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FINAL GALILEO Propulsion SYSTEM IN-FLIGHT CHARACTERIZATION

EXTENDED ABSTRACT

The Galileo Retropropulsion Module (RPM) has performed excellently during nearly seven years of Galileo mission operations. The RPM was provided by the Federal Republic of Germany to NASA to provide directed impulse to the Galileo spacecraft during all phases of the Galileo mission following Inertial Upper Stage (IUS) jettison. Galileo is an ambitious, international interplanetary mission to the planet Jupiter consisting of a Jovian atmosphere entry probe and a Jupiter orbiter. A VEEGA (Venus-Earth-Earth Gravity Assist) interplanetary trajectory was utilized to obtain sufficient orbital energy to reach Jupiter. A first, in planetary exploration, the Galileo spacecraft utilizes a dual-spin design, for optimal science return. The release of the probe in July, 1995 occurred as planned and the orbiter became the first artificial satellite of an outer planet on December 7, 1995. This paper documents the in-flight performance of the Galileo propulsion system since July, 1993, the cut off date for the last conference paper (AIAA 93-2117, "Initial Galileo Propulsion System In-Flight Characterization," T. J. Barber, F. A. Krug, and B. M. Froidevaux).

The Galileo RPM is a pressure-regulated liquid bipropellant system, utilizing earth-storable, hypergolic propellants. It is mounted on the spinning portion of the orbiter; hence, no propellant management devices are needed. The fuel is monomethyl hydrazine (MMH) and the oxidizer is nitrogen tetroxide with 0.64% nitric oxide (MON-1). High-pressure helium gas is stored in two pressurant tanks and is provided as needed via a pressure regulator to the four propellant tanks, two each of

oxidizer and fuel. The propellant tank pressures were controlled within the relatively narrow range of about 17.2 - 18.5 bar, for optimum thruster operation, from shortly after launch until the final regulator isolation on March 14, 1996.

The RPM contains 12 10-N thrusters, 6 each on two boom-mounted thruster clusters. These thrusters are used for attitude control of the dual-spin spacecraft and for small interplanetary trajectory correction maneuvers (TCMs) and, now, orbit trim maneuvers (OTMs). The lateral thrusters L1B and L2B are used for lateral velocity increments in TCMs/OTMs, and the P1A and P2A thrusters are used primarily for precession (balanced turn) maneuvers. The L-thruster couple may be utilized as the back-up P-thruster couple and vice versa. The P1A thruster may also be used to impart a POSZ (+Z) velocity increment (along the spacecraft's spin axis). There are four negative Z-thrusters, two primary (Z1B and Z2B) and two backup (Z1A and Z2A). These are used in TCMs/OTMs for NEGZ (-Z) velocity changes. Finally, there are also four spin thrusters, two primary (S1A and S2A) and two backup (S1B and S2B). The S-thrusters are used to control spin rate to the nominal 3.15 rpm, and to spin up to/down from approximately 10.5 rpm, the mandated spin rate for probe release and for the main engine firings. Use of the main engine (described below) requires the higher spin rate to (centrifugally) furnish sufficient liquid propellant to the propellant tank outlet ports and to maintain spacecraft attitude during these large maneuvers.

In addition to the assortment of 10-N thrusters, there is one 400-N rocket engine used for large ΔV maneuvers. Four 400-N main engine burns have been executed by the orbiter. The Wake-Up Burn (WUB) represented the first in-flight test of the 400-N engine components and was limited to a duration of two seconds. It occurred in July, 1995, three days before the first prolonged use of the main engine. This maneuver, the Orbiter Deflection Maneuver (ODM), diverted the orbiter from a Jupiter-entry trajectory shortly following probe release. The Jupiter Orbit Insertion (JOI) slowed Galileo down sufficiently to allow gravitational capture by Jupiter on December 7, 1995. Finally, the Perijove Raise Maneuver (PJR) occurred during March, 1996 (while at apoapsis), increasing the periapsis of subsequent orbits around Jupiter, for the purposes of radiation damage mitigation.

Operation of the Galileo 400-N engine brought very different challenges to the propulsion system given the six year "in-flight" wait time before its first use. The correct operation of all hardware components was partially verified, components which include latch valves, a pneumatic engine valve, an electromagnetic pilot valve, propellant filters, oxidizer and fuel check valves and the pressure regulator. Fig. 1 represents the flow diagram that was developed to accomplish these checks. In order to minimize the adverse effect of a valve failure (stuck open or stuck closed), two in-flight tests were performed prior to the first nominal burn. Before pressurization of the pilot valve, the 400-N latch valves were commanded (opened/closed) 25 times. All actuations were successful as indicated by Reed switches. The function of the pilot valve is to pneumatically actuate the engine valve, which starts a burn. A two-second wake-up burn was performed to verify the engine valve and pilot valve open/close function and also finally confirmed the open state of the latch valves during the burn.

A major effort during the preparation of the 400-N burns was put in the development of autonomous on-board fault protection routines to avoid mission critical impacts from malfunctioning propulsion system hardware during a burn. Potential internal helium leaks in the pilot valve were guarded against by monitoring the helium tank pressures and could have been mitigated by firing a pyrovalve and thus closing the open pilot valve port. ("helium-loss" protection). This would have required subsequent engine operation via the latch valves only, an operational mode which was tested in German ground tests. The "over-pressure" algorithm checked the propellant tank pressures against an upper limit. It would have isolated the pressure regulator via a pyrovalve if a leaking pressure regulator would have raised the tank pressures above a set limit. A "line-pressure" protection was implemented to shut down the engine in case the propellant line pressures dropped below a specified limit, caused by plugged filters. Nominal changes in tank pressures required the maintenance of the thresholds, especially for the "helium-loss" protection. Risk assessments, fault probabilities and the criticality of a given maneuver for the mission led to the decision that "helium-loss" protection was to be used for all three 400-N maneuvers, the "over-pressure" protection for ODM and PJR and the "line-pressure" protection only for EJR.

The in-flight characterization of the RPM is now complete, having completed the final 400-N engine burn and isolated the pressure regulator. Less than ten percent of the usable propellant load remains on-board the orbiter; however, this slight amount of propellant is sufficient (with margin) to execute the nominal two-year, eleven-orbit tour of Jupiter. The entire system has performed well within specifications. The only known hardware failure in the RPM is the failure of four of the twelve 10-N thruster temperature sensors (non-essential sensors, which, by the way, were added just prior to launch and whose mounting procedure was never flight qualified). Loss of these sensors has not had a significant impact on in-flight operation at all since cluster temperature measurements offer sufficient, redundancy.

Though not indicative of a complete hardware failure, there also has been a significant linear drift noted on some of the Galileo tank pressure transducers. in fact, the transducers with the worst. drift rates are now out of specification. However, the appl icabi lity of the specification may be in question given the age of these sensors, due to the numerous launch delays which delayed the Galileo mission for a number of years.

Perhaps of more interest-, there is evidently s Omc? hardware degradation that caused highly restricted flow of helium through the oxidizer and fuel check valves during 400-N engine firings. Analysis of the launch pressurization data suggests that the full required flow of helium through each check valve (of up to 0.16 g/s , necessary for 400-N engine burns) could be easily supported. Therefore, the inability of the check valves to provide the requisite helium flow, especially with first. the oxidizer and then fuel check valve being affected, suggests that. NTO may have, over time, caused some hardware degradation in the oxidizer check valve, and possibly in t-he fuel check valve.

Other evidence suggested that the oxidizer check valve might have lost its reseat pressure or even became stuck-open; however, unknown absolute tank pressure values (due to pressure transducer drift) cloud this determination. Moreover, there is good data post-PJR, fol lowing regulator i solation, that suggest. that the oxidi zer check valve must be closed. The uncertai nty i n the state of t-he oxi di zer check **valve! 1** evi ed **a** parti cul **ar** chal **1** enge on the f] ight team between ODM (July, 1995) and post -PJR (April , 1996) ; namely, to keep tank pressures and temperatures nearly constant. to avoi d any chance of openi ng t-he fuel check valve and forci ng oxi di zer vapor (and any condensed NTO) i nto the MMH tubi ng and MMH t anks .

The? pressuri zati on system was designed to ho] d the tank pressures constant during a large (i . e. , 400- N engine) propel] ant expul si on. The pressure regul at. or perf ormed perfect-ly throughout the maneuvers. As indicated by the he] i urn an d propel 1 ant tank pressures, the reconstruc ted regul at or charact eri st i c (downst ream pressure vs . upstream pressure and hel i um f 1 ow rate) ref 1 ected the pre - 1 aunch ground measurements, wi th the caveat that t-he absol ute 1 evel of the downstream pressure i s unde termi nabl e and **may have** shi fted over time. However, rest ri cted hel i urn f] ow through the check val ves resul ted i n 1 arger than anti ci pat ed press ure drops i n both the oxidizer and fuel tanks .

The oxidizer check valve showed a flow restriction during al 1 400-N engi ne maneuvers,, hav i ng a charact eri sti c: simi 1 ar to a f i xed orifice. Although the reseat. pressure could be zero (depending on the assumed downstream pressure, which is unknown due to pressure transducer drifts), the data showed an existing cracking pressure and evidence of a nominal checking function. From Fig. 2, which represents the pressure drop across the check valve vs. the helium flow rate on the oxidizer side, the check valve performed repeatably for the three maneuvers. The downstream pressure is calculated from the two (out. of three) oxidizer tank pressure transducers which show no relative drift to one another, and the upstream -pressure is derived from a pressure regulator model based on ground tests and in-flight data. In this scenario the oxidizer check valve has lost its reseat. pressure.

The fuel check valve performance was different in each maneuver. Fig. 3 illustrates this remarkable change in characteristic. At ODM it showed the highest. so far observed cracking pressure, then opened wider than required ("overshoot") and eventually delivered the required helium flow rate at a nominal pressure drop. At JOI the check valve showed a nominal performance (regarding cracking pressure and pressure drop at. full. helium flow) . At PJR it was flow restricted similar to the oxidizer check valve . However, the flow restriction was even higher than on t-he oxidizer side and the characteristic indicates that. the check valve was slowly opening throughout the maneuver rat-her than being a fixed orifice. This caused the? fuel tank pressure to decrease Throughout the burn and end up 1 .5 bar lower than predicted.

The heat transfer from the liquid propel. llant components and the tank walls into the ullage gas was significant during changes in temperature and pressure. The polytropic coefficients calculated for the helium tank depletion as well as for the -propellant tank blow-down phases demonstrated this. The low helium tank outl t-. temperatures (as low as -23 °C) caused no concerns for the propellant. components because mixing with the ullage gas arid the above mentioned heat transfer sufficiently limited the cooling effect on the gas in the propellant tanks .

Propellant vapor is negligible in the fuel tanks. On the oxidizer side, the polytropic: coefficient during blow-down was lower (n = 1.18) compared to the fuel tank (n = 1.4) due to the condensate on heat of NTO vapor. Post burn, after the helium flow fill-up was completed, a slow vapor pressure buildup caused the oxidizer tank pressure to increase further compared to the fuel side . Vapor pressure effects were even apparent. during changes in tank temperatures after pressure regulator isolation, where the vaporization/condensation heat. of NTO increased the heating/cooling time constant of the oxidizer tank compared to the fuel tank .

A total of twenty-five trajectory correction maneuvers (TCMs), including ODM and JOI, and six orbit trim maneuvers (OTMs), including PJR, have been executed on the spacecraft to date (through mid-August, 1996). Accelerometers were not used for determining thruster firing cutoff for Galileo 10-N TCMs/OTMs. The thruster burn times were determined a priori via ground software, then uplinked to the spacecraft. In contrast, all three primary 400-N engine maneuvers were terminated once the proper ΔV had been obtained, using a so-called accelerometer cut-off (conversely, the WUB burn-time was specified a priori, similar to 10-N maneuvers). This was necessary due to the high cost of underburns or overburns for ODM, JOI, and PJR.

Table 1 (two pages) represents an abbreviated TCM and OTM summary with respect to the RPM. It must be emphasized that this table represents the TCM and OTM execution errors determined by navigation, which include error sources external to the RPM. The designations ΔV_Z and ΔV_L represent the inertial velocity change of the spacecraft in the axial and lateral directions, respectively. The last three columns of Table 1 represent the execution errors in 10-N TCMs/OTMs, which consists of errors in predicting tank pressures and propellant inlet temperatures, spacecraft pointing, RPM thruster off-nominal performance, etc. For ODM, JOI, and PJR, the final column actually represents the accelerometer calibration error.

From Table 1, the errors in delivered ΔV to the spacecraft may be seen to be within three percent (three-sigma). RPM reconstruction of TCMs/OTMs has provided a breakdown of the error sources during all maneuvers. POSZ maneuvers had the largest average reconstructed errors in early mission TCMs, due to the overperformance of the P1A thruster. Software database changes have been made to account for this overperformance, which has improved the accuracy of POSZ TCMs/OTMs. Note also the improvement in the accelerometer calibration between ODM and JOI.

In addition to analyzing L-thruster, Z-thruster, and +P1A thruster performance in TCMs/OTMs, the RPM mission operations team has analyzed P-thruster, Z-thruster, and S-thruster performances during balanced precession, unbalanced precession, and spin-rate change maneuvers, respectively. The S-thrusters appear to be overperforming vs. ground test levels by 2-4%, while the P-thrusters are overperforming more significantly, by 6-7%. This P-thruster overperformance is of little consequence for the precession maneuvers, since they are used in a closed loop control mode by the Attitude and Articulation Control Subsystem (AACS). Similarly, the A-branch Z-thrusters have been used for a total of sixteen unbalanced turns to date (mid-August, 1996), with an average overperformance near 2% for the couple. The cause for the general trend of 10-N thruster overperformance vs. ground tests, roughly between -1% and 7%, is still not known.

The RPM mission operations team has analyzed the 400-N thrust performance during the three major burns. A ground-based software model, which was also used for the maneuver planning, takes the tank pressure telemetry as input and calculates the thrust profile. Because the absolute tank pressures are uncertain due to the drifting oxidizer transducers, the analysis presented here is based on the assumption that the oxidizer pressure is the average of the three transducer readings. The 400-N engine underperformed by 3% vs. the model with little variation for the three maneuvers. About 2.4% can be attributed to lower than modeled propellant flow rates. A check with ground-test data suggested a small correction downward of the simulated specific impulse of about 0.6%. By taking these corrections into account for the design of JOI and PJR, the average thrust was off by 0.2% (for JOI) and 0.8% (for PJR) compared to the predictions. The larger error on PJR was mainly due to the flow restriction in the fuel check valve and the resulting low fuel tank pressure.

Besides tracking thruster performance, the RPM mission operations team is cognizant of the RPM-related spacecraft consumables. These include thruster and latch valve cycles, propellant consumption, pressurant gas and propellant remaining. The usable propellant remaining is probably the most critical consumable on the spacecraft since it is likely to be the life-limiting resource for the mission (although radioisotope thermoelectric generator [RTG] power output decay and accumulated radiation damage from Jupiter are contenders as well). However, it should be noted that the Galileo propellant margin, defined as the propellant remaining after the completion of the nominal mission at a ninety-percent confidence level, has improved from -58 kg at launch to 41 kg (including 13 kg of project-manager reserves). This has been accomplished through excellent navigation, the selection of a low delta-V tour, and the shift of the Ganymede-1 arrival date earlier by one Ganymede orbital period.

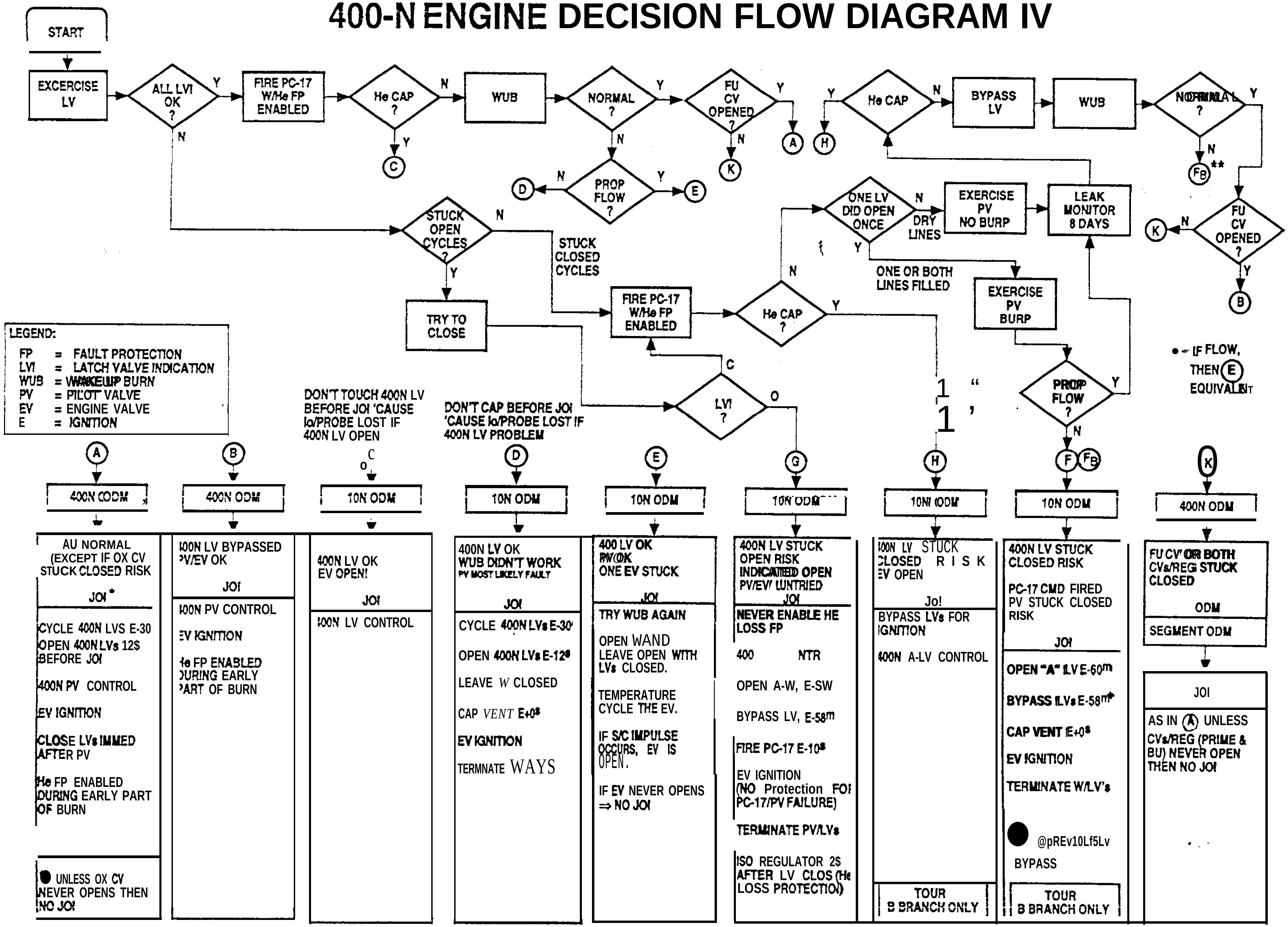
Table 2 represents a consumables summary with respect to the RPM to date (8/22/96). A noteworthy change in Table 2 vs. the equivalent table in the prior AIAA conference paper is the increase of the 10-N thruster allowed valve cycles, from 2?3000 to 35000 cycles per thruster. This was accomplished with additional experience gained from ground testing. RPM consumable usage has been within expectations, and the prospects for positive consumable margins remain excellent, even for an extended mission.

The RPM analysis team is responsible for maintaining propellant tank pressures within (somewhat narrow) acceptable ranges for 10-N thruster operation. This represents a particular challenge on Galileo, since excess RTG power is autonomously dissipated in the RPM central body to maintain RPM temperature instead of being radiated directly to space. Hence, the tank pressure control of the RPM is a complex, interactive process involving the power, thermal control, and RPM subsystems. However, this process has been simplified somewhat. with a re-engineering effort. that only allows a few distinct. "power modes" to be used during the orbital tour (with no loss of science data). This, combined with the isolation of the pressure regulator post-PJR March, 1993, has made the task of propellant tank pressure and temperature prediction much simpler. However, the tank pressures currently encountered in the Galileo mission (particularly on the fuel side, with a severe fuel check valve restriction in PJR, immediately prior to regulator isolation) are largely out-side! of well-tested regimes, both in-flight and on the ground. Sufficient ground-test. experience and ever-accumulating in-flight experience, though, suggest that ~~a~~ pressure regulator never needs to brought back on-line, even by the time of propellant depletion.

In summary, the Galileo RPM has performed very well during a challenging seven years of mission operations. An extensive characterization of the propulsion system is now complete, with routine use of the RPM anticipated for the balante of the Galileo nominal (and even possible extended) mission.

Galileo

400-N ENGINE DECISION FLOW DIAGRAM IV

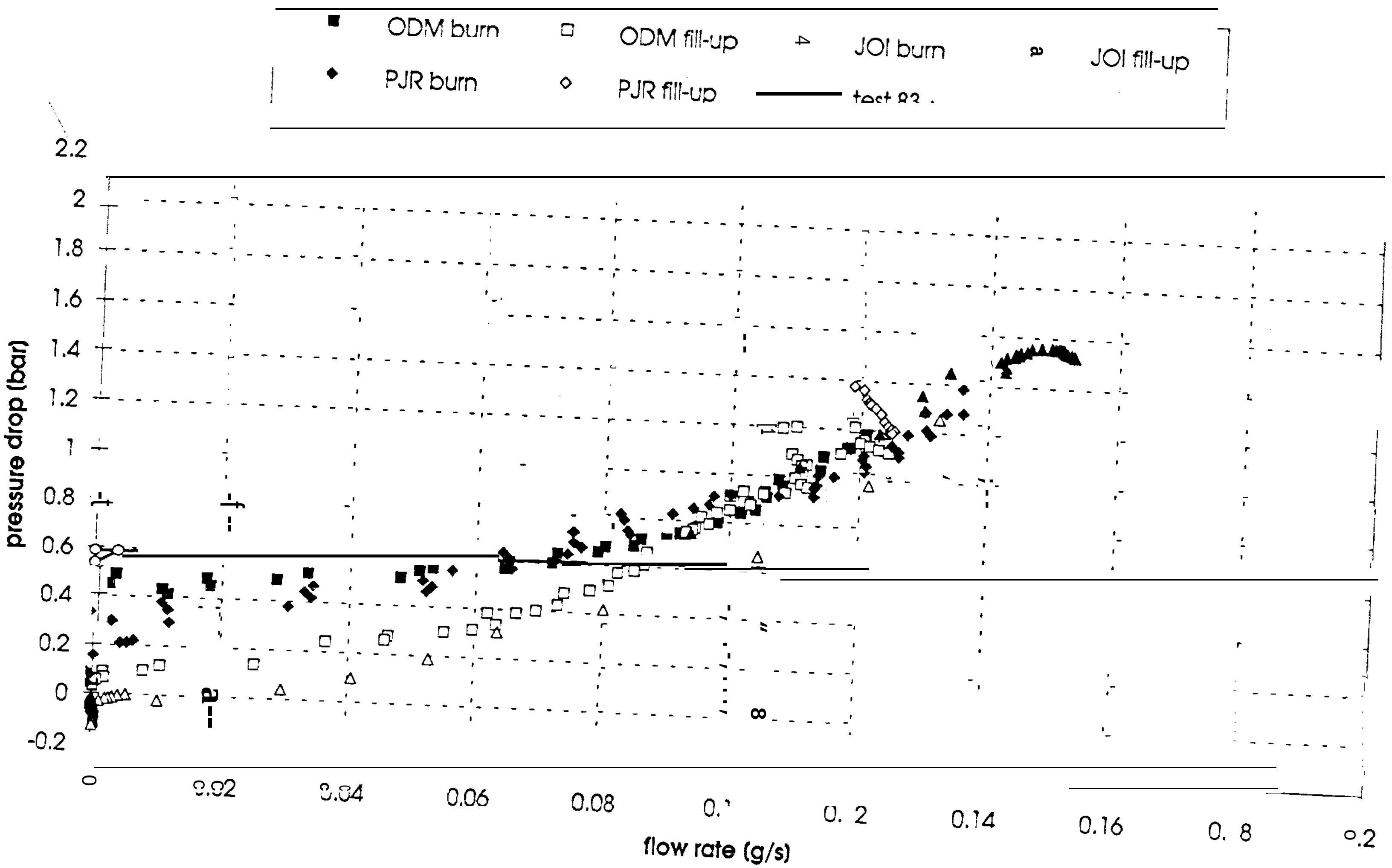


Figure"1

Approved by: W.J. O'Neil 4/21/95 Date

4/21/95

Oxidizer Check Valve Characteristic



Fuel Check Valve Characteristic

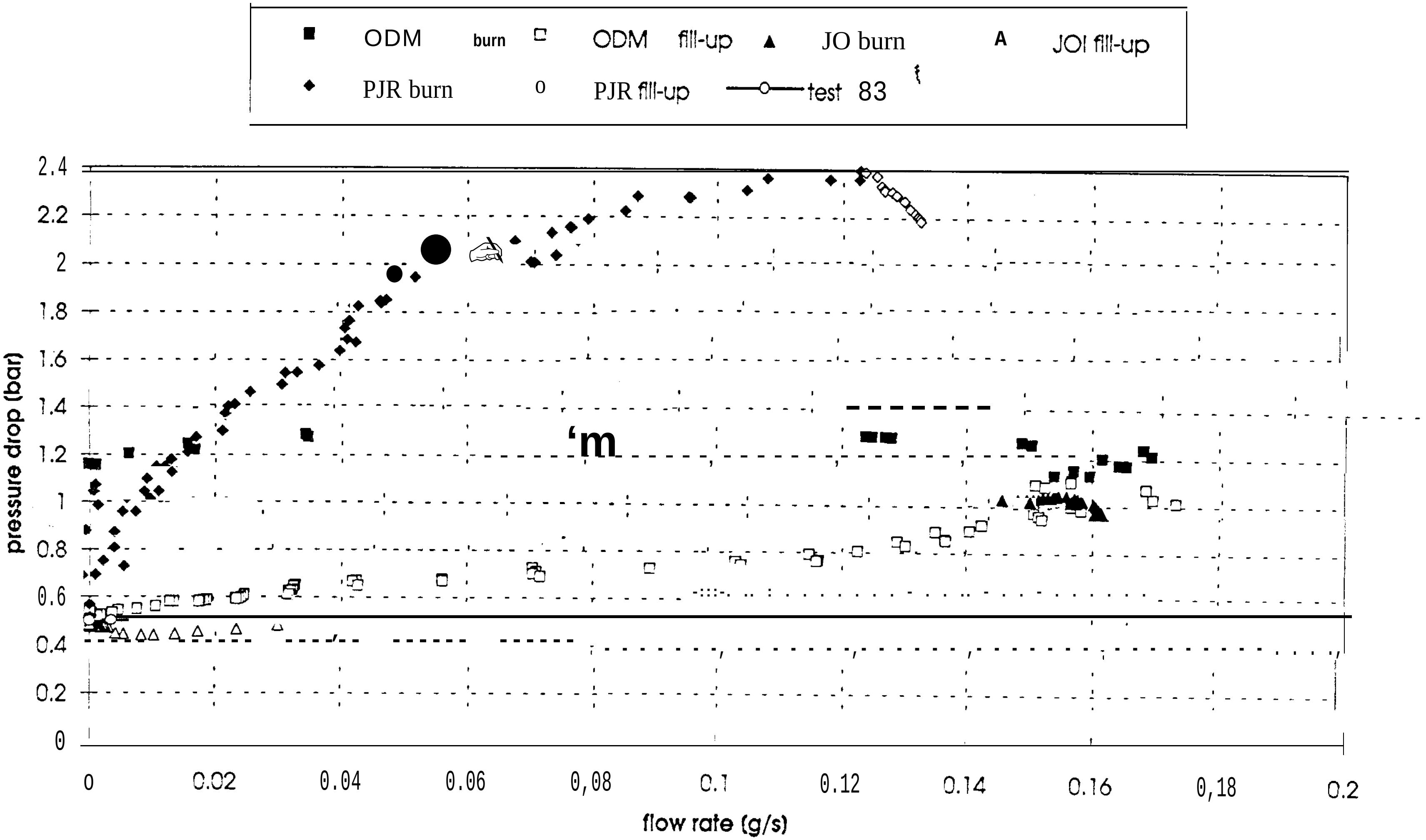


Figure 3

TCM/OTM SUMMARY TABLE (MANEUVER EXECUTION ERRORS)

TCM/OTM	DATE (S)	MANEUVER DESCRIPTION	Δv_Z m/s	Δv_L m/s	%ERR Δv_Z	%ERR Δv_L	%ERR TOTAL
TCM-1	11/9/89-11/11/89	REMOVE LAUNCH BIAS & 1ST VENUS TARGET	15.6	1,74	+1.7	+3.5	+1.7
TCM-2	12/22/89	2ND & FINAL VENUS TARGET	0.16 POSZ	0.72	42.2	+2.1	+2.1
TCM-4A	4/9/90-4/12/90	1ST EARTH-1 TARGET PART 1	----	24.7	---	-2.3	-2.3
TCM-4B	5/11/90-5/12/90	1ST EARTH-1 TARGET PART 2	----	11.3	---	-2.4	-2.4
TCM-5	7/17/90	2ND EARTH-1 TARGET	0."/2	0,59	+2.5	-0.2	+1.4
TCM-6	10/9/90	3RD EARTH-1 TARGET	0,48	0.20	+0.8	-1.6	+0.4
TCM-7	11/13/90	FINAL EARTH-1 TARGET	1.09	0.66	+1.2	+1.3	+1.2
TCM-8	11/28/90	TCM-7 CLEAN-UP TCM	0.02 POSZ	0.05	+1.2	-0.6	-0.4
TCM-9A	12/19/90	POST EARTH-1 CLEAN-UP	----	5.29	---	-0.2	-0.2
TCM-9B	3/20/91	GASPRA TARGET PART 1	0.20 POSZ	2.27	+0.5	+0.6	+0.6
TCM-10	"1/2/91	GASPRA TARGET PART 2	---	3.65	---	-0.9	-0.9
TCM-11	10/9/91	GASPRA TARGET CLEAN-UP TCM	0.09 POSZ	0.34	+0.4	+0.0	+0.0
TCM-12	10/24/91	GASPRA TARGET CLEAN-UP TCM	0.02	0.21	+0.6	+0.2	+0.2
TCM-14	8/4/92-8/7/92	1ST EARTH-2 TARGET	0.41	21.0	+2.7	+1.3	+1.3
TCM-15	10/9/92	2ND EARTH-2 TARGET	0.40	0.61	+0.4	+0.8	+0.6
TCM-16	11/13/92	FINAL EARTH-2 TARGET	----	0.89	---	-0.5	-0.5
TCM-17	11/28/92	EARTH-2 TARGET CLEAN-UP TCM	0.02	0.02	+0.0	+0.0	+0.0
TCM-19	3/9/93	FINAL IDA TARGET	2.12	----	-0.3	---	-0.3
TCM-20	8/13/93	IDA TARGET CLEAN-UP TCM	0.07	0.61	-0.3	+0.5	+0.4
TCM-22	10/4/93-10/8/93	FINAL PROBE ENTRY TARGET	----	38.6	---	-0.2	-0.2

Table 1

TCM/OTM SUMMARY TABLE (MANEWER EXECUTION ERRORS) (cont)

TCM/OTM	DATE (S)	MANEWER DESCRIPTION	Δv_Z m/s	Δv_L m/s	%ERR Δv_Z	%ERR Δv_L	%ERR TOTAL
TCM-22A	2/15/94	PROBE TARGET CLEAN-UP TCM	0.09 POSZ	0.04	-0.2	+0.0	-0.1
T'CM-23	4/12/95	PROBE TARGET' CLEAN-UP TCM	0.05 POSZ	0.06	-0.3	+0.0	-0.1
T'CM-25 (ODM)	7/27/95 .(-//24 WUB)	WAKE-UP BURN & ORBITER DEFL.	66.27	----	-1.3	----	-1.3
T'CM-26	8/29/95	1ST & FINAL ODM CLEAN-UP TCM	0.86	0.44	-0.8	-0.2	-0.6
I'CM-29 (.To])	12/7/95	JUPITER ORBIT 3NSERTION	644,4	----	+0.1	----	+0.1
OTM-3 (PJR)	3/14/%	PERIJOVE RAISE MANEUVER	377.1	----	-0,2	----	-0.2
OTM-4	5/3/96	1ST G1 T'ARGE'I' CLEAN-UP OTM	0.45	1.17	+0.3	-0.1	+0.0
O'I'M-5	6/12/96	2ND G1 TARGET CLEAN-UP OTM	0.18 POSZ	0.50	-0.1	-0.1	-0.1
OTM-6	6/24/96	FINAL G1 TARGET CLEAN-UP OTM	0.06 POSZ	0.48	+1.1	-0.4	-0.2
O'I'M-7	6/30/96	1ST POST-G1 CLEAN-UP OTM	0.58 POSZ	----	+0.3	----	+0.3
OTM-8	8/5/96	G1 TO G2 APOAPSIS OTM	0.24	4.61	0.0	-0.5	-0.5

AVERAGE 10-N MANEUVER EXECUTION ERROR = +0.1%
STANDARD DEVIATION = ± 1.0%
DEMONSTRATED 3 SIGMA DELIVERY = -2.9% TO +3.0%

Table 1 (cont)

RPM CONSUMABLE SUMM.?_RY AS OF 8/22/96

RPM Consumable	Used	Lifetime	%Used
Z1A Thruster Valve (cycles)	2260	35000	6.46%
Z2A Thruster Valve (cycles)	2267	35000	6.48%
P1A Thruster Valve (cycles)	11433	35000	32.67%
F'2A Thruster Valve (cycles)	10517	35000	30.05%
L1B/L2B Thruster Valves (cycles)	15310	35000	43.74%
S1A Thruster Valve (cycles)	2034	35000	5.81%
S1B Thruster Valve (cycles)	255	35000	0.73%
S2A Thruster Valve (cycles)	1867	35000	5.31%
S2B Thruster Valve (cycles)	255	35000	0.73%
B-Branch Latch Valves (cycles)	595	4000	14.88%
A- Branch Latch Valves (cycles)	)035	4000	25.88%
400-N Latch Valves (cycl es)	30	4000	0.75%
Oxidizer (kg N'TO)	515.95	571.3	90.31%
Fuel (kg MMH)	315.46	353.7	89.19%
Total propellant (kg)	831.41	925. 0	89.88%
Propellant Usage Breakdown (kg)			
TCMs/OTMs	739.22		88.91%
HGA Anomaly Activity	49.21		5.92%
Attitude Control	36.49		4.39%
RPM Maintenance	6.49		0.78%

Table 2