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SPACE SHUTTLE ON-ORBIT PROPULSIVE CAPABILITIES

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ABSTRACT

NASA's space shuttle orbiter is the premier manned spacecraft. The space shuttle orbiter allows astronauts to perform many tasks such as docking with space stations, deploying satellites, rendezvousing with and repairing the Hubble Space Telescope, etc. The shuttle orbiter would never be able to perform such tasks without its rocket propulsion system. Whenever the orbiter makes changes to its orbit, or performs orbital maneuvers, it uses propellant from its on board orbital propulsion system. The ability to perform such orbital maneuvers depends on the orbital mechanics, spacecraft dynamics, and rocket propulsions. The purpose of this paper is to gain insight into the propulsive capabilities of the space shuttle orbiter. The analysis will reveal the limits of the space shuttle's ability to perform multiple orbital maneuvers on any given mission.

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BACKGROUND

March 26,1926 Dr. Robert H. Goddard launched the first liquid fueled rocket in history, and began the modern age of rocketry [1]. That first liquid propellant rocket only flew 184 feet, but it began the science that eventually put man into outer space. On April 12,1961, Yuri Gagarin became the first man in outer space [1]. Exactly twenty years after the first man reached space, the first reusable spacecraft flew its first mission. The space shuttle orbiter is known for its unique ability to take off like a rocket, but land like a plane. While on orbit, the orbiter also performs like a rocket. Actually, it uses several rocket engines to change its attitude or orbit.

Rockets, like the one Dr. Goddard launched, work by providing a change in velocity, known as a delta V. The delta V a rocket can provide is based on the momentum, velocity and mass, of the propellant as it exits the rocket. According to Newton's third equation of motion, for every action there is an equal but opposite reaction. The momentum of the rocket fuel leaving the rocket is equal to the momentum of the rocket moving forward. Since the mass of the rocket is much greater than the mass of fuel leaving, it does not move as fast. Therefore, to accelerate a rocket to high speeds, the rocket fuel must expend great amounts of fuel at extremely high velocities.

To know what a delta V will do to a spacecraft requires an understanding of orbits. Johann Kepler discovered that the planets' orbits are elliptical. In general, the shape of orbits can be described as conic sections. That is to say bodies in space moving in paths based on the force of gravity will look like circles, ellipses, parabolas, or hyperbolas. As a rocket increases the velocity of a spacecraft, it increases the energy of the spacecraft. The effect is to alter the geometry of the orbit. More orbital mechanics will be discussed later.

SHUTTLE PROPULSION SYSTEMS

LAUNCH

The space shuttle relies on its main engines (SSMEs) to provide the majority of the thrust required for achieving orbit. The main engines use a propellant with liquid oxygen (LOx) for oxidizer and liquid hydrogen (LH_2) for fuel. This liquid rocket fuel is combusted and ejected out of three nozzles, the main engines, located at the rear of the space shuttle orbiter [2]. In order to provide enough thrust to leave the earth's atmosphere, a rocket needs to expend an incredible amount of mass: 710,801 kg of LOx/LH_2 [3]. For this purpose, the shuttle keeps the propellant for the main engines in an external tank (ET). The ET holds 378,000 gallons of LH_2, and 139,623 gallons of Lox [4]. The ET can be dropped off when it runs out of propellant, thus relieving the orbiter of 37,452 kg of dead mass [3]. This complex system is augmented by solid rocket boosters (SRBs) to help the orbiter produce enough thrust to initially lift off the ground [2]. The shuttle uses all or almost all of the liquid oxygen and liquid hydrogen propellant reaching space. Once the fuel stops combusting, the main engines are cut off (MECO). If there is any remaining propellant for the main engines then it is purged [5]. This means that for the rest of the space flight the shuttle can not use the main engines. It must rely on its on orbit system.

ON ORBIT

Once in orbit, the space shuttle uses several rocket engines known as the orbital maneuvering system (OMS) and the reaction control system (RCS). The orbital maneuvering system is the space shuttle's propulsion system for three-axis control and major orbital changes such as "orbit insertion, orbit circularization, orbit transfer, rendezvous, ...", and deorbit [5]. The OMS can be used to achieve orbit if the space shuttle's main engines malfunction at a high enough altitude [2]. The orbital maneuvering system consists of two engines in the rear of the space shuttle orbiter just above the three main Engines [5]. Each of the OMS engines are rated for 6,000 pounds (26,688 Newtons) of thrust [3]. The OMS engines can be gimbaled to provided thrust vectoring whether one or both engines are used. Orbital maneuvers requiring delta Vs greater than 6 feet per second use both OMS engines[6]. If only one OMS engine is used, then it uses the gimbaled thrust vectoring in a similar manner to when both engines are used. Whenever only one OMS engine fires, the thrust vector control ensures the thrust is through the spacecraft's center of gravity, and the RCS maintains roll control [6].

For small velocity maneuvers the orbiter relies on the 44 engines of the reaction control system. The reaction control system is located around the nose and the tail of the orbiter [5]. The RCS at the rear of the orbiter is in the same area as the OMS. It is housed in the McDonnell Douglas OMS/RCS pods [2]. The forward and aft RCS engines also provide attitude control and three-axis translation during external tank separation, insertion and on-orbit maneuvers and roll control for a single-OMS-engine operation. Since each OMS burn is programmed to fire for specific burn durations, the RCS is usually needed to correct small errors in the velocity, velocity residuals that may exist following the cutoff [6]. Appendix A has schematics of systems located on the shuttle orbiter, the OMS/RCS pod, and the forward RCS.

The engines fire in a coordinate system relative to the space shuttle. The X-direction is in line with the body of the orbiter, from the tail to the nose. The Y-direction is in line with the wings, from left wing to right wing. The Z-direction is in line with the tail, from body towards tail. The OMS engines are in line with the X-axis as well as a series of RCS jets called X-jets. There are 7 X-jets thrusting in the plus or minus X-direction. The 12 RCS jets thrusting in the plus or minus Y-direction provide Y translation and yaw only. The 19 RCS jets thrusting in the plus or minus Z-direction provide Z translation and roll or pitch rotation control and are considered independent of other axes. These 38 jets are the primary RCS engines. There are 6 more RCS engines called vernier engines. Of the 44 engines, only good engines will be used [5]. Warning lights will indicate leaking jets, and failed jets whether or not the orbiter is trying to fire them.

Astronauts can manually command the RCS or use the flight computer to rotate the orbiter. The flight computer can rotate the orbiter while simultaneously translating the orbiter. However, if multiple translations are requested simultaneously, the flight computer performs each translation one-at-a-time in order of priority. For example, if both plus X and minus Z translations are commanded simultaneously, plus X translation receives priority [5].

For the OMS thrusting period, the orbital state (position and velocity) vector is produced by navigation incorporating inertial measurement unit delta velocities during powered and coasting flight. This state is sent to guidance, which uses target inputs to compute thrust direction and spacecraft attitude for flight control Flight control converts the commands into OMS engine gimbal angles (thrust vector control) for an automatic thrusting period.

PROPELLANT

Both on-orbit propulsion systems use the same type of propellant: a bipropellant with nitrogen tetroxide (N_2O_4) for the oxidizer and monomethyl hydrazine (MMH) for the fuel. The N_2O_4/MMH is mixed in the combustion chamber where the two chemicals produce a hypergolic reaction releasing energy in the form of heat. Each of the OMS engines has independent fuel systems, independent of the other OMS engine and independent of the RCS in the same pod. However, the fuel tanks are connected [2]. If one of the OMS engines needs more fuel, astronauts can control a connection between the two OMS/RCS pods. Likewise, the RCS engines can obtain fuel from the OMS supply if needed. Each OMS/RCS pod can transfer 1,000 pounds of propellant from the OMS to the RCS [2]. Actually, more propellant can be transferred but the astronauts on board will be alerted to the fact that more than 8.37% of the OMS fuel is not available [5].

Both the OMS and RCS use titanium fuel tanks identical to the oxidizer tanks. The OMS uses cylindrical titanium tanks 96.38 inches long with a diameter of 49.1 inches. The RCS uses spherical tanks with a 39-inch diameter [5]. The oxidizer and fuel are pressurized by helium. Each OMS/RCS pod also contains pressurized nitrogen used for purging the combustion chamber of propellant remaining after each burn. The tanks are shown in Appendix A.

NORMAL SYSTEM USE

ORBIT INSERTION

The mission requirements determine how high and how fast the shuttle will be upon MECO. Typically this occurs around an altitude of 92-miles (148 km) with an inertial velocity of approximately 25,660 feet per second (7.82 km/s) [2]. This flight profile allows the ET to enter the atmosphere and burn up upon reentry after the tank has been separated. Next, the RCS engines perform a small minus z translation. The OMS engines are then fired to place the shuttle in an orbit that will not degrade significantly during the mission. When the shuttle was first launched on April 12, 1981, MECO occurred at 81 nautical miles. This was apogee, the highest point, of an elliptical orbit with a perigee, the lowest point, of 13 nautical miles [7]. The first OMS burn, OMS-1, fired two minutes later for 1 minute 27 seconds. This changed the orbit to 132 by 57 nautical miles. To perform this orbital change, the OMS had to change the velocity by 164.7 feet per second [7]. The second burn, OMS-2 was completed over half an hour later to circularize the orbit at 132 nautical miles (244.5km) [7]. This first space flight used a series of such burns over a period of seven hours to put the shuttle in a circular orbit of 150 nautical miles (278 km).

Normally, the first OMS thrusting period, referred to as OMS-1, raises the orbiter's low elliptical orbit to the desired apogee after the external tank is jettisoned, and the second OMS thrusting period, referred to as OMS-2, typically places the spacecraft into the circular orbit designated for that mission. However, this is not always the case. One exception is in the case of a direct insertion. If the shuttle carries a light load, and launches due east, the main engines can put the shuttle at an altitude of over 115 nautical miles [7]. Then, the OMS engines can place the shuttle into a low orbit with only one burn. Table 1 lists data on some OMS burns made by the OV-102 Columbia. The table lists the change in orbit provided by the thrusting, the burn duration of the thrusting, and the total delta V provided by the thrusting. Data for table 1 can be found in The Voyages of Columbia.

Columbia Mission OMS Burns		
Orbital Change - km From Apogee/Perigee To	Burn Duration - s	Delta V - km/s
STS-1 150.0/024.1		
244.5/105.6	087.0	0.0502
244.8/244.8	077.0	0.0416
A 273.2/243.9	039.0	0.0078
276.5/273.4	040.0	0.0091
B 272.2/264.8		
C 270.4/000.0	159.5	0.0907
STS-2 Retro Burn 261.1/-3.70	175.0	0.0955

TABLE 1

NOTES FOR TABLE 1:
A: The orbit decayed slightly
B: The RCS put the shuttle in a nose-to-earth attitude to demonstrate gravity gradient. Then the RCS cicularized the orbit to 266.68 km. Subsequent RCS firings degraded the orbit to 147nm by 143 nm (272km by 265km)
C: Retrograde firing to deorbit

The operational mission altitude is figured into the launch, so that the main engines and solid rocket boosters do as much work as possible. However, the SSMEs and SRBs may not perform as expected. Contingencies for such scenarios have been created which require the OMS-1 and OMS-2 burns to compensate for the failure by selecting a delayed OMS-1 to attain the mission orbit, abort before orbit, or achieving a low orbit for a safe return. The OMS engines may have problems of their own. Under normal circumstances, failure of a single OMS engine will not prevent the orbiter from reaching the mission orbit.

ON ORBIT

The major orbital tasks include achieving the proper position, velocity and attitude necessary to accomplish the mission objectives. To do this, the guidance, navigation, and control (GN&C) computer keeps track of state vectors, targets, and initiates maneuvers to point the orbiter at a target. The GN&C software used for on-orbit operations is known as OPS 2 [5]. OPS 2 plans orbital activities with several constraints in mind, including fuel consumption, vehicle thermal limits, payload requirements and rendezvous operations considerations. For propulsive capabilities examined in this paper, only fuel consumption is considered. The thermal limits or other constraints are ignored because the orbital maneuvers considered place the shuttle in normal operating regimes.

DEORBIT

To bring the orbit back into the earth's atmosphere, the shuttle must slow down significantly. The method of doing this requires the OMS engines to burn in the opposite direction of flight. The RCS engines burn to place the shuttle in an attitude of flying tail first. Then the OMS retrograde burn is executed for 2.5 minutes. The RCS engines must then turn the space shuttle forward and slightly nose high. The deorbit burn can be accomplished with only one OMS engine, or with no OMS engines. These burns would rely on much more fuel consumption from the RCS engines, and the burns would be much longer in duration. If the RCS engines had to provide all of the delta v, they would burn three times longer than the OMS retro burn. However, the amount of fuel required to decelerate the orbiter is the same amount. In practice, slightly more fuel is expended with the alternate forms of deorbit burns as the RCS is used more to control roll. During reentry, the only remaining propellant used is in the lower portion of the aft RCS tanks. The RCS jets can be used for attitude control until the aerodynamic surfaces of the shuttle become useable coast mode until the atmosphere (dynamic pressure buildup) is reached at approximately 400,000 feet (121.92 km) [7]. This is called the entry interface.

ENTRY

Five minutes before reaching entry interface, the orbiter is at an altitude of about 557,000 feet, traveling at 25,400 feet per second, and is 5,000 miles from the landing site. This is the beginning of the entry phase of flight. At entry interface, the forward RCS jets are deactivated. The aft RCS jets maneuver the spacecraft until a dynamic pressure of 10 pounds per square foot is sensed; at which orbiter's ailerons become effective [7]. When ailerons can be used, the aft RCS roll jets are inhibited. At a dynamic pressure of 20 pounds per square foot, the orbiter's elevators become effective, and the aft RCS pitch jets are deactivated. By the time the shuttle reaches 45,000 feet, the rudder becomes effective and the aft RCS yaw jets are deactivated.

Table 2 summarizes the normal OMS and RCS use. Data for Table 2 can be found in the Space Shuttle Operator's Manual.

NOMINAL OMS/RCS USE	
Mission Time T+: time after launch L-: time before landing	Activity Maneuver: RCS BURN OMS: OMS BURN
T +0:10:35	Maneuver of -Z translation
T +0:10:39	OMS-1
T +0:12:24	OMS-1 cut-off
T +0:45:58	OMS-2
T +0:46:34	OMS-2 cut-off
L -1:15:00	Maneuver to place tail-first attitude
L -1:00:00	OMS-retro
L -0:58:00	OMS-retro cut-off
L -0:52:00	Maneuver for entry

TABLE 2

ANALYSIS

ASSUMPTIONS

With the information about the on-orbit propulsion system, many assumptions were made that affected the analysis. Since the fuel system is connected, the total N_2O_4/MMH consumption can be considered and compared against the total N_2O_4/MMH capacity. This saves concern over the amount of fuel used or remaining in individual tanks. Also, the fact that the nitrogen system purges the combustion chamber of uncombusted propellant reveals a well-known fact in propulsions. Not all of the propellants used perform as desired to produce the expected delta V. However, the effect is negligible, so all of the propellant is assumed combusted. Overall, analysis assumes the most efficient values.

The analysis concentrates on minimizing the velocity change required by the OMS/RCS. However, minimizing delta V often makes the orbital maneuver very lengthy in time. According to The Space Shuttle Operator's Manual, flights can last up to 30 days. None of the orbital maneuvers considered approached the limiting time. To understand what types of maneuvers spacecraft may make and the associated delta V requires orbital mechanics.

ORBITAL MECHANICS

Orbits can be expressed mathematically in several ways. A common way of describing orbits and spacecraft position in orbit is a group of parameters known as the classical orbital elements (COEs). Figure 1 illustrates how the different COEs relate to an orbit. The explanation of COEs that follows is simplified. Actual definitions are more precise.

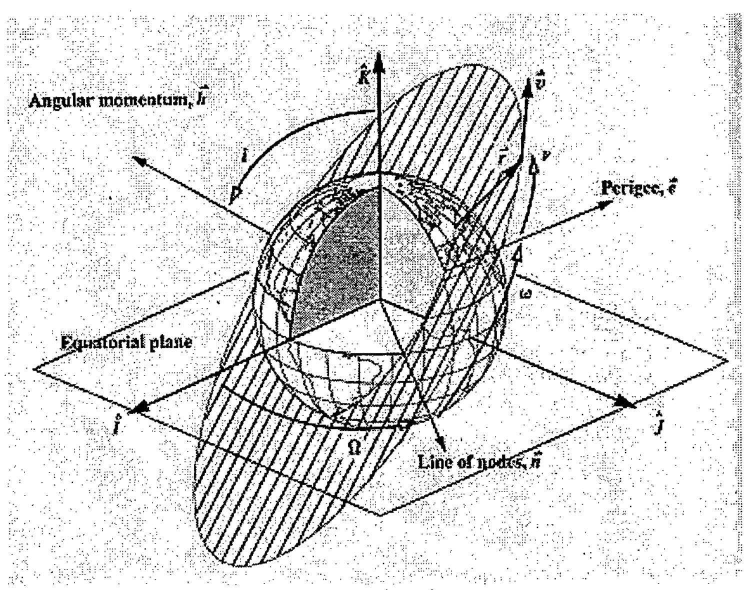

FIGURE 1

COEs

As stated earlier, orbits are in the shapes of conic sections. Eccentricity, e, is the parameter for the shape of orbits. Table 3 shows how the value of e corresponds to the shape of orbits.

Value of e	Shape of orbit
$e=0$	Circle
$0<e<1$	Ellipse
$e=1$	Parabola
$e>1$	Hyperbola

TABLE 3

The semi-major axis, a, is the parameter for half the distance between perigee, and apogee. Inclination, i, can be thought of as the angle between the equator and the path a spacecraft makes as it crosses the equator. Longitude of ascending node, Ω, can be thought of as the point where a spacecraft crosses from below the equator to above the equator. Argument of perigee, ω, is the angular distance from the ascending node to perigee. The angle between perigee and the spacecraft position is true anomaly, ν. If the shape and location of an orbit is known then true anomaly is a convenient parameter to indicate where a spacecraft is in orbit. These six parameters make up the set of COEs. Another parameter for calculations is the gravitational parameter for an attracting body, μ. For earth, μ is 398600.44 km^3/s^2.

FORMULAS

The radial position of a body in orbit, r, is the distance from the center of the earth to the object. For circular orbits, a is equivalent to r. To determine r, based on its true anomaly, use the polar equation for conic sections, $r=\frac{a(1-e^2)}{1+e\cos(\upsilon)}$ (1) [8]. To determine the velocity of an object given r, use the equation $v=\sqrt{\frac{2\mu}{r}-\frac{\mu}{a}}$ (2). When changing from one velocity to another, the delta V is given by $\Delta v=\sqrt{v_1^2+v_2^2-2v_1v_2\cos(\theta)}$ (3).

To understand the angle θ, it helps first to understand flight path angle. Flight path angle, φ_{fpa}, is the angle between the velocity and the local horizontal, or line perpendicular to the position vector. Flight path angle will be zero at apogee and perigee for elliptical orbits. Flight path angle will be zero everywhere for circular orbits. This should make sense given the flight path angle can be found using the equation $\tan(\varphi_{fpa})=\frac{e\sin(\upsilon)}{1+e\cos(\upsilon)}$ (4)[8]. This concept will be important for minimizing delta V during complex plane changes. The figure below can be found in Fundamentals of Astrodynamics and Applications. It should help clarify the geometry involved.

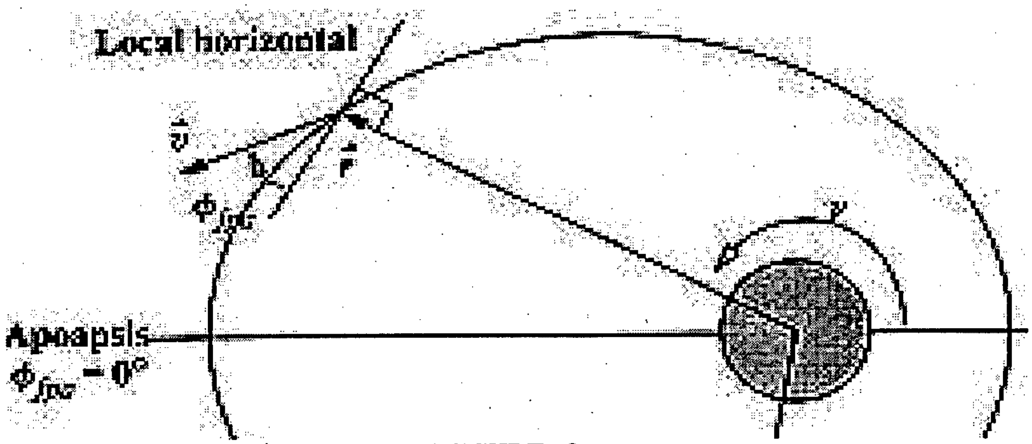

FIGURE 2

The angle θ required for Equation 3 is the angle between the velocity vectors of two orbits. If the orbits are in the same plane, the angle may only be the difference in flight path angles at the point of the delta V. If the flight path angles are zero, and the inclination is being changed, then the angle is just the difference in inclination. However, when performing complex plane changes, the spacecraft may change inclination when the flight path angle is nonzero. If this is the case, then spherical trigonometry is needed to determine the angle θ. Consider Figure 3 below. It shows that the flight path angle is in the same plane as velocity. Also, the inclinations are in the same plane with Δi as the difference in inclinations. Figure 3 shows the relation ship in a 3-axis coordinate system, and then the equivalent outside angles of a sphere. As a result of the spherical trigonometry, the angle θ, between the velocity vectors is given by the equation $\cos(\theta) = \cos(\Delta i)\cos(\varphi)$ (5.1).

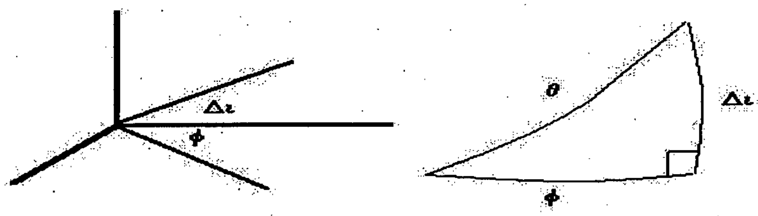

FIGURE 3

This affects complex plane changes where inclination and longitude of ascending node change while simultaneously changing orbit size. Both Ω and i might change if the shuttle changes from a normal orbit to the orbit of a space station. If this circumstance arises, θ needed for equation 3 is the angle α depicted in Figure 4. The spherical geometry for the figure results in the following relation, $\cos(\alpha) = -\cos(i_1)\cos(180\text{-}i_2) + \sin(i_1)\sin(180 - i_2)\cos(\Delta\Omega)$. This reduces to $\cos(\alpha) = \cos(i_1)\cos(i_2) + \sin(i_1)\sin(i_2)\cos(\Delta\Omega)$ (6). Thus, if φ_{fpa} is nonzero then Equation 5.1 is transformed to the equation $\cos(\theta) = \cos(\alpha)\cos(\varphi)$ (5.2). These are the formulas needed when changing multiple orbit parameters.

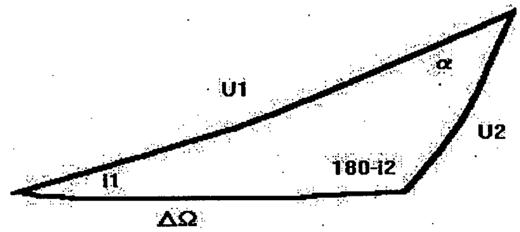

FIGURE 4

Whenever the shuttle orbiter must change orbital parameters, it mainly changes altitude. The most fuel-efficient means of changing from one orbit altitude to another is known as a Hohmann transfer. In performing a Hohmann transfer from a small orbit to a large orbit, the first burn changes the shape of the orbit making the point of the burn perigee. Upon reaching the new apogee, a second burn is performed to slow the spacecraft down to the circular velocity for that altitude. Table 4 shows the delta V required to perform a few select Hohmann transfers. The highest altitude used is 1,100 km, the maximum altitude the shuttle can reach according to <u>the Space Shuttle Operator's Manual</u>. The delta Vs were calculated using Equation 2 and Equation 3.

Simple Hohmann Transfers				
Altitude km		Delta V m/s		
Orbit 1	Orbit 2	1st Burn	1st Burn	Total
212	270	17.02	16.98	34.00
212	380	48.79	48.48	97.27
212	600	110.41	108.85	219.26
212	1,100	241.69	234.17	475.87
270	380	31.70	31.57	63.27
270	600	93.20	92.08	185.28
270	1,100	224.23	217.73	441.96
380	600	61.26	60.77	122.03

TABLE 4

One last common orbital maneuver is phasing. If two objects are in the same orbit, but one needs to rendezvous with the other, phasing is required. Call the object trying to rendezvous the interceptor; call the other object the target. In order to rendezvous, the interceptor will thrust into a slightly smaller or slightly larger orbit. This phasing orbit, depicted in Figure 5, intersects the target's orbit at the point of the thrusting. By entering the phasing orbit, the interceptor travels at a different angular frequency, n, than the target. Because of the difference in angular frequencies, the target will eventually be at the same point where the interceptor originally thrusted. The formula for angular frequency in radians per second is given by $n = \sqrt{\frac{\mu}{a^3}}$, (7). The phasing orbit is selected with a specific semi-major axis to force a rendezvous in a desired number of revolutions. The number of revolutions can be converted to time using the formula for a period $Period = 2\pi\sqrt{\frac{a^3}{\mu}}$ (8).

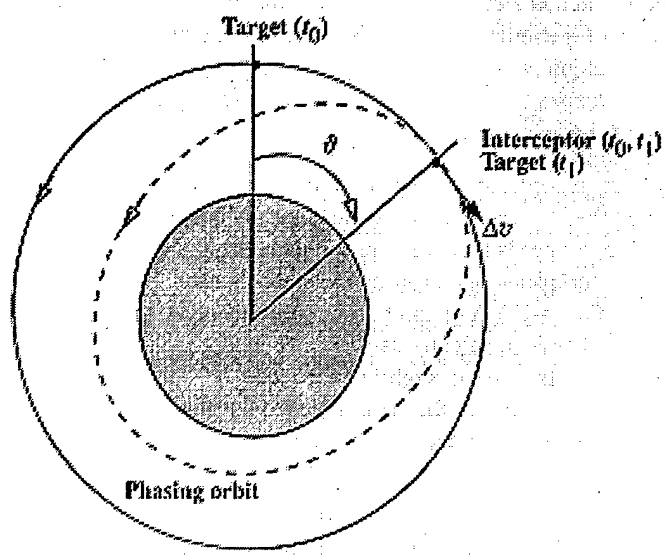

FIGURE 5

In actuality, if the orbiter ever wanted to change from its normal orbit to a space station's orbit then it would have to do a Hohmann transfer while changing inclination. Also, in order to rendezvous within a limited amount of time, the shuttle might even need to provide a phasing orbit. All of these elements are illustrated as a complex plane change in figure 6. In addition to combining all of these elements into an orbital maneuver, the longitude of ascending node would most likely need to be altered since the shuttle and space station would not be crossing the equator at the same point.

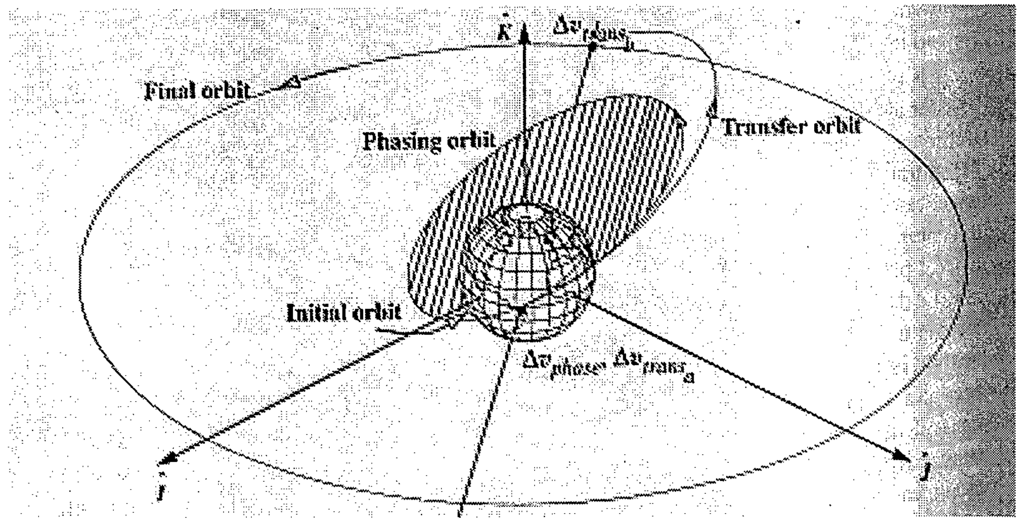

FIGURE 6

ORBITS

Analysis concentrated on a few specific scenarios. The scenarios considered typical orbits that the shuttle flies or can fly. Data was gathered using several web pages. The altitude of a nominal shuttle orbit comes from data about the first nine missions as well as STS-73 and STS-90 [7,9,10]. The nominal shuttle orbit has an inclination of 28.5° and an altitude of 270 km or slightly higher. Information about the orbits of space station Mir and the Hubble Space Telescope (HST) come from ephemeris listed on Satellite Tool Kit software by Analytical Graphics Inc. The Mir is in an orbit inclined at 51.6° with an altitude of 380 km. The Mir's orbit is very similar to the orbit planned for the International Space Station. The Mir is slightly higher. The HST is in an orbit inclined at 28.5° with an approximate altitude of 600 km. All the orbits have eccentricities close to zero; so for analysis, orbits are assumed circular.

The shuttle can launch into any of these orbits, so they serve as a good baseline for analysis. The Hohmann transfer's listed in Table 4 show how much delta V is required to reach those altitudes if the shuttle is in the same plane (i.e. same i and Ω).

SCENARIOS

As mentioned before, the purpose of this paper is to gain insight into the propulsive capabilities of the shuttle while in orbit. One way to measure the capabilities of the shuttle is to classify scenarios it can or can not perform. With this in mind, analysis examines a few scenarios. Scenario one begins with the shuttle orbiter in the same orbit as the HST but at a different location in the orbit. Scenario one examines the ability of the orbiter to perform a simple phasing orbit for rendezvous in case the HST needs to be serviced. Scenario two begins with the shuttle performing a routine mission. Then for some reason, perhaps a rescue, the shuttle needs to rendezvous with the Mir Space Station. This orbital maneuver requires a complex plane change with a $\Delta\Omega$ of 5°. Scenario three is the same as scenario two except the $\Delta\Omega$ is 45°. For differences in Ω greater than 90°. The delta V can be enormous because the spacecraft is required to reverse the direction of flight.

Scenario one, as it turns out, is almost trivial for a few reasons. Generally, the shuttle can launch directly into a low earth orbit. From the lower orbit, the shuttle can wait until geometry is sufficient for performing a simple Hohmann transfer to rendezvous. This would save the extra fuel needed for a phasing orbit. However, a situation may arise that puts shuttle in the HST but phased apart by some angle. The worst case scenario is if the shuttle is phased 180° away. Still, this is almost trivial because the delta V can be diminished as the time spent in the phasing orbit increases. In order to reduce the delta V to below 50m/s when phased 180°, the shuttle could enter a phasing orbit for just over three days.

Scenarios two and three provide for much more interesting analysis, in part because there are an infinite number of possibilities for performing the complex plane changes. For instance, all of the inclination and longitude of ascending node may be changed at the first burn. Another way to perform the plane change is to change half of the inclination at the first burn, and the rest of the inclination as well as all of the longitude of ascending node at the second burn. Using Microsoft Excel, I performed the analysis to minimize the delta V required for complex plane changes. No matter how much Ω is changed at the first burn, some of the inclination is changed at the first burn. APPENDIX B contains charts that shows the delta V required for cases where all, half, or none of Ω is changed at the first burn.

The first chart in APPENDIX B shows that for scenario 2, if all of Ω is changed at the first burn, then 75.3% of the inclination should also be changed at the first burn. As more of Ω is changed at the second burn, more of the inclination is changed at the second burn. For scenario 3, the charts show that changing all or half of Ω at the first burn requires significantly more delta V than changing all of Ω at the second burn. This seems reasonable considering the velocity of spacecraft at a high orbit is slower than at a low orbit, and delta V required for identical maneuvers is smaller for smaller velocities. However, the charts for scenario 2 and 3 are almost identical when all Ω is changed at the second burn. The minimum delta V required for a $\Delta\Omega$ of 45 ° is only 0.77 m/s more than for a $\Delta\Omega$ of 5°. This seems counterintuitive. By examining the spherical geometry, it seems that α from Figure 4 is always close to the change in inclination over the range of $\Delta\Omega$ used. With this analysis of orbital mechanics complete, I began to determine if the shuttle could make such maneuvers. To understand such capabilities of the shuttle requires knowledge about its mass.

MASS

To gain insight into typical operational masses, Table 5 was compiled using data from The Voyages of Columbia.

First Six Launches FOR OV-102 (Columbia)				
Flight	Launch Weight Pounds	Cargo Weight Pounds	Landing Weight Pounds	Nominal Altitude Miles
STS-1	4,461,620	9,300	196,500	166
STS-2	4,475,943	19,388	204,000	157
STS-3	4,478,954	21,293	207,500	147
STS-4	4,482,888	Not Available DOD 82-1	209,500	184-197
STS-5	4,488,599	33,013	204,103	184
STS-9	4,503,095	*33,584 Spacelab	*221,000 landed w/cargo	155.3

TABLE 5

Each orbiter has a slightly different empty mass because of the way they were built [4]. For instance the mass of the OV-102 Columbia is about 3,000 kg heavier than the OV-103 Discovery and OV-102 Atlantis [11]. Data on the system mass was compiled using information from the website www.ksc.nasa.gov/resources/orbiters/shuttle-stats.txt to form Table 6 [12]. The payload mass of 29,500 kg shown in Table 6 is the maximum payload the orbiter can carry. With that payload, the orbiter can provide a delta V of 304 m/s [5]. The HST is a significantly smaller payload, weighing about 11,000 kg [13].

SYSTEM MASSES	
ITEM	MASS KILOGRAMS
LAUNCH	
SRB (each)	
Mass empty	82,879
Propellant	505,627
Subtotal	586,506
For Both	1,173,012
ET	
Mass empty	37,452
LOX	609,195
LH2	101,606
Subtotal	748,253
SYST. Total	1,921,265
ORBITER	
Mass empty	68,040
Launch payload	29,484
Launch return	14,515

TABLE 6

PROPULSIONS

With knowledge about the system masses, and some knowledge of propulsion, the shuttle orbiter's delta V can be computed. As mentioned earlier, acceleration from rocket propulsions is fundamentally tied to Newton's third law of motion. The formula for the force produced by a rocket engine is derived from the change in momentum of the rocket. Variables used in subsequent equations are explained in Appendix C. For more information about propulsions, see Space Propulsions Analysis and Design by Ronald Humble.

The equation for force produced by a rocket engine is given by $F = \lambda[\dot{m}v_e + (P_e - P_a)A_e]$ (9) [14]. The equation for force can be manipulated as follows, $F = \dot{m}c = \dot{m}Ispg_o$ (10) [15]. To determine the velocity changed as a result of expending mass, use the ideal rocket equation, $\Delta v = Ispg_o \ln\left(\frac{m_f}{m_i}\right)$ (11) [14].

The ideal rocket equation can be manipulated into the form $m_f = m_i e^{\left(\frac{\Delta v}{Ispg_o}\right)}$ (12) to give the mass of the rocket after thrusting, given delta V and the mass of the rocket before firing [14].

VALIDATION

Since I found detailed information about the first shuttle flight, I tried to analyze the data and check for consistency. Some of the data has already been presented in tables such as Table 1 and Table 3. Some information found was inconsistent such as the OMS Isp. The Shuttle reference home page listed the Isp of the OMS engines as 313 seconds, while Aerojet, the designers of the engine, claim the Isp is 334 seconds [15]. For the sake of limiting the shuttle's capabilities, analysis uses an Isp of 334 seconds. If the shuttle can not perform a maneuver with an Isp of 334 seconds, it can not perform the same maneuver with an Isp of 313 seconds.

The OMS engines produce 6,000 pounds of force when thrusting by expelling 19.160 lb/s [5]. Using Equation 2 with the force of the engines and the Isp stated by Aerojet results in a mass flow rate of 19.122 lb/s. This is reasonably close, so I felt more confident using 334 seconds for the value of Isp. Also, the shuttle can provide a delta

V of 305 m/s with a payload of 29,000 kg [14]. This was reasonable for the shuttle orbiter to achieve with the higher ISP. Using the lower ISP, the shuttle would probably have to draw upon the RCS to achieve the delta V.

Next I summed the burn duration for the first shuttle mission. From the data provided in Table 1, the OMS engines fired for 402.5 seconds. Multiplying the burn duration by the mass flow rate gives 7,000 kg of propellant burned with both OMS engines during the mission. Making some gross assumptions about the system mass at each burn, I calculated the shuttle used 6,200 kg of propellant on its maiden voyage. That's a 12% error that can be explained by the mass assumptions shown in Table 7.

STS-1 SYSTEM MASS AND PROPELLANT DEPLETION DUE TO OMS BURNS				
SYSTEM MASS kilograms	ACTION	PROPELLANT kilograms	Delta V m/s	PROPELLANT USED Kilograms
106744.09	OMS-1	10861.3	50.2	1622.966
105121.12	OMS-2	9238.33	41.6	1326.215
103794.91	OMS-3	7912.12	7.8	246.796
102485.43	OMS-4	6602.64	9.1	287.187
102241.74	release cargo	6358.95	---	0.0
98014.47	RETRO	6358.95	90.7	2675.992
95388.48	-----	3682.96	---	

TABLE 7

As mentioned before, 1,100 km is the maximum altitude the shuttle can reach as stated by the Space Shuttle Operator's Manual [5]. As shown in Table 4, the delta V required by the shuttle to reach a circular orbit at an altitude of 1,100 km from an altitude of 212 km is 476 m/s. 212 km (115 nautical miles) is the maximum altitude the shuttle can reach without using the OMS or RCS. Using the weight of STS-1 after external tank separation, the shuttle could not provide enough delta V. I tried to use more optimistic numbers. I estimated the OMS could have no more than 11,802 kg of propellant given the volume of the OMS propellant tanks (2.546 cubic meters), the density of N_2O_4 (1440 kg per cubic meter), and the density of MMH (878kg per cubic meter) [14]. Using this value for total OMS propellant, which is actually higher than the shuttle can have, the shuttle still can not produce enough delta V to reach a circular orbit with a 1,100 km-altitude. In fact, the shuttle can not provide 476 m/s delta V unless it weighs 87,000 kg at ET separation. This value is ridiculously low since one of the lightest missions ever weighed over 100,000 kg at ET separation. The shuttle can enter an elliptical orbit with an apogee of 1,100 km, but it would not have enough propellant to change its orbit back to a circular orbit with an altitude of 212 km. I am confident the value stated in The Space Shuttle Operator's Manual by Ballantine Books is a mistake.

Since I knew the HST has been delivered by the orbiter to a circular orbit of 600 km, I attempted to verify the shuttle could accomplish this feat. I recreated the conditions of STS-31 using the optimistic propellant mass of

11,802 kg and the mass value for the OV-103 Discovery which launched the HST [16]. STS-31 weighed 113,231 kg at ET separation [16]. From Table 4, OMS-1 and OMS-2 should be 110.4 m/s and 108.8 m/s respectively. This uses a total 7328.8 kg of the OMS propellant. After releasing the 11,000 kg payload, the OMS can provide 158 m/s delta V to the shuttle. This will change the orbit so that apogee is at 600 km and perigee is at 50 km. In actuality, the shuttle probably had to use the RCS engines to circularize in a low earth orbit before deorbit, but the numbers I used confirm the shuttle's ability to deliver the HST.

CONSEQUENCES

The values of delta V described above were much lower than the 3 km/s needed for scenario 2 or 3. Therefore, the shuttle could not accomplish the maneuvers prescribed for scenarios 2 or 3. As it turns out, the shuttle can not perform much of a plane change at all. Appendix D is a chart that shows the delta V required to change θ of equation 4. Clearly the shuttle can not change its inclination or longitude of ascending node by very much: not even 3 degrees. If the shuttle has enough propellant to spare 50 m/s then it could change inclination by 0.3°.

CONCLUSIONS

The shuttle is limited in its orbital maneuvers. Thus, mission planning is critical because the shuttle can not react to situations as described by scenarios 2 and 3 while it is in orbit. The orbiters' ability to change major orbital elements other than altitude is almost nonexistent.

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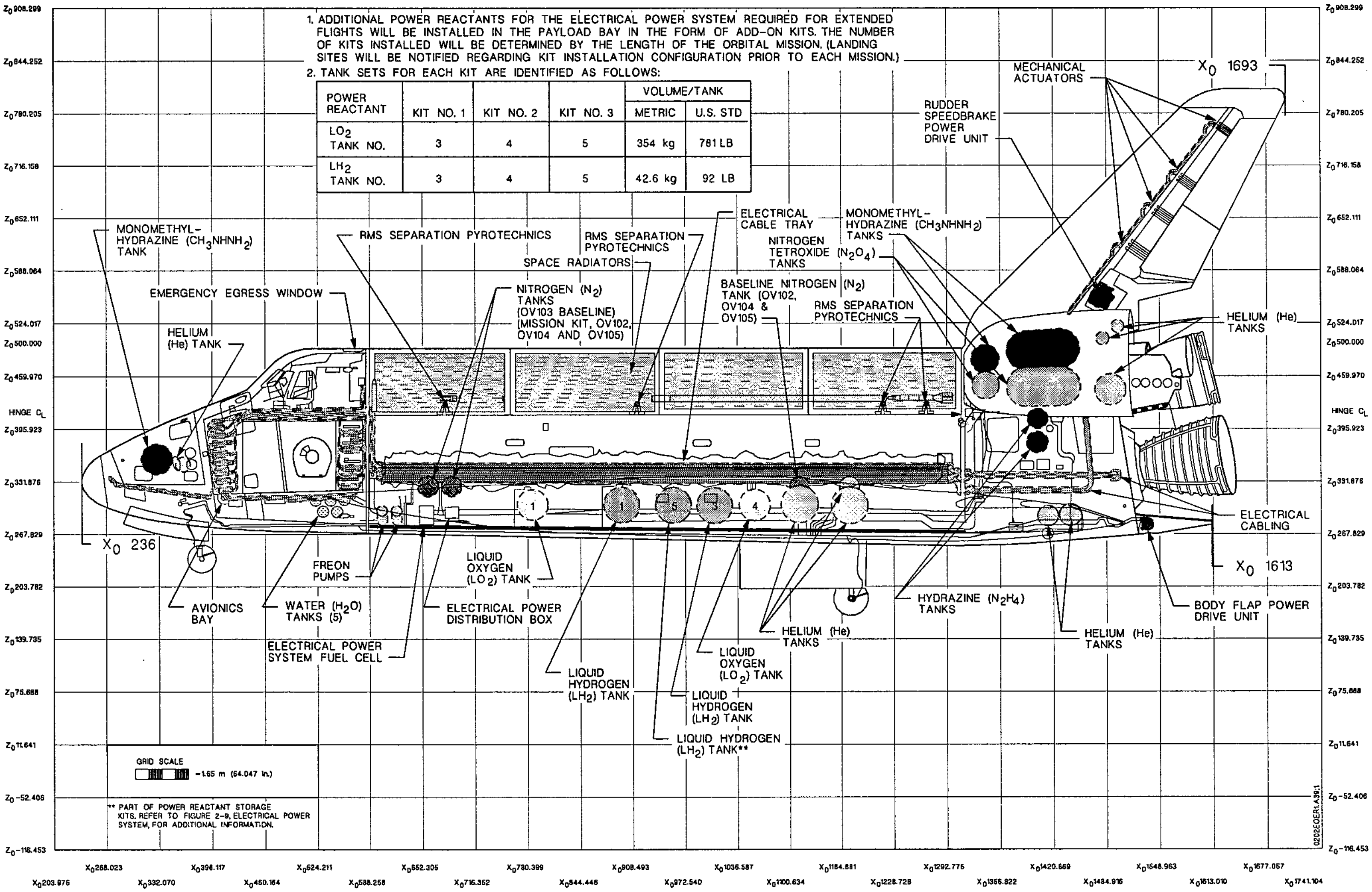
APPENDIX A: SCHEMATICS

1. SCHEMATIC OF SHUTTLE SYSTEMS
2. SCHEMATIC OF OMS/RCS POD (COLOR)
3. SCHEMATIC OF OMS
4. SCHEMATIC OF AFT RCS
5. SCHEMATIC OF FORWARD RCS (COLOR)
6. SCHEMATIC OF FORWARD RCS

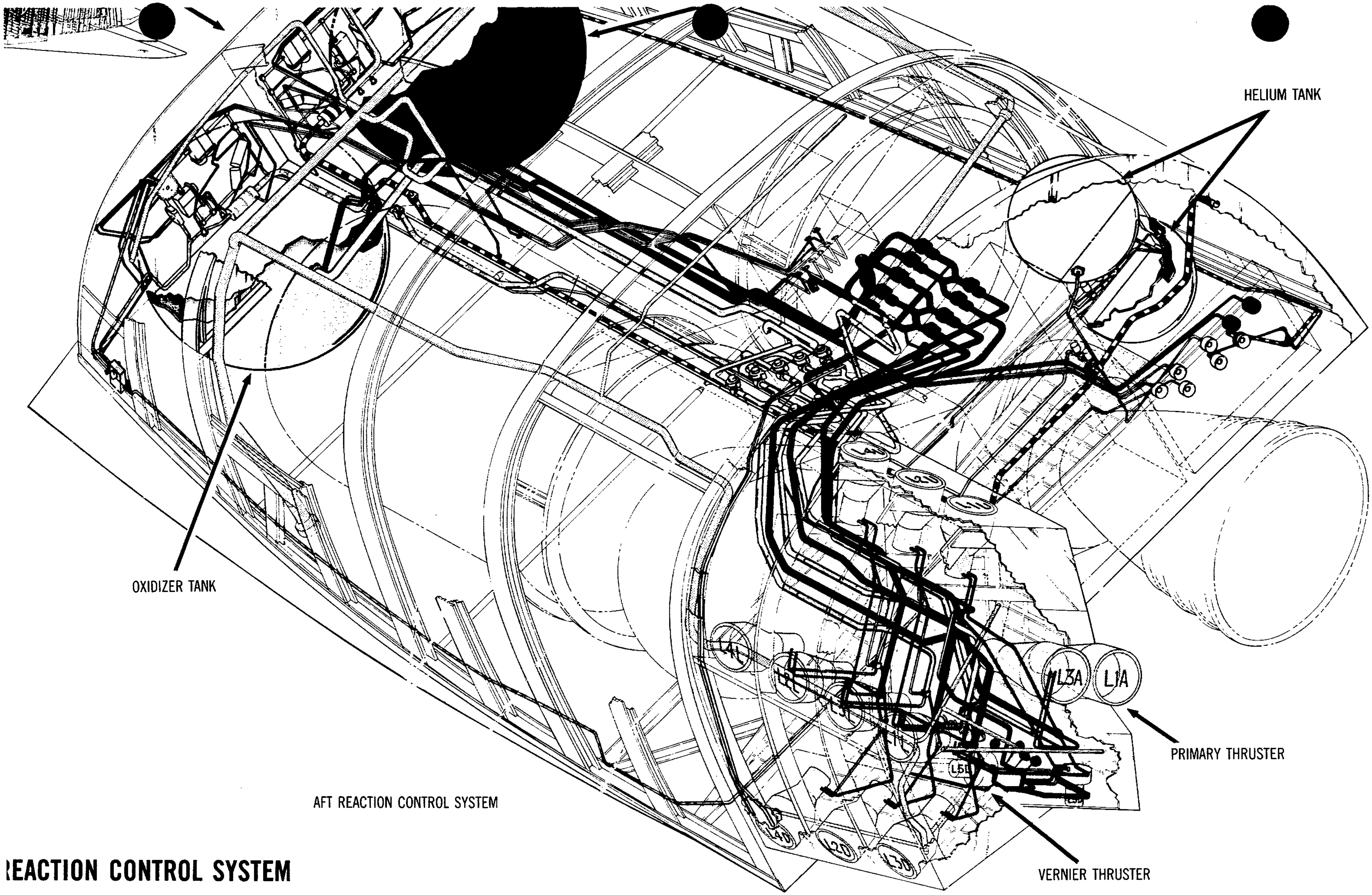


1. ADDITIONAL POWER REACTANTS FOR THE ELECTRICAL POWER SYSTEM REQUIRED FOR EXTENDED FLIGHTS WILL BE INSTALLED IN THE PAYLOAD BAY IN THE FORM OF ADD-ON KITS. THE NUMBER OF KITS INSTALLED WILL BE DETERMINED BY THE LENGTH OF THE ORBITAL MISSION. (LANDING SITES WILL BE NOTIFIED REGARDING KIT INSTALLATION CONFIGURATION PRIOR TO EACH MISSION.)
2. TANK SETS FOR EACH KIT ARE IDENTIFIED AS FOLLOWS:

POWER REACTANT	KIT NO. 1	KIT NO. 2	KIT NO. 3	VOLUME/TANK	
				METRIC	U.S. STD
LO_2 TANK NO.	3	4	5	354 kg	781 LB
LH_2 TANK NO.	3	4	5	42.6 kg	92 LB

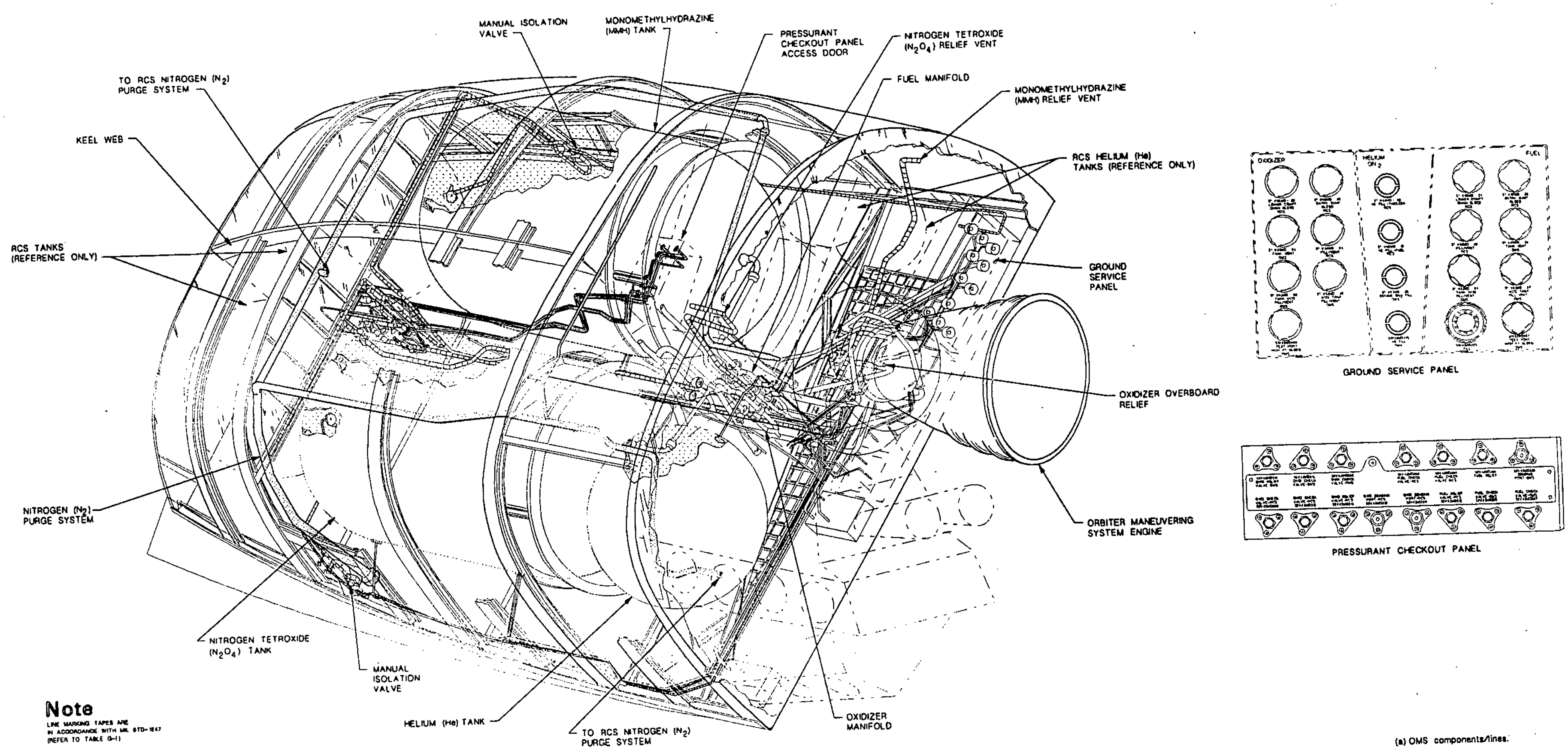
(e) Component/system location.

Figure 2-2.- Concluded.



AFT REACTION CONTROL SYSTEM

ƖEACTION CONTROL SYSTEM

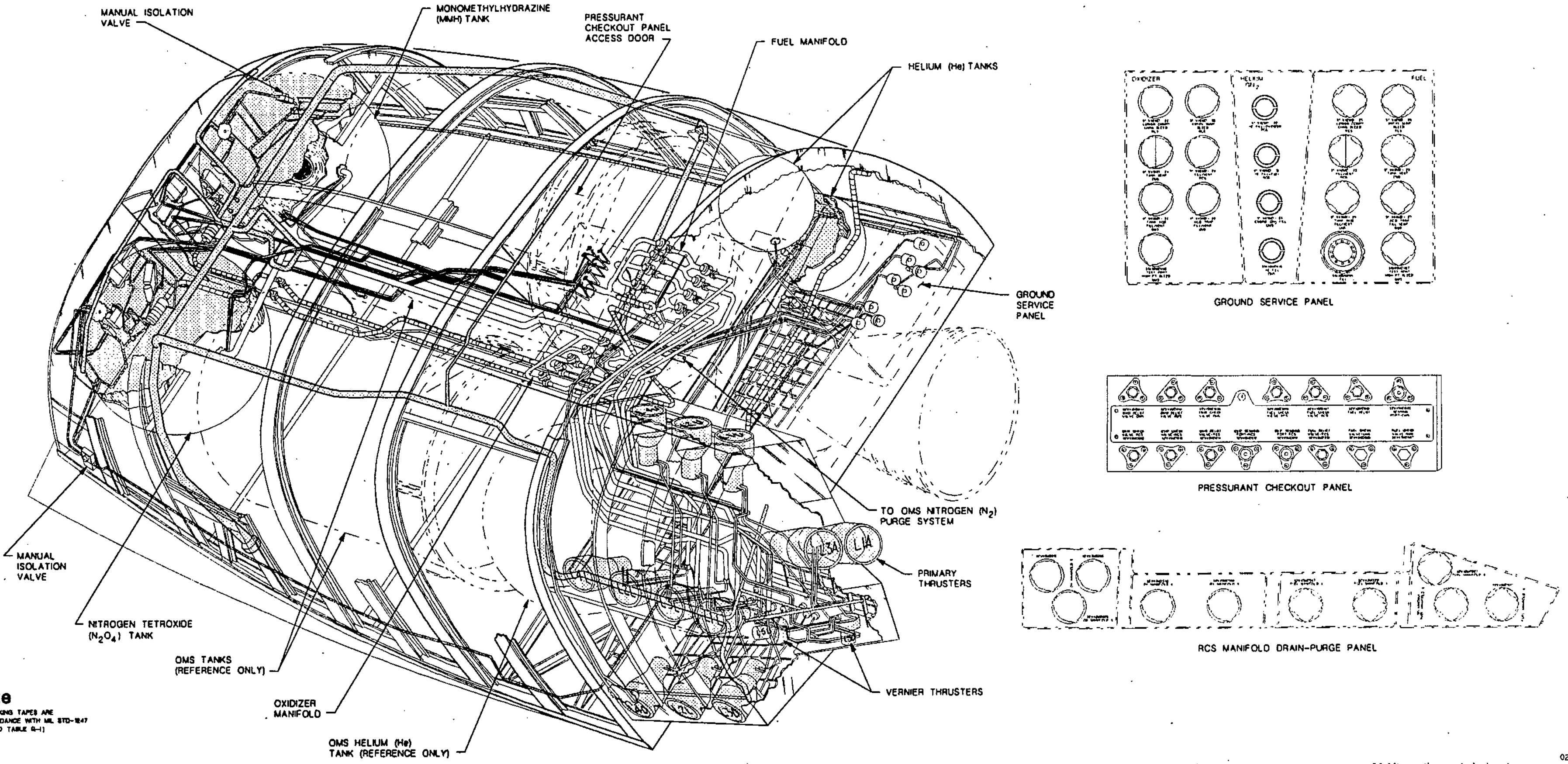


Note
LINE MARKING TAPES ARE IN ACCORDANCE WITH MIL STD-1247 (REFER TO TABLE G-I)

0213AOERLA20.1

(a) OMS components/lines.

Figure 2-14.- Orbital maneuvering system component/line locator.

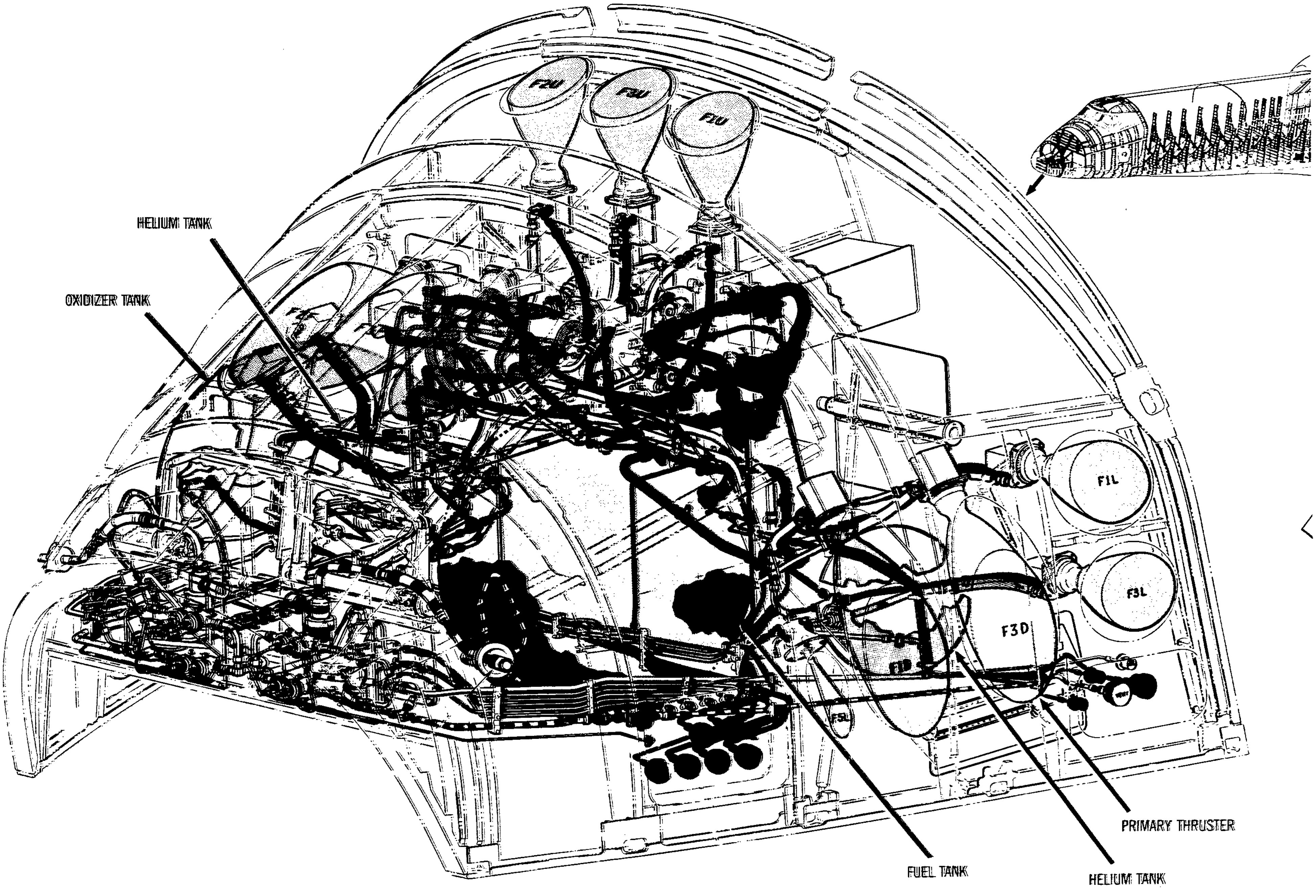


Note
LINE MARKING TAPES ARE IN ACCORDANCE WITH MIL STD-1247 (REFER TO TABLE 9-1)

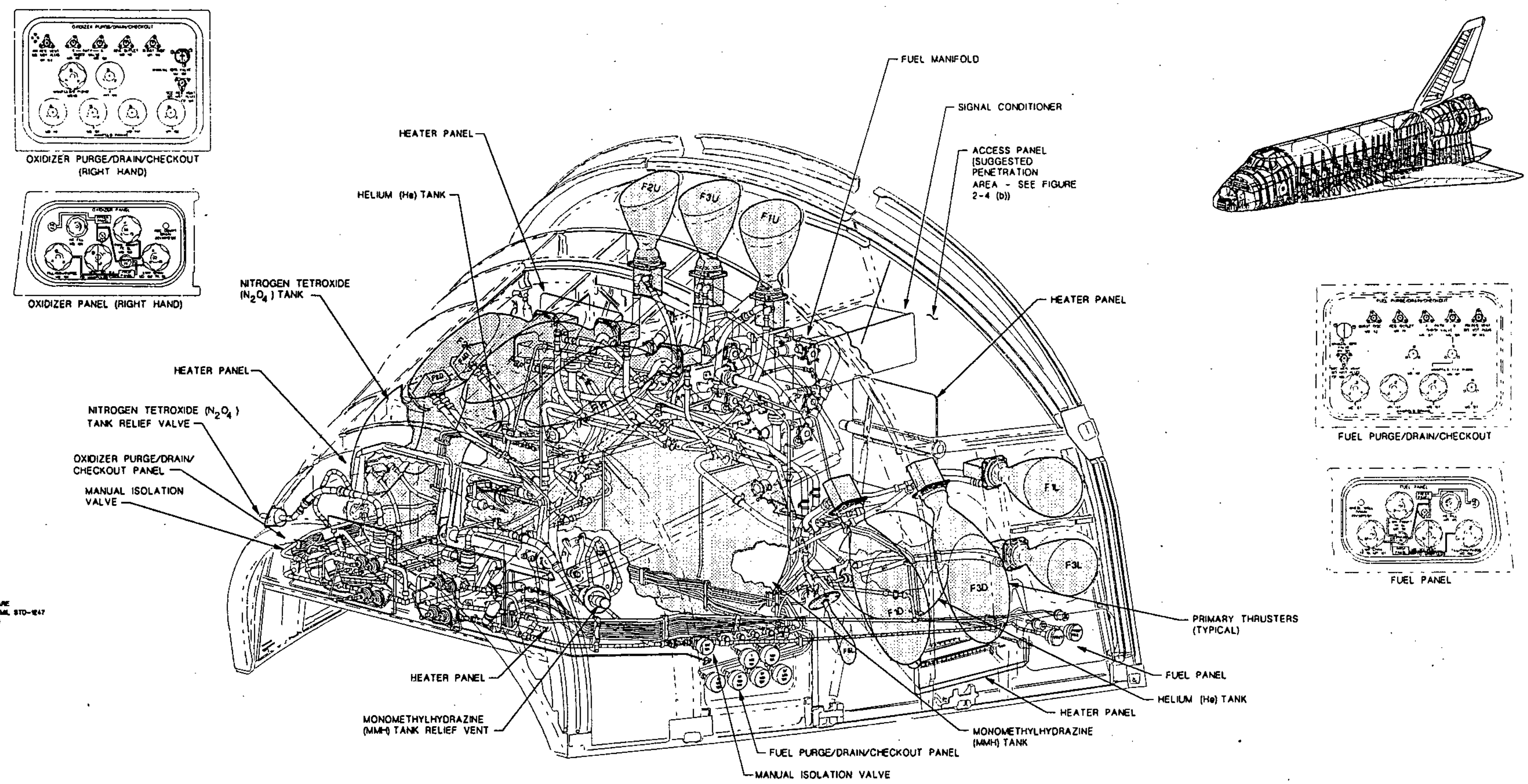
0213BOER1.A20.1

(b) Aft reaction control subsystem.

Figure 2-13.- Concluded.



HELIUM TANK
OXIDIZER TANK
F2U
F3U
F1U
F1L
F3L
F3D
PRIMARY THRUSTER
FUEL TANK
HELIUM TANK



Note
LINE MARKING TAPES ARE IN ACCORDANCE WITH MIL STD-1247 (REFER TO TABLE G-I)

(a) Forward reaction control subsystem

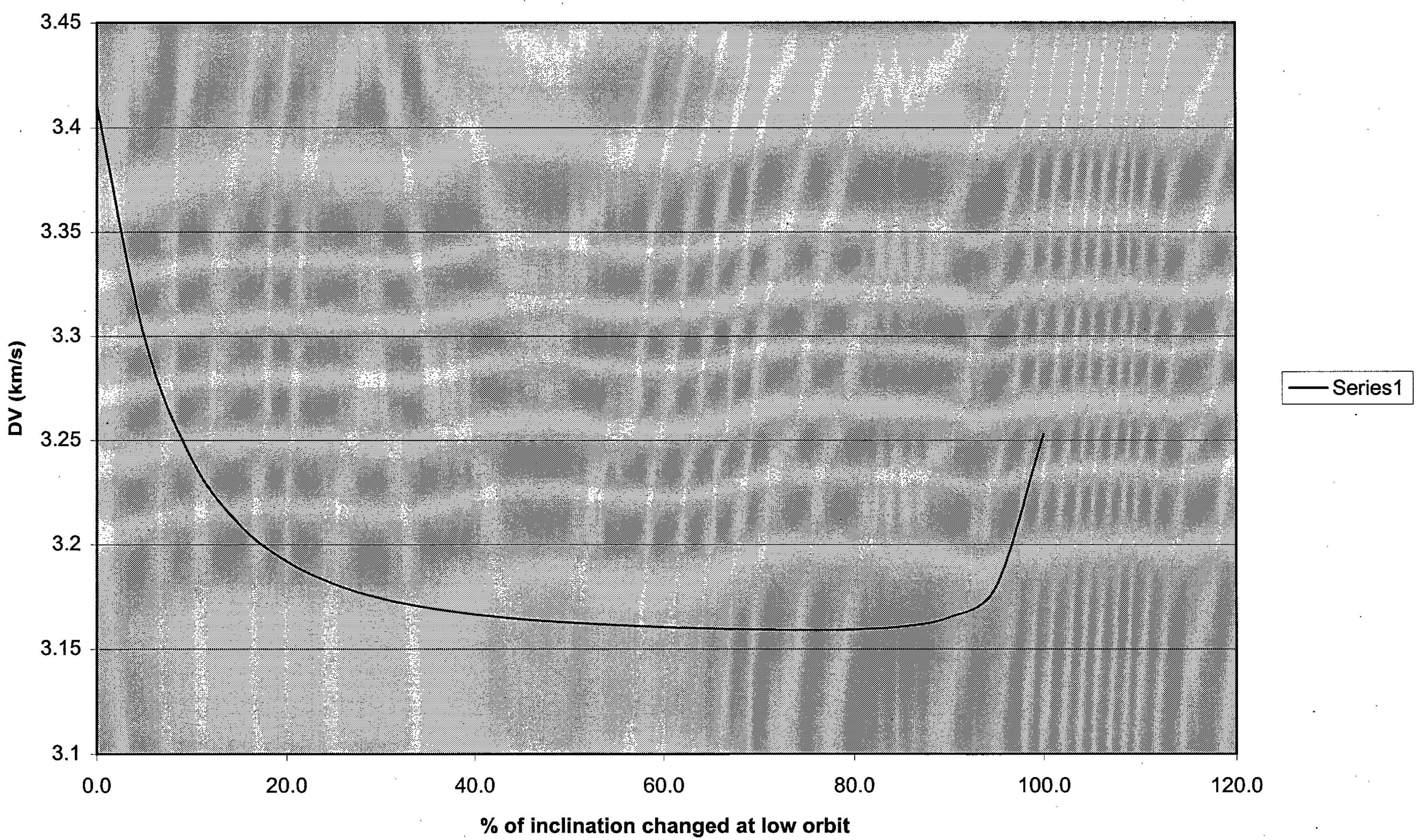
Figure 2-13.- Reaction control subsystem component/line locator

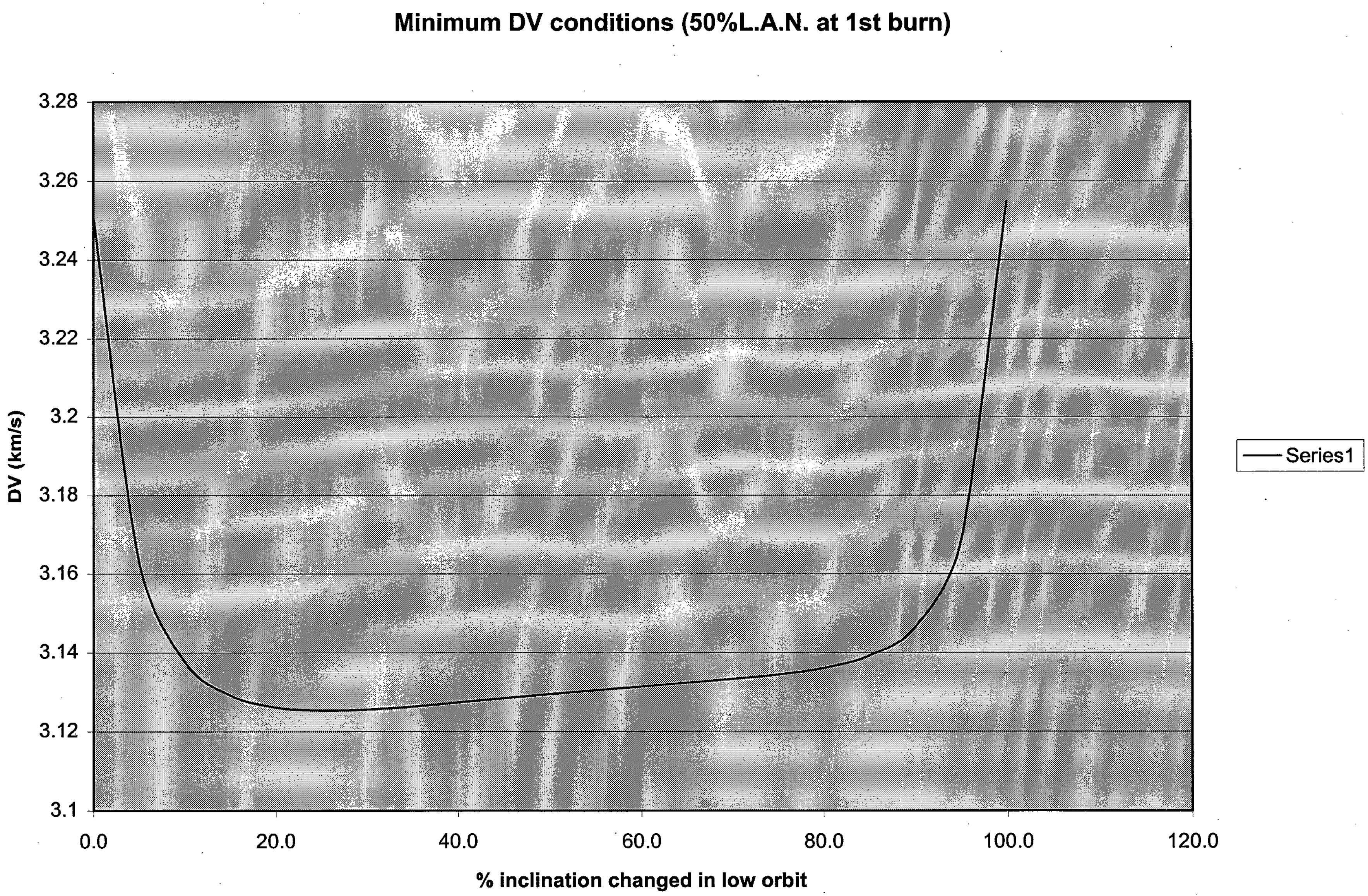
APPENDIX B: COMPLEX PLANE CHANGE REQUIRED DELTA V

1. SCENARIO 2
2. SCENARIO 3

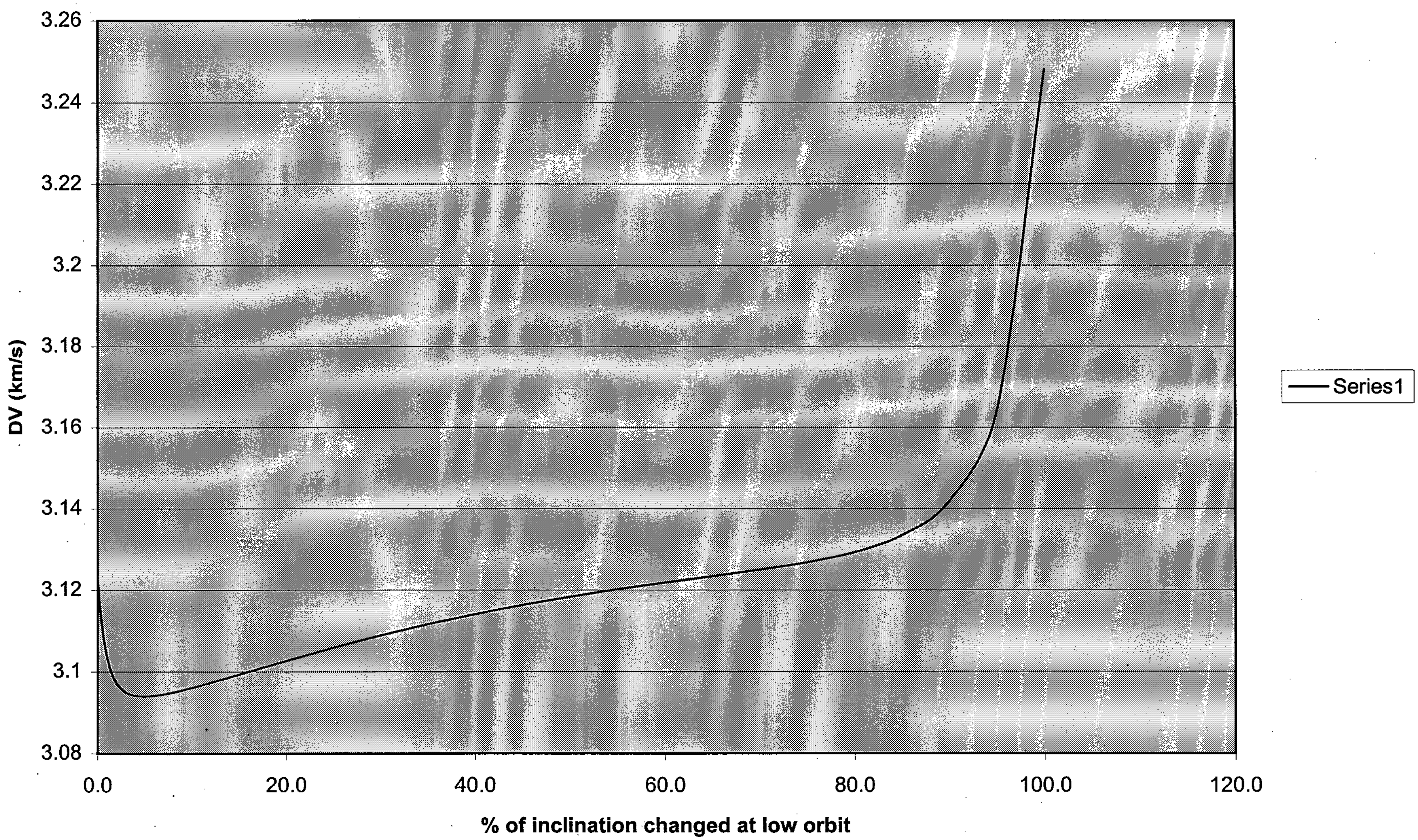
1. SCENARIO 1

Minimum DV conditions(all L.A.N changed at 1st Burn)



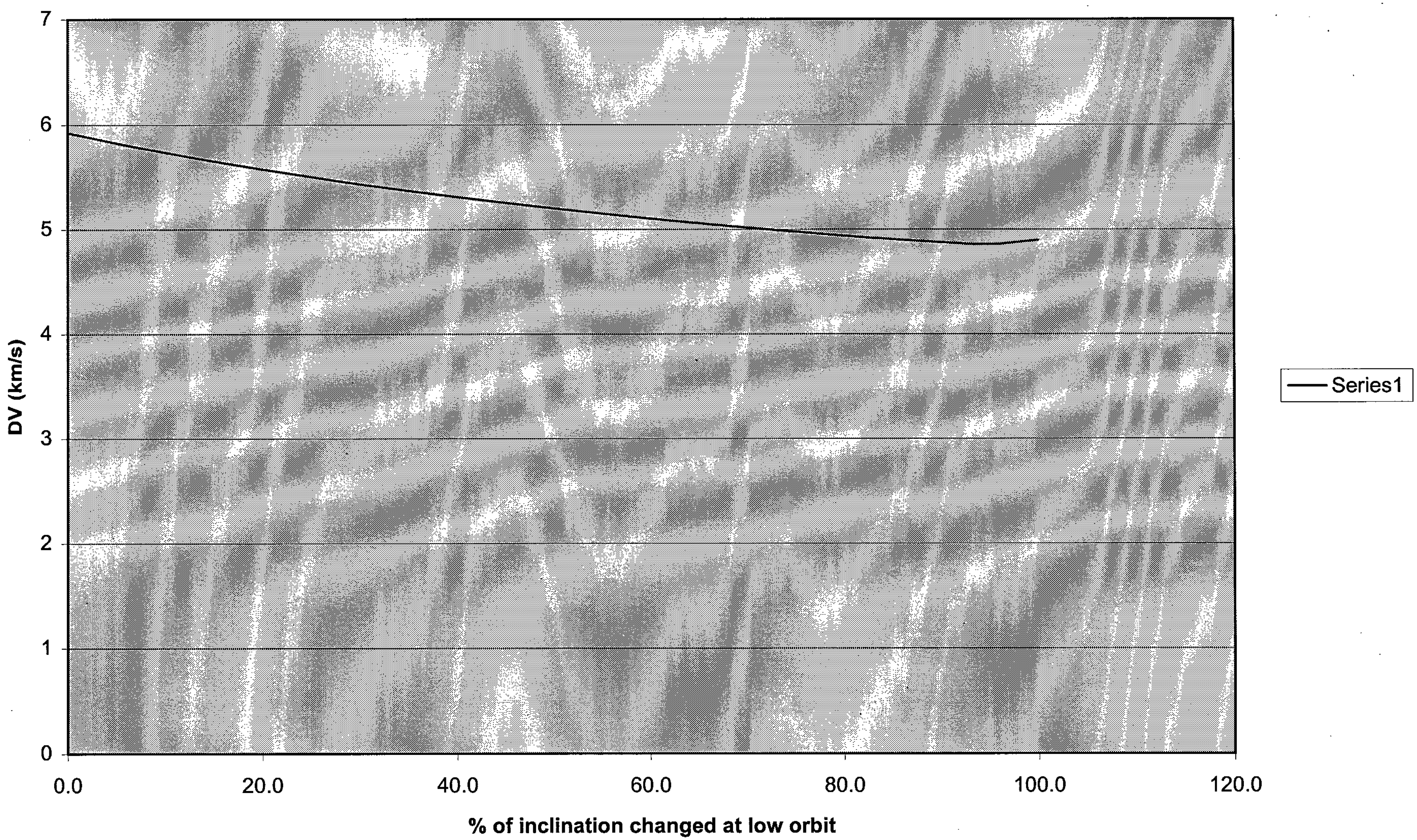

Minimum DV conditions (50%L.A.N. at 1st burn)
DV (km/s)
3.28
3.26
3.24
3.22
3.2
3.18
3.16
3.14
3.12
3.1
0.0
20.0
40.0
60.0
80.0
100.0
120.0
% inclination changed in low orbit
Series1

Minimum DV conditions (all L.A.N changed at 2nd burn)

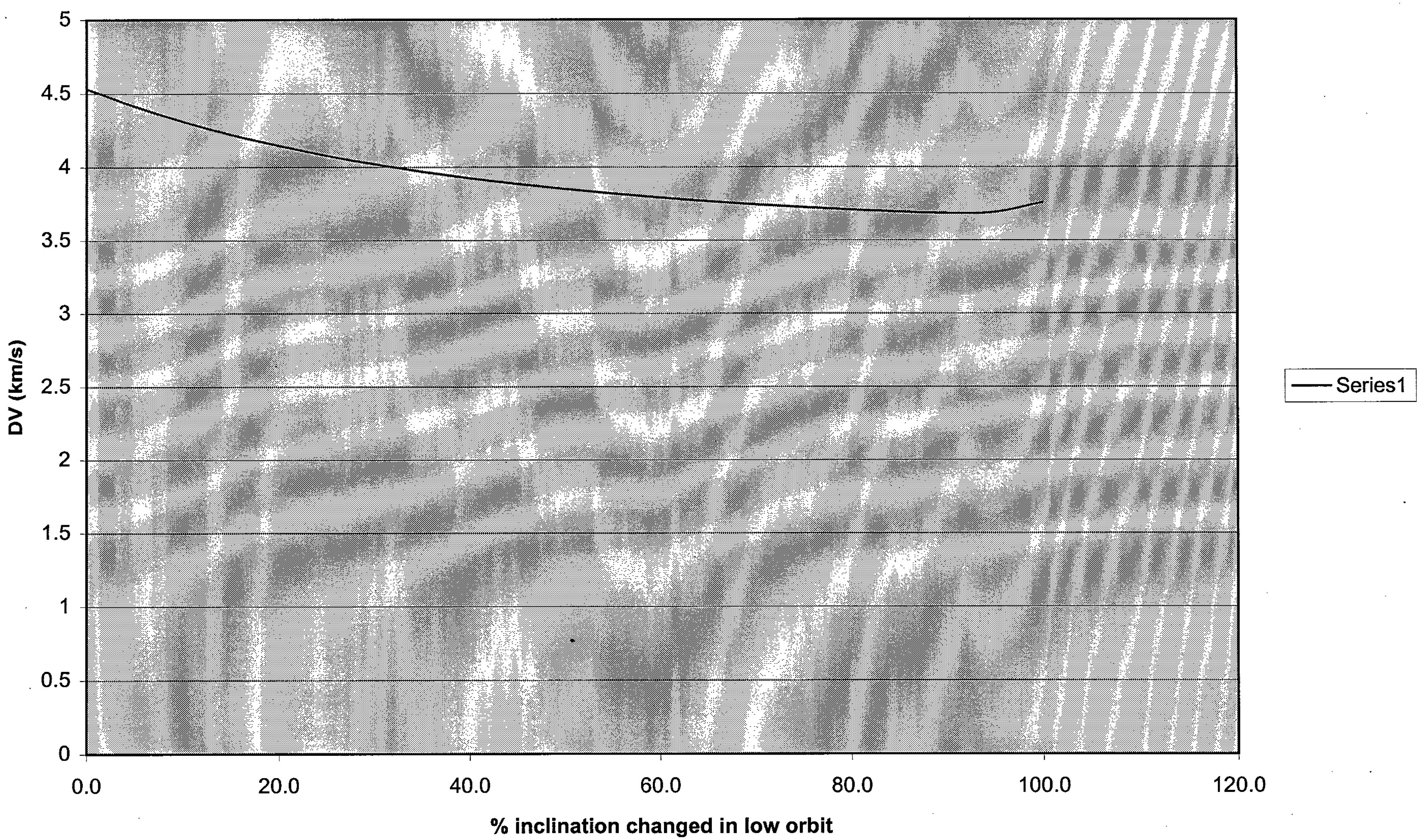


2. SCENARIO 2

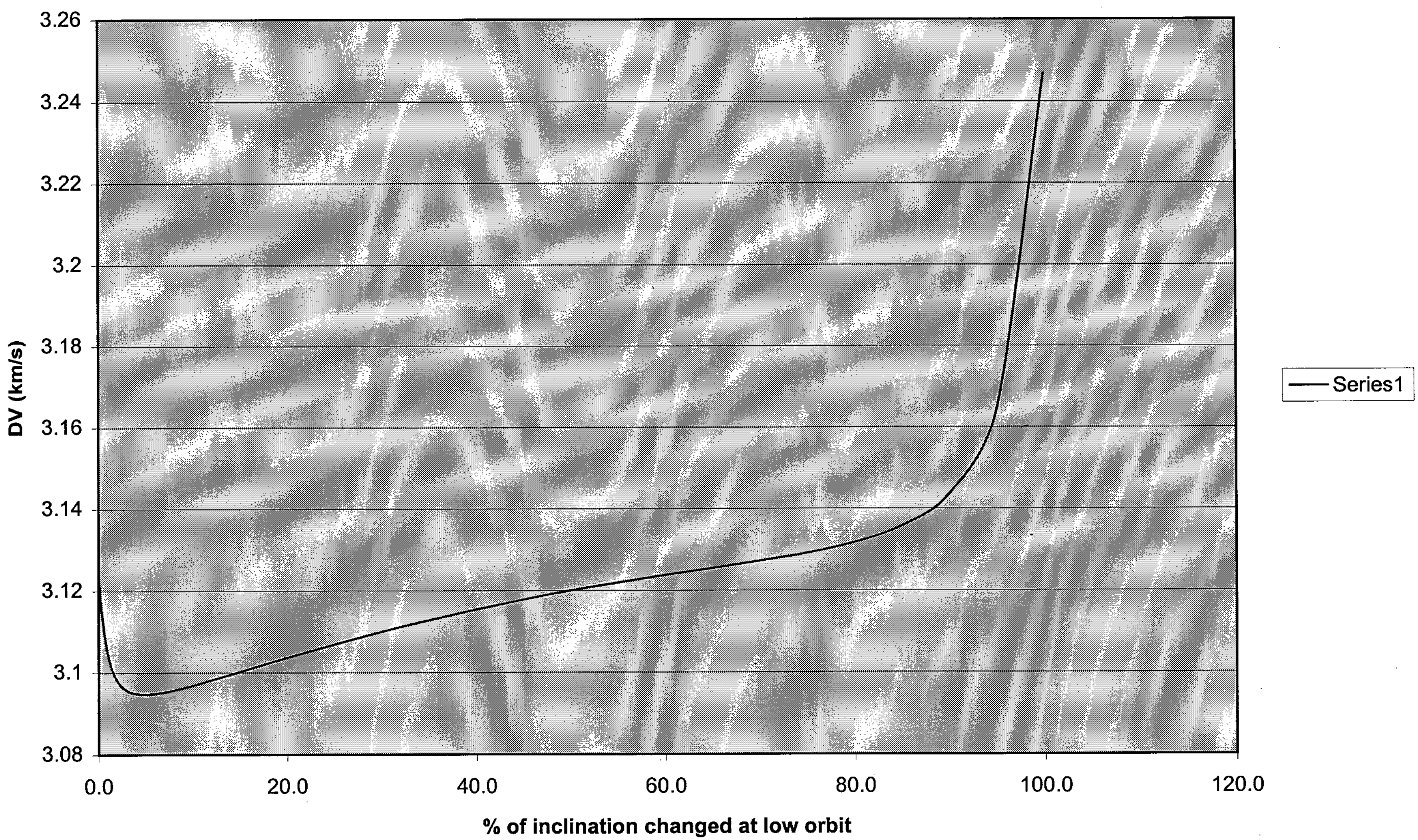
Minimum DV conditions(all L.A.N changed at 1st Burn)



Minimum DV conditions (50%L.A.N. at 1st burn)



Minimum DV conditions (all L.A.N changed at 2nd burn)



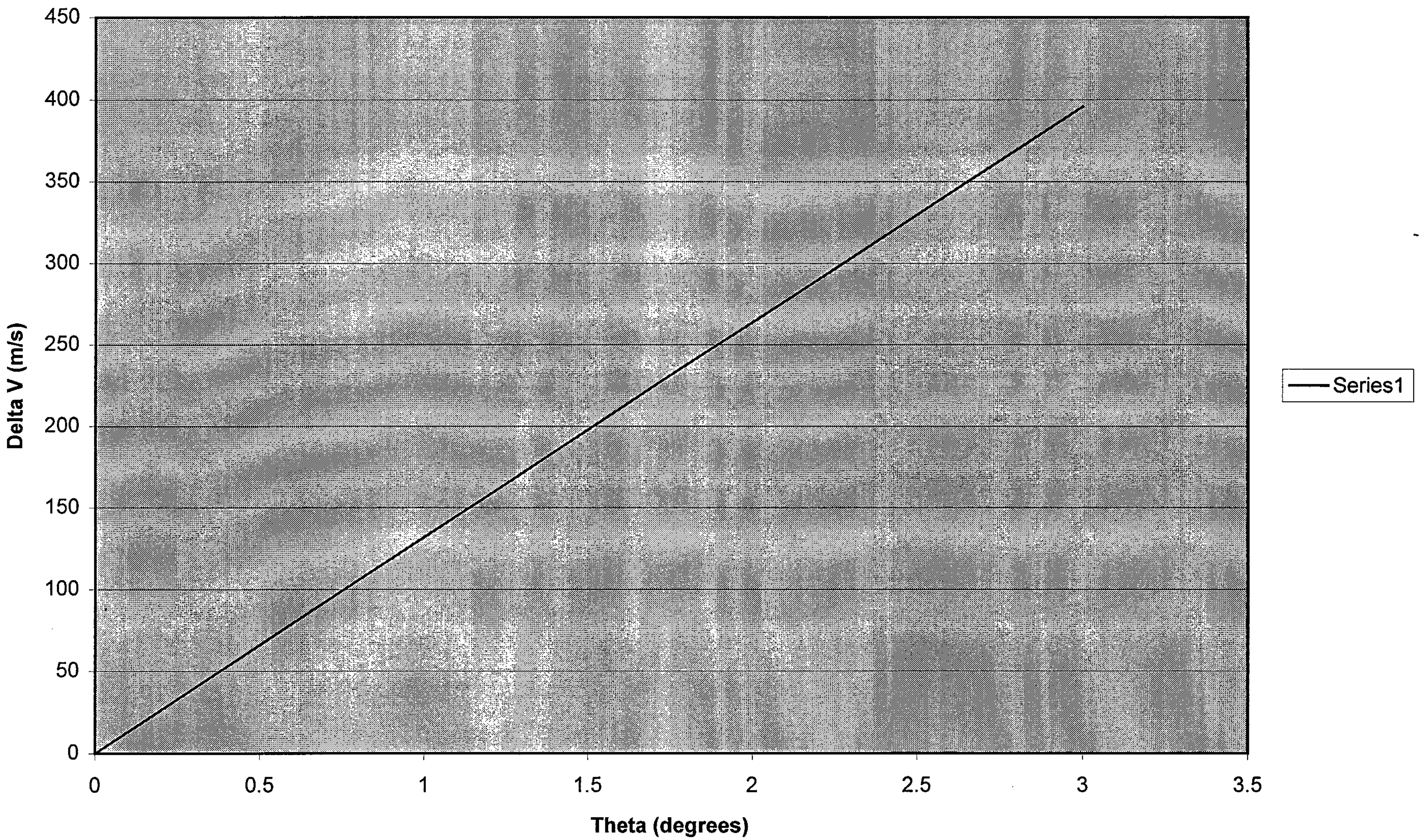
APPENDIX C: PROPULSION VARIABLES

Isp Specific Impulse (a measure of efficiency)

F	Thrust
m_{dot}	Mass flow rate
λ	Nozzle efficiency
v_e	Exhaust velocity
p_e	Exit pressure
p_a	Ambient pressure
A_e	Exit area
g_o	sea level gravity
Δv	change in velocity
m_i	Initial mass
m_f	Final mass

APPENDIX D: THETA VS DELTA V AT HUBBLE ALTITUDE

Delta V vs Theta



ABSTRACT

NASA's space shuttle orbiter is the premier manned spacecraft. The space shuttle orbiter allows astronauts to perform many tasks such as docking with space stations, deploying satellites, rendezvousing with and repairing the Hubble Space Telescope, etc. The shuttle orbiter would never be able to perform such tasks without its rocket propulsion system. Whenever the orbiter makes changes to its orbit, or performs orbital maneuvers, it uses propellant from its on board orbital propulsion system. The ability to perform such orbital maneuvers depends on the orbital mechanics, spacecraft dynamics, and rocket propulsions. The purpose of this paper is to gain insight into the propulsive capabilities of the space shuttle orbiter. The analysis will reveal the limits of the space shuttle's ability to perform multiple orbital maneuvers on any given mission.

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