40% of the mission. While demonstration of the OMS-to-ARCS feed mode was an STS-1

Table 2 Sample life requirements for major OMS components

	Life[a]	
	Basis	Requirement
Helium bottle	Pressure cycles	1,000
Helium isolation valve	Actuation cycles	2,700
Series pressure regulator	Flow cycles (main stage)	2,107
Quad check valve	Flow cycles	100,000
Propellant tank	Pressure cycles	600
A.C. motor valve	Open/close cycles	2,500
Orbit maneuvering engine	Firing cycles	1,000
Orbit maneuvering engine	Firing time, s	54,000

[a]Requirements include scatter factor of 4.0 on tanks and control components.

objective, it was utilized more extensively than had been planned. (The thermal tile on the pod forward surface had been damaged during launch and it was decided to minimize ARCS propellant usage so that the forward-located ARCS tanks could act as heat sinks during entry.) Up to four ARCS thrusters were operated simultaneously while in the OMS-to-ARCS feed mode. Table 4 summarizes OMS propellant usage for STS-1. At launch, the OMS tanks were loaded to approximately 65 and 73% for the left- and right-hand pods, respectively. Landing residuals were approximately 9 and 17% for the left- and right-hand pods, respectively.

Feed System

In-flight system performance was assessed by comparing telemetry data to preflight predictions. The APS system performance math model (UP07 digital computer code) was developed for performance prediction and analysis. The model simulates a quasi-steady-state system operation. That is, the entire system is assumed to be at equilibrium at a given point in time, but the computed parameters are allowed to vary with time. Included are the thermodynamics of the pressurant bottles and propellant tanks, and heat transfer within these tanks. The fuel and oxidizer feed networks are iteratively balanced, comparing theoretically and empirically calculated chamber pressures. Component performance parameters are based on acceptance records, and the entire program has been validated using system level development test results.

The flight data from STS-1 agreed well with analytical predictions. OMS helium bottle pressures ranged from 4700 to 2630 psia in the left-hand (LH) pod and 2720 psia in the right-hand (RH) pod over the course of the mission. Bottle pressures and temperatures were within 50 psia and 10°F, respectively, of analytical predictions. Regulated pressures were very stable, with steady-state tank pressures averaging 252.6 psia (fuel) and 251.2 psia (oxidizer) for the LH pod, and 252.4 psia (fuel) and 251.0 psia (oxidizer) for the RH pod, well within the required tolerance.

Figure 5 presents RH pod feed system pressure histories for OMS-1. The slight offsets between tank ullage and engine inlet preburn readings represent transducer shifts. The tanks were initially above the regulator lock-up pressure of 266 psia due to ground pressurization, and so the first portion of the burn was performed in the blowdown mode.

One anomaly was observed on the RH oxidizer inlet pressure trace. Approximately 12 s after the start of OMS-1 a discrete drop in pressure was observed. An accompanying reduction in chamber pressure indicated that the condition was not merely an instrumentation shift. Figure 6 compares measured RH oxidizer feed system pressure differentials to analytical predictions and shows that a 4-8-psi discrepancy existed over the course of the mission. For reference, RH fuel and both LH fuel and oxidizer pressure differentials agreed quite closely to analytical predictions. The effect of this anomaly on mission performance was minimal, resulting in a 2-psi reduction in chamber pressure and a 0.07 shift in mixture ratio.

A post-flight inspection revealed the presence of an amber colored crystalline material deposited on the RH OME oxidizer inlet filter and in the convolutes of the gimbal bellows located immediately upstream. The contaminant was identified as a partially oxidized polyethylene/acrylic acid copolymer, and was found to have physical and chemical

Table 3 OMS operation summary

OMS burn	Purpose	Operating mode	Mission elapsed time, h:	min:	s	Duration h:	min:	s
1	Insertion	LH OMS to LH OME RH OMS to RH OME	0:	10:	32			86.3
2	Circularization	LH OMS to LH OME RH OMS to RH OME	0:	44:	00			74.8
3	Crossfeed demonstration	LH OMS to RH OME	6:	21:	41			28.8
4	Crossfeed demonstration	RH OMS to LH OME	7:	05:	31			33.1
	Attitude control	LH OMS to ARCS	21:	39:		8:	21:	
	Attitude control	RH OMS to ARCS	30:	00:		6:	20:	
	Attitude control	RH OMS to ARCS	44:	52:		7:	32:	
5	Deorbit	LH OMS to LH OME RH OMS to RH OME	53:	31:	04			156.0

Table 4 OMS propellant usage

Usage, lbm	LH pod	RH pod
Quantity loaded	8500	9390
OME	6640	6485
OMS-to-ARCS	710	725
Landing residuals	1150	2180
Propellant consumed	7350	7210

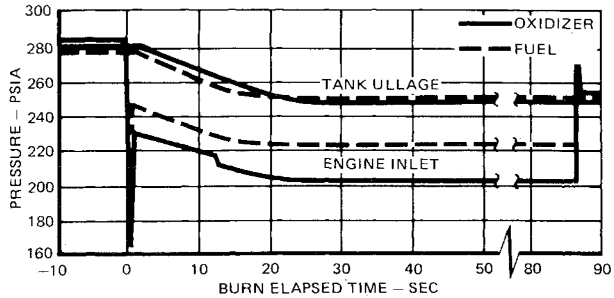

Fig. 5 OMS-1 pressure histories (right pod).

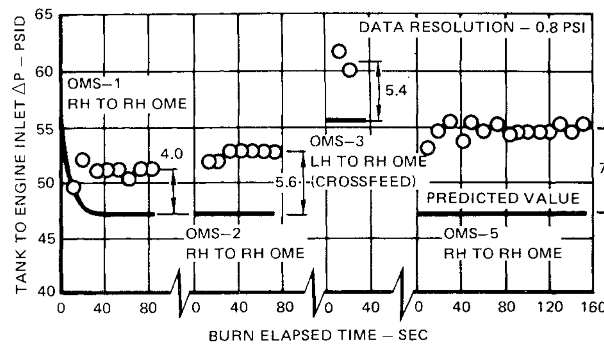

Fig. 6 Oxidizer feed system ΔP (right OME).

properties similar to a polymer film called "Surlyn." Although an infrared spectrophotometry comparison of the contaminant and Surlyn exposed to nitrogen tetroxide or nitric acid did not yield a complete match, it was concluded that the contaminant must have originated from this generic type of material. However, none of the known packaging/processing materials used in the manufacture of the system fall within this class, and therefore no definitive conclusions were made regarding the source of the contaminant. The line was cleaned and the filter was replaced prior to STS-2. During that flight there were no indications of any reoccurrence.

OMS Acquisition System

The OMS tank aft compartment had been sized by the worst-case assumption that up to 1 ft^3 of gas would transfer across the bulkhead screens during OME startups, and that all OMS-to-ARCS propellants would come from the aft compartment without replenishment. The conservatism of these assumptions was demonstrated in STS-1 when the aft compartments in all four OMS tanks remained completely full until their respective forward compartments were entirely drained. This means that the bulkhead screens remained in contact with forward compartment propellant during all periods of outflow, regardless of the quantities remaining.

In the case of the LH pod, propellant was successfully transferred across the bulkhead without gas ingestion, with as little as 4% of forward compartment propellants remaining for both OMS-to-ARCS usage and OME start. The bulkhead/tank wall geometry therefore provides for propellant contact with the bulkhead screens when a minimum surface energy condition exists in the forward compartment. The fact that the aft compartments remained full also indicates that no propellant spilled across the bulkhead screens as a result of adverse acceleration orientations. Table 5 summarizes the OMS acquisition assembly performance.

The implications of STS-1 experience is that the OMS acquisition system is not mission constrained in terms of number of engine starts or quantity of propellant fed to ARCS thrusters. Plans for future missions call for increased OMS-to-ARCS usage and these data will further confirm these findings.

OMS Gaging System

The three primary gaging system objectives were as follows: provide a propellant loading accuracy of 0.5%; provide a stable output following the 14-s lockout at the start of each OMS firing; and provide an on-orbit accuracy of 1.4%. These objectives were fully satisfied for the oxidizer probes. The fuel probes did not fully satisfy the on-orbit performance goals, but minor modifications have been identified to eliminate fuel probe discrepancies on future flights.

Table 6 compares gaging system output to loading facility flow-meter data and to analytical predictions for on-orbit operation. Differences were within the 0.5% loading requirement for both propellants and were generally well within the on-orbit accuracy goal for the oxidizer system. Figure 7 presents a typical output trace. The fact that the oxidizer output transitions smoothly from the initial integration phase to the direct output phase indicates that the lockout period is sufficient to allow for bulk propellant settling. The 0.25-cycles/s frequency is the U-tube oscillation between the tank and probe, as predicted by the analyses of Ref. 2.

Table 5 OMS acquisition assembly performance

Design goals/requirements	STS-1 performance
Launch with off-loaded tanks	Tanks loaded to 65-73% at launch
Engine start without settling maneuver	Settling maneuvers not required
Gas-free propellant feed	No evidence of gas ingestion
Up to ten OMS starts	Four burns performed from each pod per mission timeline
Aft compartment sizing constraints 1 ft^3 per OMS start 1000 lbm per pod fed to ARCS thrusters	Aft compartments completely full until forward compartments drained
Expulsion efficiency >97.7%	Landing residuals as planned, ranging from 7.6 to 17.0%

Table 6 Gaging system error

Mission phase	%Full scale			
	LH pod		RH pod	
	Oxidizer	Fuel	Oxidizer	Fuel
Loading	0.2	0.4	0.1	0.1
Post-OMS—1	0.1	0.7	0.2	0.9
Post-OMS—2	0.0	1.4	1.0	3.4
Post-OMS—3	0.1	1.6	1.2	1.6
Post-OMS—4	0.0	1.6	0.0	6.4
Post-OMS—5	0.4	1.4	1.0	18.6[a]

[a]Aft channel error 0.5% for OMS—5. Aft compartment full for other burns.

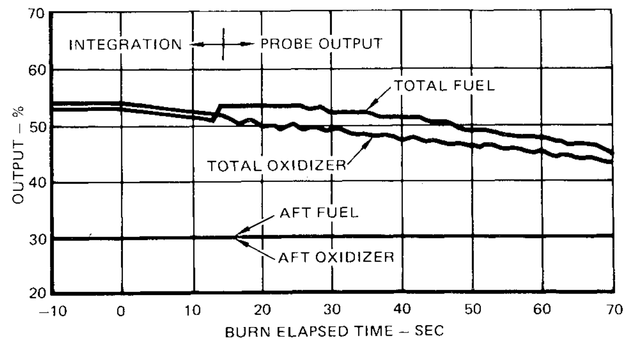

Fig. 7 Typical gaging system output (OMS-2 left pod).

The forward fuel probe output was characterized by sluggish performance, as shown in Fig. 7. Following the lockout phase, probe output increased several percent and then lagged behind actual propellant outflow. This problem was traced to insufficient vent area at the top of the forward fuel probe. In a 1-g environment probe response is acceptable but in low-g the gravitational forces are insufficient to clear the vent path of propellant. This problem is being alleviated by locating additional vents near the top of the fuel probe. Evaluation of the second flight data for this probe indicated that the modifications had completely eliminated this response problem.

A second anomaly occurred with the fuel, and to a minor extent, with the oxidizer probes of the RH pod. Drain holes in the probe support cone had been sized to provide fluid damping, thereby minimizing the amplitude of output oscillations. However, the drain area was distributed among 12 holes, and during STS-1 it was discovered that a fluid column trapped within the probe could be supported by surface tension forces in the small holes, as shown in Fig. 8. The OMS-5 burn started with propellants below the probe lower sense points in the RH pod, and fluid columns were trapped in both the fuel and oxidizer probes. The oxidizer probe cleared momentarily, and accuracy was not seriously degraded. However, the fuel column remained stable for the duration of the burn, and as a result total channel output was significantly in error. This problem is being resolved by revising the drain port configuration to two larger holes having the same total area as the current design.

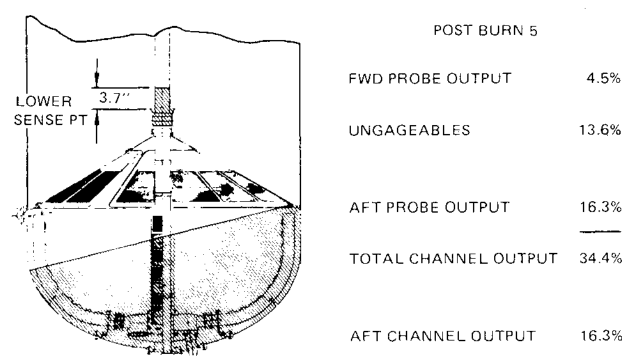

Fig. 8 Fuel gaging probe anomaly (right pod).

Summary

The near perfect performance of the aft propulsion subsystem on STS-1 marks a significant milestone in the design and development phase. Many of the system operating modes have been exercised on this mission, and the operating envelopes are expected to be extended without difficulty on future development flights. The capability to design and develop surface tension acquisition systems suitable for use on manned vehicles over a wide range of operating conditions represents a milestone in propellant management technology. Problems with a contaminant within the oxidizer feed system and sluggish fuel gaging performance were encountered. However, neither condition represented a serious threat to mission success and steps have been taken to preclude similar occurrences on future missions.

References

[1]Schweickert, T.F., "Design of the Aft Propulsion Subsystem for Long Life," Paper presented at the 1981 JANNAF Propulsion Meeting, New Orleans, La., May 1981.

[2]Anglim, D.D., "Low-g Testing of the Space Shuttle OMS Propellant Tank," AIAA Paper 79-1258, June 1979.