Shuttle Primary Reaction Control Subsystem Thruster Fuel Valve Pilot Seal Extrusion - A Failure Correlation

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Introduction

Pilot operated valves (POVs) are used to control the flow of hypergolic propellants monomethylhydrazine (fuel) and nitrogen tetroxide (oxidizer) to the Shuttle orbiter Primary Reaction Control Subsystem (PRCS) thrusters. The POV incorporates a two-stage design: a solenoid-actuated pilot stage, which in turn controls a pressure-actuated main stage. Isolation of propellant supply from the thruster chamber is accomplished in part by a captive polytetrafluoroethylene (PTFE) pilot seal retained inside a Custom 455®[1] stainless steel cavity.[2]

Extrusion of the pilot seal restricts the flow of fuel around the pilot poppet, thus impeding or preventing the main valve stage from opening. It can also prevent the main stage from staying open with adequate force margin, particularly if there is gas in the main stage actuation cavity. During thruster operation on-orbit, fuel valve pilot seal extrusion is commonly indicated by low or erratic chamber pressure or failure of the thruster to fire upon command (Fail-Off). During ground turnaround, pilot seal extrusion is commonly indicated by slow gaseous nitrogen (GN_2) main valve opening times (> 38 ms) or slow water main valve opening response times (> 33 ms). Poppet lift tests and visual inspection can also detect pilot seal extrusion during ground servicing; however, direct metrology on the pilot seat assembly provides the most quantitative and accurate means of identifying extrusion. Minimizing PRCS fuel valve pilot seal extrusion has become an important issue in the effort to improve PRCS reliability and reduce associated life cycle costs.

Background

Although PRCS thruster fuel valve pilot seal extrusion was first documented in 1994, inspection of valve maintenance records going back to 1981 revealed a significant number of earlier fuel valve failures. This necessitated a review of extrusion cases within the broader historical context of PRCS fuel valve failures, and a comparison of the service histories of failed versus active fuel valves.

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[1] Custom 455® is a registered trademark of Carpenter Technology Corporation, Reading, Pennsylvania.
[2] Propellant isolation is also accomplished by the main poppet/seat.

Extrusion Mechanisms

Two primary mechanisms have been proposed for fuel valve pilot seal extrusion; one or both may be occurring. The first mechanism is referred to as *thermal extrusion,* which is thought to be caused by excessive or prolonged heating after thruster firing (soakback). Other heat inputs that may contribute to this type of extrusion are vacuum bakeouts during ground acceptance test procedures (ATP); or ascent, descent, and solar heating during mission.

The second mechanism is referred to as *oxidizer-induced extrusion*, which is thought to be caused by oxidizer leakage on-ground from the adjacent oxidizer valve on the same thruster and subsequent exothermic fuel-oxidizer reaction. The 1991 installation of the universal throat plug accessory (UTPA), which effectively traps leaking oxidizer vapor inside the thruster chamber, is thought to be one of the factors responsible for oxidizer-induced extrusion. To mitigate possible problems associated with the UTPA, a GN_2 trickle purge of all thrusters was implemented at Kennedy Space Center (KSC) between 1998 and 2000.

The common feature in thermal and oxidizer-induced extrusion is thermal-expansion mismatch of adjacent PTFE and Custom 455 thruster parts. Therefore, minimizing PRCS fuel valve pilot seal extrusion requires control of heat inputs during the seal's service lifetime. Cold flow and internal stress relief of PTFE seals in the absence of heating are other overlooked factors that may contribute to extrusion [1,2].

Extrusion Types

Two types of fuel valve pilot seal extrusion have been observed: extrusion of the whole seal across the sealing and nonsealing surfaces of the pilot seal (*Type I extrusion*); or extrusion of the non-sealing surface along the outer diameter of the seal (*Type II extrusion*). Micrographs of Type I and Type II extrusion appear elsewhere [1]. It is possible although not proven that oxidizer-induced extrusion results in Type I cases (more catastrophic), while thermal extrusion results in Type II cases (more incremental). Alternatively, both extrusion types could arise from differences in the cumulative loading at temperature during service, independent of oxidizer effects.

Failure Distribution

Understanding the distribution of fuel valve failures in general, and extrusion failures in particular, within the historical context of major PRCS milestones is informative (Figure 1). Extrusion was first documented after thruster Serial Number (S/N) 325 Failed-Off during Space Transportation System Flight (STS)-68 in December 1994 [3,4]. Through 2000, there have been ten other (eleven total) in-flight anomalies (IFAs) involving thrusters that were later shown to have extruded pilot seals. The breakdown of the IFAs in which extrusion was involved or detected during follow-up testing is as follows:

- 7 Fail-Off IFAs (caused by fuel valve pilot seal extrusion)
- 3 Fail-Leak IFAs (caused by oxidizer valve leakage)
- 1 Heater Fail-Off IFA (not caused by fuel or oxidizer valve failure)

Another 38 fuel valves with extruded pilot seals were detected between 1994 and 2000 during routine and nonroutine thruster repair and replacement (R&R) at NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) Depot, giving a total of 49 extrusion cases (Table 1).

Prior to STS-68, another 39 fuel valves were repaired for various reasons. Most of those valve repairs were made by Marquardt (Van Nuys, California; now General Dynamics, Redmond, Washington). Gypsum intrusion after the 1982 STS-3 landing, and the Shuttle Orbiter Forward Reaction Control Pod Number 2 (FRC2) Power-On anomaly during the 1986 STS-61C flow, account for 10 of the 39 pre-STS-68 failures. Extrusion has been implicated in 92 percent (49 of 53) of the fuel valve failures since and including STS-68; however, if or to what extent extrusion played a role in earlier thruster failures is unknown. Nonsystematic visual examination of pilot seals taken from valves that failed before STS-68 did not reveal severe extrusion.[1] Information about the specific causes of pre-STS-68 fuel valve failures (e.g., information contained in Marquardt-issued Failure Mode Reports) could offer added insight into the reasons behind past and present fuel valve failures.

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[1] Wichmann, H. Private communication. Consultant, L&M Technologies, White Sands Test Facility, Las Cruces, New Mexico. December 2001.

Objective

The objective of this investigation was to correlate the incidence of PRCS fuel valve pilot seal extrusion with:

- Thruster R&R frequency at WSTF Depot
- Pilot seat assembly retainer weld type
- Service history (years in service and firing history)
- Attitude (solar), ascent, and descent heating
- Oxidizer valve R&Rs, especially those caused by leakage
- Other miscellaneous ground heating events, such as the May 1995 RP01 fire at KSC
- Vacuum bakeout histories

Approach

The approach consisted of examining the dependence of extrusion on service history parameters such as number of years in service,[1] number of burns, ontime, and time per burn. The correlation between extrusion and thruster duty cycle (firing priority, duration, and sequence during mission) was not investigated. The dependence of extrusion on oxidizer leakage was then examined, thus testing the validity of the oxidizer-induced extrusion mechanism. Finally, the dependence of extrusion on other heat sources such as attitude heating and vacuum bakeouts was examined.

Investigative Results

Firing history and flight data were obtained from JSC Orbital Maneuvering Subsystem (OMS)/RCS Operations. Fuel and oxidizer valve R&R and flush history data were obtained from KSC Reusable Space Systems and WSTF Depot. Desiccant tube changeout data from recent Orbiter Maintenance Down Period (OMDP) Shuttle flows were obtained from KSC. Vacuum bakeout histories were obtained from the WSTF Chamber Lab. Compilation and reduction of the above service history data was the basis for the current investigation.

Correlation with Thruster Repair and Replacement Frequency

Table 2 summarizes the failure distribution of PRCS thruster fuel valves from 1981 through 2000. Inspection of the fuel valve failure distribution since STS-68 in December 1994 shows that a majority of extrusion cases (28 of 49 cases, or 57 percent) were detected during routine OMDP water flushes (Table 2, column 3). To put this into historical context, OMDP water flushes were not begun until 1992 [5]. The first three OMDPs between 1992 and 1994 during the STS-53, -66, and -73 flows did not involve flushing of ship sets, while the most recent OMDPs between 1995 and 1999 during the STS-82, -89, -101, and -107 flows did.[2] Even more compelling than the high number of extrusion cases observed during OMDPs is the good correlation between the number of fuel valve failures and the number of thrusters submitted to WSTF Depot between 1991 and 2000. Most of the fuel valve failures between 1991 and 2000 (49 of 59 cases, or 83 percent) were due to extrusion. A plot of failures versus thrusters submitted revealed a correlation coefficient (goodness of fit parameter R^2) of 0.84 (Figure 2).

Between 1998 and 2000, 14 extrusion cases were observed, compared to 34 during the previous three-year interval between 1995 and 1997 (Table 2 and Figure 3). It would be tempting to attribute the lower extrusion incidence between 1998 and 2000 to the beneficial impact of the GN_2 purge at KSC, since this purge would reduce or eliminate the occurrence of oxidizer-induced extrusion. Full implementation of the GN_2 purge, however, was not completed until August 2000. Conclusions about the benefit of the purge are, therefore, premature. Also, the GN_2 purge would have had no effect on the incidence of thermal extrusion. Other factors could have contributed to a lower extrusion incidence:

- Fewer OMDPs – one between 1998 and 2000 compared to three between 1995 and 1997
- Fewer shuttle missions – 13 between 1998 and 2000 compared to 22 between 1995 and 1997
- Passing the maximum in the fuel valve failure distribution:
  - average service for active fuel valves = 10.1 years, 1373 burns, 410 s ontime

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[1] The number of years in service for each valve was based on thruster installation and removal dates, instead of thruster shipping dates from the manufacturer or repair facility, or pod-on and pod-off dates at KSC.

[2] A ship set consists of 38 primary thrusters.

- average service for fuel valves exhibiting extrusion = 10.0 years, 2240 burns, 592 s ontime

- Beneficial effect of cycling firing priorities
  Water flushing and molecular sieve implementation (improved oxidizer valve reliability)

Correlation with Retainer Weld Type

Only one of 13 Type II extrusion cases had an intermittently welded pilot seat assembly, while about half (12 of 23) of Type I extrusion cases had intermittently welded assemblies. Intermittently welded assemblies are thought to be more prone to fuel migration through the pilot seal cavity, leading to an increased likelihood that fuel could react with oxidizer vapor downstream of the pilot seal, thus generating heat and causing extrusion. Therefore, it is tempting to categorize Type I cases as oxidizer-induced extrusion (more fuel migration), and Type II cases as thermal extrusion (less fuel migration). It must be noted, however, that weld type probably has less influence on fuel migration or leakage than pilot seal flaws, or poor fit between the pilot seal and pilot seal poppet. Also, comparison of years in service for all extrusion cases shows that Type II cases are slightly older (Figure 4), consistent with the presence of a deeper poppet footprint. Although the age difference is small (12.5 ± 3.0 years service on average for valves exhibiting Type II extrusion versus 8.9 ± 4.1 years service on average for valves exhibiting Type I extrusion), this difference suggests that extrusion type is influenced more by pilot seal age than retainer weld type.

Correlation with Firing History

Firing history data through STS-105 (flown August 2001) were obtained from JSC OMS/RCS Operations. Although most data are complete and in raw (unverified) or final (verified) form, gaps do exist (Table 3).

Available firing history data were combined with fuel valve R&R histories obtained from WSTF Depot (*PRCS Major Configuration Table*).[1] This allowed the years in service, number of burns, cumulative ontime, and average time per burn to be determined at the valve level. As a control, the firing histories of valves that failed due to extrusion were compared to the firing histories of active valves that have yet to fail for any reason.

Firing history distributions of Type I and II extrusion cases were compared and were found to overlap (Figure 5). Many Type I failures with a low number of burns were noted along the 'Years in Service' axis (from origin: P331, P601, P223, P227, P101, and P451), consistent with fewer valve actuations and a less prominent poppet footprint. Type II cases were characterized by slightly more burns (2373 versus 2256), higher ontimes (738 versus 531 s), and a slightly higher time per burn (0.31 versus 0.24 s) compared to Type I cases. The scatter in the data, however, would undercut assertions that such differences are significant.

Valves subjected to longer burns tended to fail with fewer accumulated burns than valves with shorter burns (Figure 5 inset). The correlations between time per burn and accumulated burns were weak ($R^2 = 0.17$ for Type I extrusion (23 cases); $R^2 = 0.36$ for Type II extrusion (13 cases); $R^2 = 0.45$ for extrusion cases of unknown type (13 cases)), suggesting that other factors might be contributing to extrusion, such as oxidizer leakage, attitude heating, or vacuum bakeouts. Long burns were less of a factor in fuel valve failures attributed to reasons other than extrusion either before STS-68 ($R^2 = 0.03$ (39 cases)), or after STS-68 ($R^2 = 0.15$ (4 cases)). As a control, long burns were found to have virtually no effect on the number of burns accumulated by fuel valves still in use ($R^2 = 0.07$ (191 cases)).

The majority (36 of 49 cases, or 73 percent) of all extrusion cases have involved OEM-installed valves. This preponderance suggests that extrusion occurs preferentially in valves near the end of their service lifetime. If true, OEM valves with extruded pilot seals would be expected to have more accumulated service than OEM valves still in use. Available data do in fact show more accumulated burns despite having fewer years in service for OEM valves with extruded pilot seals (Table 4); however, the large data scatter lowers confidence in any conclusion.

Attitude, Ascent, and Descent Heating

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[1] In-house document. *PRCS Major Configuration Table.* WSTF intranet at S4\:wstfgrp\prop\depot\p-config\ps-config.mdb, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico, most recent update.

Thruster P574 failed prematurely with the lowest number of burns (26) and highest time-per-burn ratio (2.65 s/burn) of all extrusion cases investigated to date. Initial indications were that long burns contributed to the failure. However, when corresponding mission data were analyzed, the most prominent thermal feature was not long burns (although temperatures in excess of 66 °C (150 °F) were noted), but attitude heating during STS-53, five missions before the failure during STS-72 (Figure 6, top). The attitude heating experienced by P574 in the left aft L1A position, however, was identical to the heating experienced by P417 in the right aft R1A position (Figure 6, bottom). Also, P417 was still active at the time of this report (no extrusion). Therefore, other factors may have contributed to the failure of P574.

Although the attitude heating experienced by P574 during STS-53 may not be unique, overall concerns about attitude, ascent, and descent heating cannot be dismissed completely. For example, flight rules are currently in place to protect orbiter hardware from overheating. Rules include but are not limited to restriction of the orbital β–angle, and consequently, the angle between incident solar radiation and affected components such as thrusters during mission.[1] Another study conducted by Marquardt during the early phases of the Shuttle program investigates worst-case thruster heating scenarios caused by excessive atmospheric friction during ascent and descent [6].

Correlation with Oxidizer Leakage

Between 1981 and 2000, 201 oxidizer valves were replaced, compared to 92 fuel valves.[2] The predominant mode of oxidizer valve failure was leakage, while that of fuel valve failure, at least since 1994, was pilot seal extrusion. Previous studies have implicated oxidizer leakage as a factor in fuel valve pilot seal extrusion [3]. One might, therefore, expect a higher incidence of concurrent oxidizer valve failure or oxidizer leakage in extrusion cases.

Comparison of R&R histories showed a lower incidence of concurrent oxidizer valve failure in extrusion (29 of 49 cases, or 59 percent) versus nonextrusion-related fuel valve failures (31 of 43 cases, or 72 percent) (Table 5, next-to-last row). The lowest incidence of concurrent oxidizer valve replacement was noted for Type I extrusion failures (11 of 23 cases, or 48 percent), contrary to the expectation that oxidizer valve problems would be prevalent in this type of extrusion. Last, the oxidizer : fuel valve replacement ratio in extrusion cases (46 oxidizer valves: 49 fuel valves = 0.94) was comparable to the oxidizer/fuel valve replacement ratio in nonextrusion-related fuel valve failures (35 oxidizer valves: 43 fuel valves = 0.81) (Table 5, last row).[3] For these reasons, extrusion does not appear to be linked to concurrent oxidizer valve failure.

To examine the possibility that extrusion was linked specifically to oxidizer leakage, R&R records [7] going back to July 1988 were examined (Table 6). These records contain a comment field for thruster cause for return. Typical entries include “IFA – Fail Off,” “Ox leakage – Grnd,” “OMDP,” etc. These records show:

- A higher incidence of current or previous oxidizer leakage in extrusion cases (26 of 49 cases or 52 percent) than in active fuel valves (39 of 130 or 38 percent) (Table 6, next-to-last row)
- A higher incidence of current oxidizer leakage in Type I extrusion cases (9 of 23 cases or 39 percent), than in Type II (2 of 13 cases or 15 percent) or unknown type extrusion cases (1 of 13 cases or 8 percent) (Table 6, second row)

Because of the abbreviated nature of the comment field in the KSC R&R records and the lack of complementary information about the severity and duration of oxidizer leakage events, it is unknown if the incidence of oxidizer leakage reported in extrusion cases (52 percent) is significantly higher than the incidence of oxidizer leakage reported for active fuel valves (38 percent). Also, although there was a higher incidence of current oxidizer leakage in Type I extrusion cases, those valves did not fail with less accumulated firing service on average than the other Type I extrusion cases with previously noted incidences or no incidence of oxidizer leakage.

After the 1991 UTPA implementation, desiccant tubes were installed on thrusters with leaky oxidizer valves to prevent moisture intrusion and nitric acid generation. Thrusters with severe oxidizer leakage required more desiccant tube change-outs. Data were collected for the number of desiccant tube change-outs for all thrusters with fuel valves exhibiting extrusion detected through mid-1998. This encompassed 22 of the 23 Type I cases, all 12 of

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[1] Arrieta, S. Private communication. The Boeing Company, OMS/RSC Operations, Houston, Texas. April 2001.

[2] Valve replacement totals include only those valves that have known mission usage.

[3] Fuel valve R&Rs stemming from the STS-3 gypsum intrusion and STS-61C flow power-On anomalies not included.

the 13 Type II cases, and 4 of the 13 extrusion cases of unknown type. An oxidizer leakage—burns—onetime distribution (Figure 7) shows that oxidizer leakage was very pronounced for thrusters (left to right) P601, P223, P603, P332, P237, P317, and P571. Interestingly, only P223 was documented in R&R records as having been returned for repair due to oxidizer leakage [7]. The incidence of oxidizer valve leakage given in Table 6, therefore, could be underestimated.

Inspection of desiccant tube change-out data showed that as severity of leakage increased, there was numerical decrease in the number of years in service, number of burns, and cumulative ontime realized by affected thrusters (Table 7). However, even the best correlation, obtained by plotting the change-outs per day against the number of burns accumulated before fuel valve failure, was poor ($R^2 = 0.19$). This poor correlation, coupled with the large scatter in the data in Table 7, undercuts attempts to link extrusion with oxidizer leakage as measured by desiccant tube change-outs. There are other inconsistencies as well. First, no leakage (0 desiccant tube changeouts) was reported prior to the P325 failure during STS-68, which has been touted as a leading candidate for oxidizer-induced extrusion. Second, more leakage could entail a higher rate of thruster return and subsequent fuel valve R&R (Figure 3), thereby artificially lowering the number of years in service, number of burns, and cumulative ontime realized by a given thruster. Third, severe oxidizer leakage was observed for many thrusters that have yet to fail due to extrusion.

RP01 Ground Fire

On May 4, 1995, a fire erupted during the replacement of thruster P318[1] in position R1A on pod RP01 during the STS-69 flow at KSC. Four thrusters in close proximity to R1A later failed due to extrusion: 1) P219 in position R2U during STS-88 in December 1998 (Fail-Leak IFA); 2) P337 in position R2R after STS-80 in November 1996 (OMDP GN_2 response); 3) P476 in position R3R after STS-69 (oxidizer leakage); and 4) P628 in position R1U during STS-81 in January 1997 (Fail-Off IFA). The initial concern was that fire was a factor in these extrusion cases; however, the fuel valve on thruster P415 in position R3A (closest to R1A) passed response ATP shortly after the fire and is still active. Also, injector temperatures did not exceed 34 ºC (93 ºF) on any other thruster on RP01 at the time of or immediately after the fire.[2] In addition, inspection of the soot and burned areas after the fire showed that the fire burned upward and outward away from R1A. Together these observations indicate that the fire was localized to R1A and not a factor in later extrusion cases on the same pod.

Correlation with Vacuum Bakeout Histories

Potentially more problematic than heat soakback after thruster firing are vacuum bakeouts conducted during routine water-flushing and nonroutine valve R&R. During routine water flushing, thrusters are subjected to sequential 8-h and 1.5-h vacuum bakeouts.[3] During nonroutine valve R&R, an additional 8-h preburn bakeout is performed, followed by 8-h and 1.5-h postburn bakeouts.[4] Temperatures during bakeouts can range from 54 to 77 ºC (130 to 170 ºF) depending on the process. Thrusters also occasionally receive an epoxy coating, which is cured at 90 ± 5 ºC (194 ± 9 ºF) for 1 h. Bakeout and curing temperatures are of the same magnitude or greater than the maximum PRCS thruster operational temperature limit of 69 ºC (157 ºF) stipulated by flight rules.

By comparison, the older bakeout procedure performed by Marquardt entailed shorter times (3 h during initial decontamination and subsequent acceptance tests), and opening of the valve using a mechanical fixture to facilitate water removal [8]. There may be an added advantage to opening the valve during vacuum bakeouts. During vacuum bakeouts, the compressive force of the pilot poppet on the pilot seal is equal to the poppet spring force of 1.8 lb_f (2.6 MPa).[5] Valve opening during bakeout lessens the possibility that the compressive yield strength of the PTFE pilot seal could be exceeded (Figure 8).

To address concerns that vacuum bakeouts could be contributing to extrusion, WSTF vacuum bakeout histories were compiled (Table 8) using WSTF Chamber Lab Work Orders logged between January 1995 and

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[1] P318 was shipped from WSTF on 1/12/00 after being on site for 1685 days, and was undergoing metrology to ascertain degree of pilot seal extrusion at the time of this report.

[2] Kelly, T. Private communication. The Boeing Company, HSF&E Florida Operations, Kennedy Space Center, Florida. January 2002.

[3] In-house document. *PRCS Thruster Flush Procedure.,* WJI-PROP-CTF-0010.D, Issued Sept. 17, 1999, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico.

[4] In-house document. *WSTF PRCS Thruster Valve Overhaul and Repair – Valve Acceptance Test Procedure.,* WJI-PROP-CTF-0018.D, Issued Sept. 26, 1999, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico.

[5] During mission, the compressive force of the pilot poppet on the pilot seal is the sum of the poppet spring force plus the force due to nominal propellant pressure of 3.8 lb_f (5.6 MPa), giving a total force of 5.6 lb_f (8.3 MPa).

May 1997. For thrusters processed at WSTF before or after the 1995-1997 interval, bakeout times were assumed (8 + 1.5 = 9.5 h at 130 +20 –10 °F for thruster flushes; 8 + 1.5 +8 + 8 + 1.5 = 27 h at 130 +20 –10 °F for valve R&Rs).

Results show that the total bakeout time at temperature was actually greater for fuel valves exhibiting no extrusion (columns 2 and 3: 23.4-24.4 h) compared to valves exhibiting extrusion (columns 4 and 5: 18.5 –21.6 h). Also, when OEM valves alone were compared (columns 2 and 4), it was determined that thrusters had been returned to Marquardt at the same rate (2.0 returns per thruster), regardless of whether or not they later failed due to extrusion. Consequently, earlier bakeouts performed at Marquardt do not appear to be predominantly linked to later observations of extrusion. The possible linkage between extrusion and exposure to epoxy curing temperatures was still being evaluated at the time of this report.

Conclusions

The conclusions of this investigation are summarized as follows:

- The incidence of extrusion follows R&R frequency. For example, the recent drop-off in the number of extrusion cases could be due to fewer OMDPs and missions since 1998 compared to the period from 1995 to 1997.
- Extrusion may have contributed to at least some of the fuel valve failures before STS-68, especially in view of the fact that 92 percent (49 of 53) of all fuel valve failures since STS-68 are thought to be due to extrusion.
- Valve age and cumulative poppet loading at temperature may explain the occurrence of Type II extrusion (deeper poppet footprint), not lack of oxidizer leakage.
- Although correlations are weak, long burns appear to be a factor in fuel valve pilot seal extrusion.
- The preponderance of extrusion cases (73 percent) involving OEM valves suggests that extrusion occurs preferentially in valves near the end of their service lifetime.
- Extrusion does not appear to be linked with oxidizer valve failure.
- Oxidizer leakage has been documented in a significant number of fuel valve failures in which there is no known extrusion.
- Available desiccant tube changeout data provide the most compelling evidence that oxidizer leakage contributes to extrusion; however, correlations are still low.
- The poor correlations and large data scatter noted throughout this investigation suggest multiple factors contribute to extrusion.
- Vacuum bakeouts do not appear to contribute to a higher incidence of extrusion.

Recommendations

Several recommendations stem from this investigation:

- Determine if thruster valves exposed to epoxy-curing temperatures had an increased incidence of failure due to extrusion.
- Pay special attention to any 2001-2002 OV-103 OMDP response failures.
- Determine annualized failure rates of OEM versus non-OEM replacement parts. A better understanding of failure rates could lend insight into the possible detrimental and beneficial roles of UTPA and GN_2-purge implementation, respectively.
- Investigate fuel valves on an individual basis that failed prematurely with low accumulated ontime or number of burns.
- Review Marquardt or other archival documentation, especially Marquardt Failure Mode Reports (FMRs) issued during the 1980s and early 1990s, for evidence of earlier occurrences of extrusion.

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2. Wichmann, H. *TFE Seat Evolution Report.* ICS Report 90201. PO T-92270, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico, February 1999.

3. Ross, B., R. Lynch, and G. Pfeifer. *RA24(R) Failure Analysis Report, Primary Thruster S/N 325 Failed Off During STS-68.* WSTF-PT-FAR-003. NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico, September 29, 1995.

4. Litwinski, J., D. Sueme, and C. Wittman. *Failure Investigation of RCS Fuel Valve Extruded Teflon Seals.* M&P Engineering Report 5965-2007, Rockwell International Materials & Process Engineering Laboratories, Downey, California, April 1996.

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7. Kennedy Space Center. *RCS Primary Engine R&R History, July 1988 through December 2000.* Kennedy Space Center, Florida, 2000. URL: http://p51.ksc.nasa.gov/dept/oms/primary.htm.

8. Marquardt Test Specification 1323, *Acceptance Test Performance Reaction Control Subsystem Thruster.* Marquardt, Van Nuys, California, February 1978.

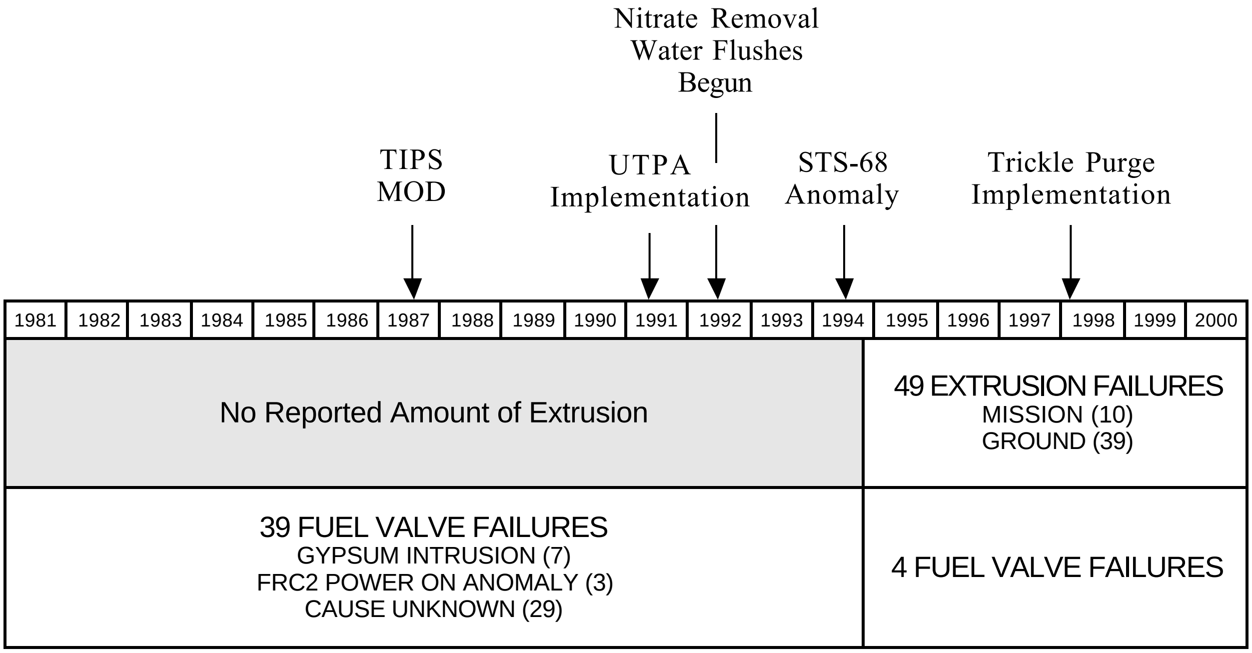

Figure 1
Chronological Distribution of PRCS Fuel Valve Failures, Including Extrusion
(numbers based on last mission service prior to failure)
(NOTE: TIPS = Thruster Instability Protection System)

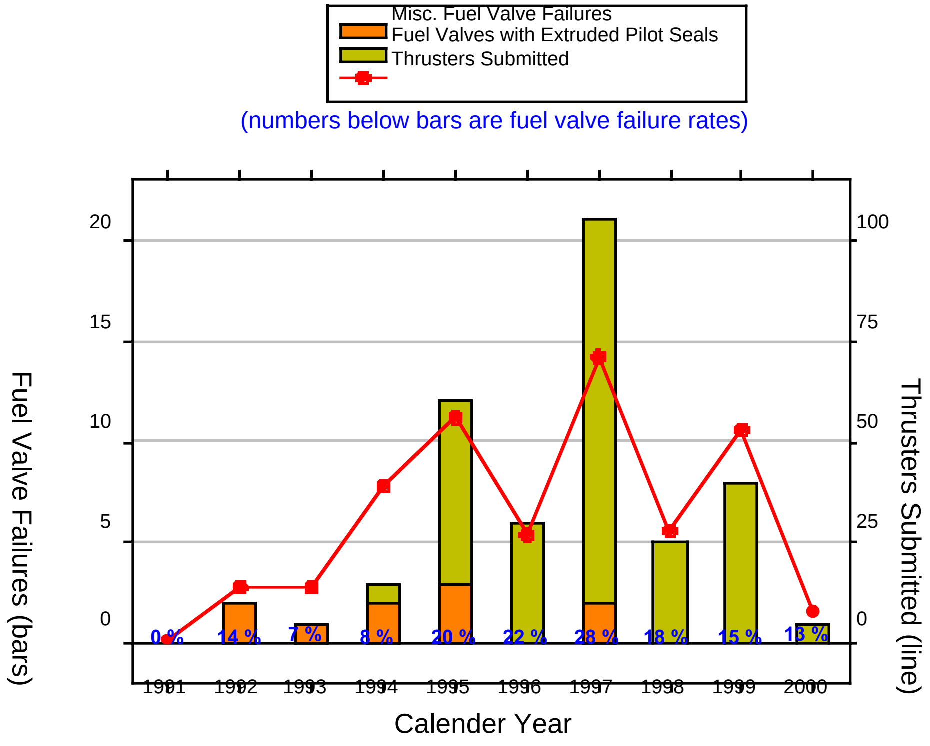

Figure 2
Incidence of PRCS Fuel Valve Pilot Seal Extrusion
(numbers based on dates corresponding thrusters were submitted to WSTF Depot)
(NOTE: OMDP flushes of ship sets occurred in 1995, 1996, 1997, and 1999)

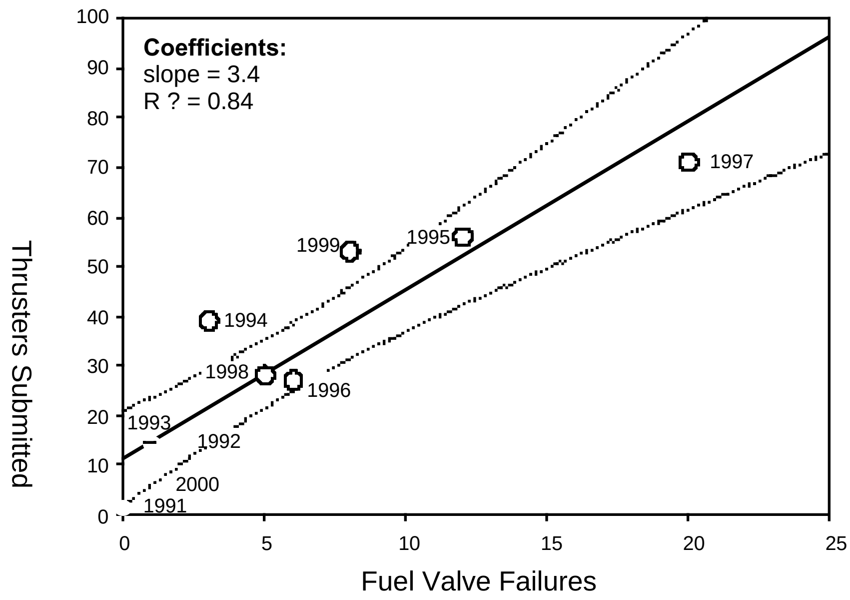

Figure 3
Correlation Between the Number of PRCS Fuel Valve Failures
and the Number of Thrusters Submitted to WSTF Depot
(49 of 58, or 84 percent of failures, were due to pilot seal extrusion)
(95 percent confidence interval given by dotted lines)

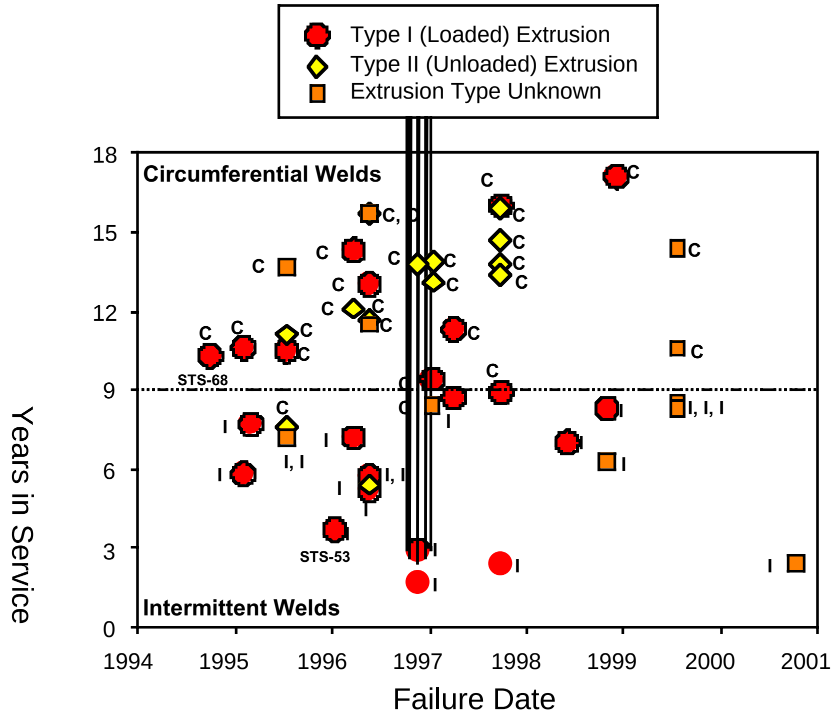

Figure 4
Distribution of Extrusion Type and Retainer Geometry
(NOTES: C = circumferentially welded (old design); I = intermittently welded (new design);
failure date based on last mission service)

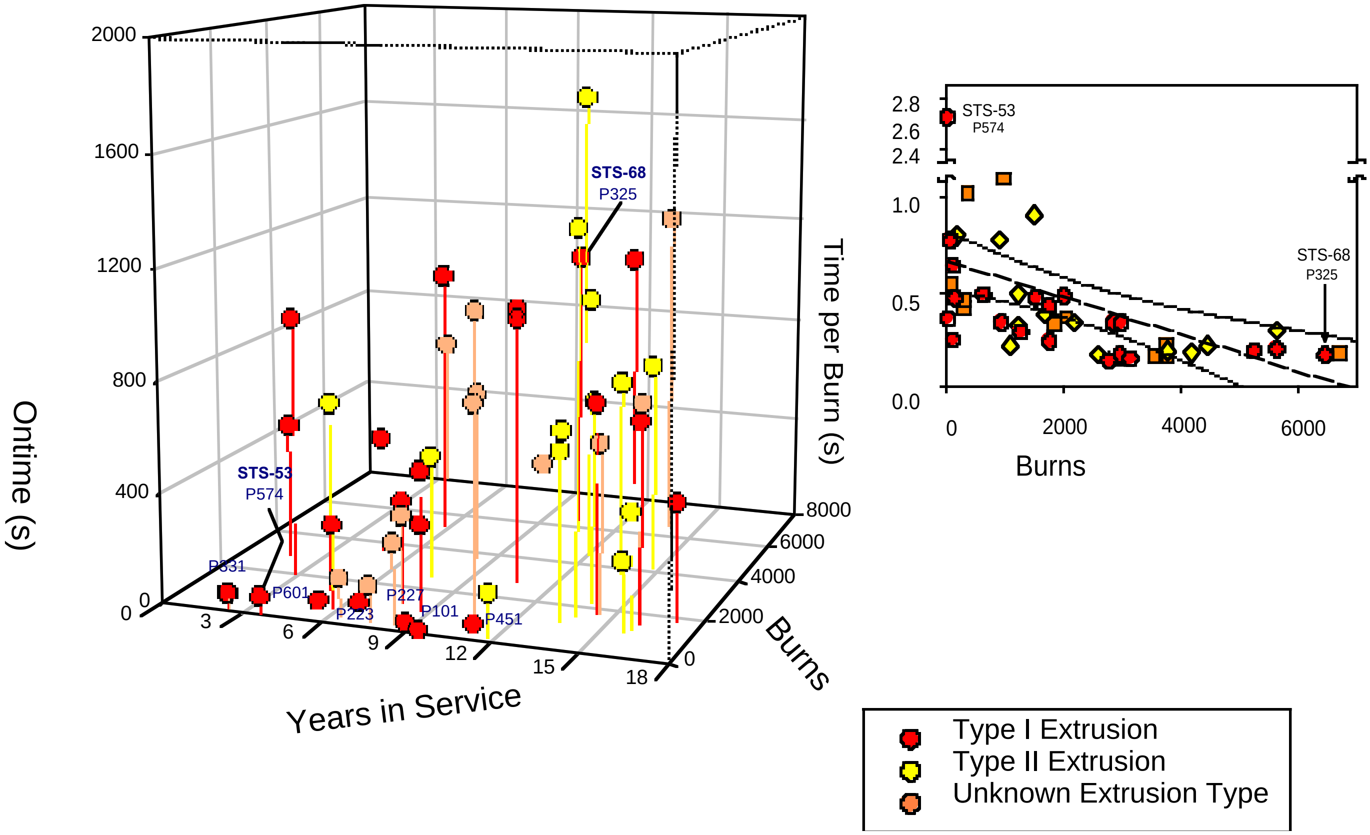

Figure 5
Distribution of Extrusion Type with Selected Service History Parameters (left), and Drop in Burn Time with Number of Burns for PRCS Fuel Valves with Extruded Pilot Seals (inset)
(95 percent confidence interval given by dotted lines in inset)

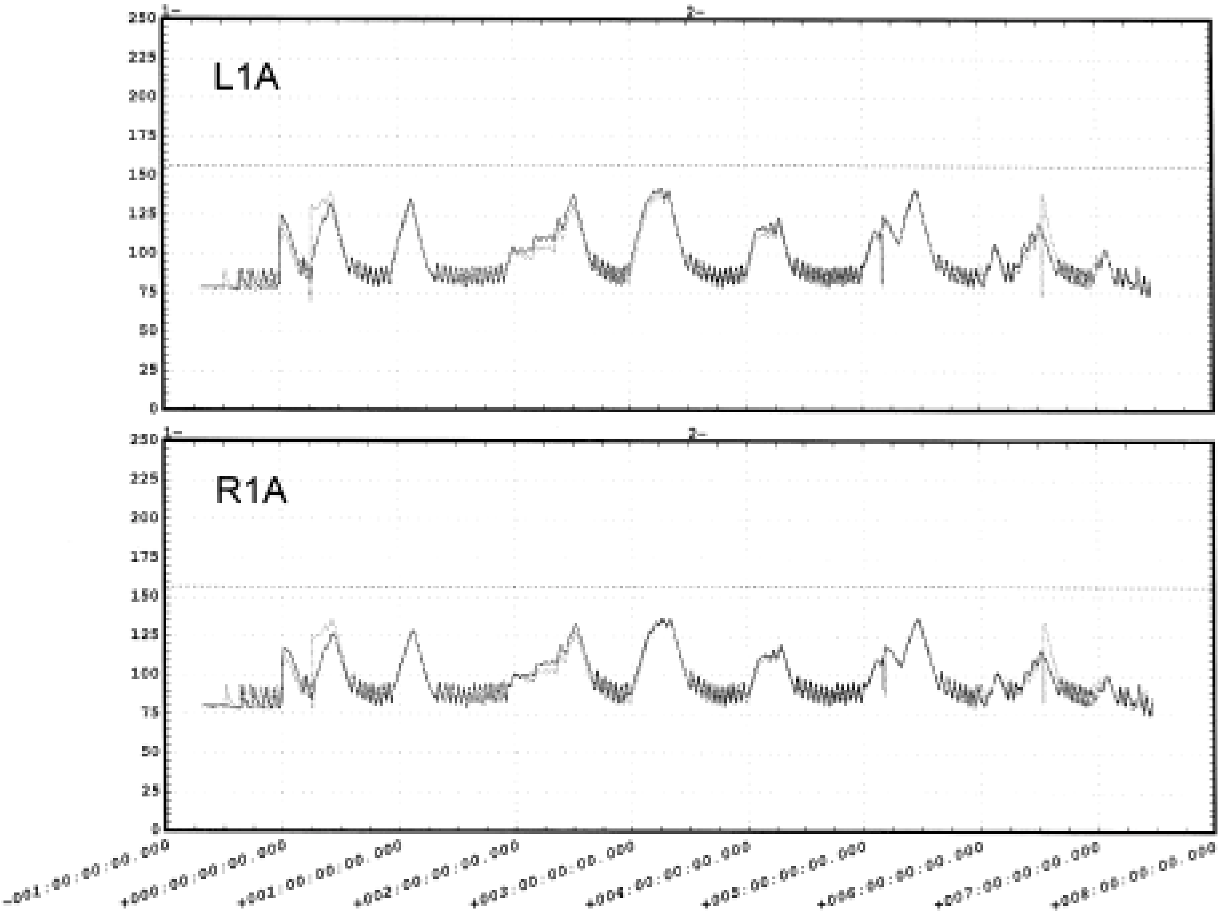

Figure 6

Left aft L1A (top) attitude heating during STS-53 for primary thruster S/N 574
five missions before STS-72 thruster failure due to fuel valve pilot seal extrusion.
Right aft R1A (bottom) heatings during STS-53 are shown for comparison.
(NOTE: Temperatures (ordinate) are in Fahrenheit, and were measured by thermocouples located at fuel and oxidizer stand-offs. Ox temp typically lower. Time stamps along abscissa are in day increments.)

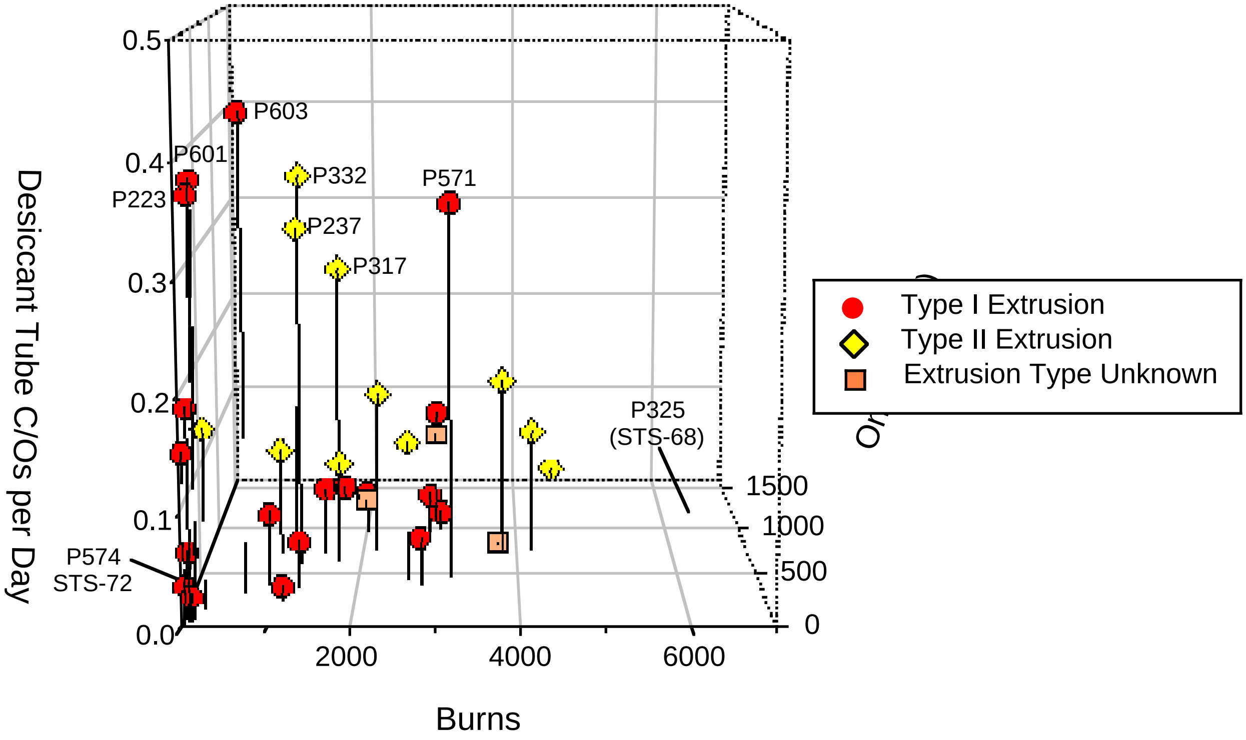

Figure 7

Oxidizer Leakage–Burns–Onetime Distribution Oxidizer leakage
was measured by the number of desiccant tube changeouts during the Shuttle flow prior to failure.

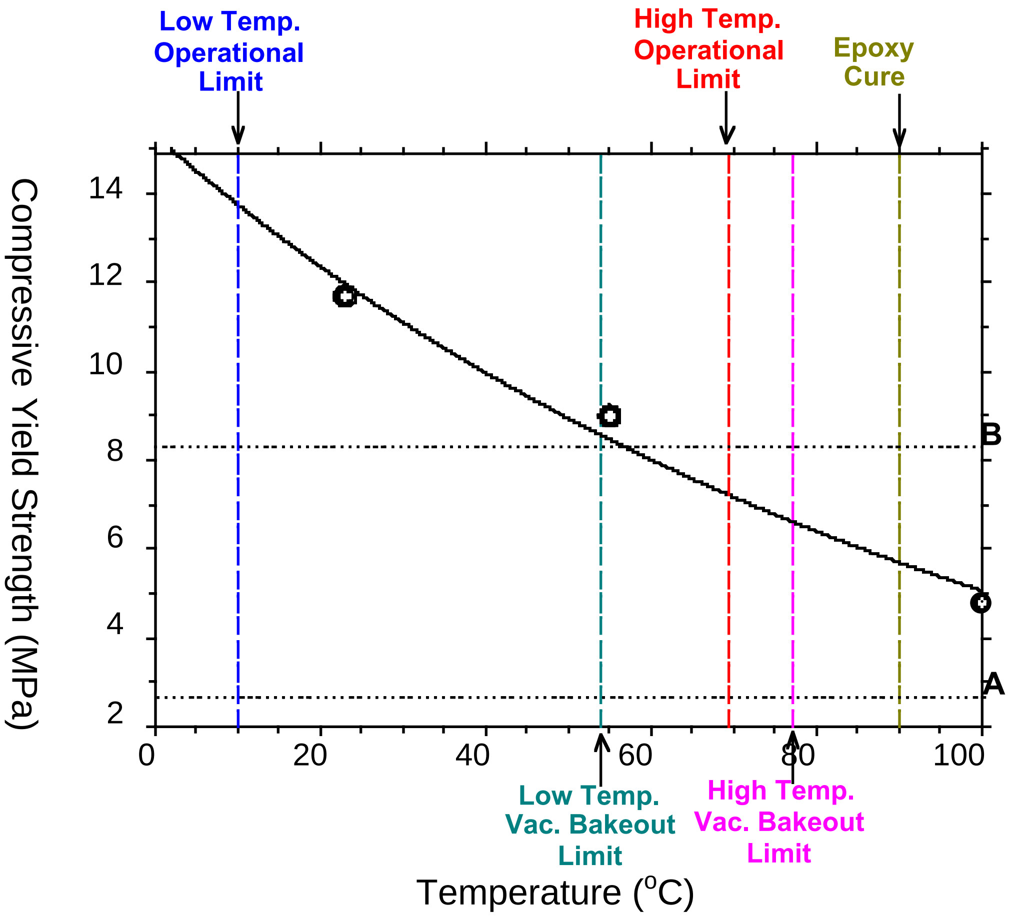

Figure 8
Drop in Compressive Yield Strength[1] of PTFE with
Respect to Operational and Ground Temperature Limits
(NOTE: Line A denotes compressive load of the pilot poppet distributed over pilot poppet/pilot seal contact area during vacuum bakeouts and epoxy cures (propellant absent). Line B denotes compressive load of the pilot poppet distributed over pilot poppet/pilot seal contact area during mission operation (propellant present).)

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[1] Black solid line, adopted from McCane, D. I., *Encyclopedia of Polymer Science and Technology,* Wiley, New York, Vol. 13, 623 (1970).

Table 1

Known and Suspected Extrusion Cases through 2000

Case No.	Thruster S/N	Fuel Valve S/N	Last STS	Mission Date	Years in Service.	No. of Burns	Ontime (s)	Time per Burn (s)	Last Firing Position	Proud Height (in.)	Extrusion Type	Basis for Extrusion	Weld Type	Why Pulled
1	101	254	81	Jan-97	9.4	36	13	0.36	F3F	0.0093	Type I	water Mo, Met	C	IFA-Fail Off
2	217	508	86	Sep-97	16.0	1,532	720	0.47	R1A	0.0081	Type I	Water Mo, Met	C	OV 104 OMDP
3	219	525	88	Dec-98	17.1	1,772	432	0.24	R2D	0.0035	Type I	GN2 Mo & Mc, Met	C	IFA-Fail Leak
4	223	548	76	Mar-96	7.2	128	82	0.64	R4D	0.0047	Type I	GN2 & water Mo, PLT, Met	I	PM
5	227	681	86	Sep-97	8.9	114	29	0.25	L4U	0.0084	Type I	GN2 Mo, PLT, Met	C	OV 104 OMDP
6	228	724	95	Oct-98	8.3	9,221	1432	0.16	R4D	0.0078	Type I	GN2 Mo, Met	I	PM
7	234	528	76	Mar-96	14.3	1,772	754	0.43	R4R	0.0060[a]	Type I	Water Mo, PLT	C	IFA-Fail Off
8	305	710	83	Apr-97	8.7	938	320	0.34	F3D	0.0045[a]	Type I	GN2 Mo, PLT	I	PM – Ox Leak
9	325	530	68	Sep-94	10.3	6,471	1,068	0.17	L3D	0.0100	Type I	GN2 Mo, Met	C	IFA-Fail Off
10	325	553	80	Nov-96	1.7	2,976	500	0.17	R1U	0.0041	Type I	GN2 Mo, Met	I	OV 105 OMDP
11	327	580	77	May-96	13.0	5,648	1,107	0.20	R3D	0.0076	Type I	Water Mo, Met	C	PM-Ground Leak (Ox)
12	331	544	63	Feb-95	10.6	2,856	979	0.34	L2L	0.0065	Type I	GN2 Mo, PLT, Met	C	PM-Ground Leak (Ox)
13	331	718	86	Sep-97	2.4	78	61	0.78	R2R	0.0035[a]	Type I	GN2 Mo, PLT	I	OV 104 OMDP
14	337	594	80	Nov-96	12.9	2,014	962	0.48	R2R	0.0057	Type I	GN2 & water Mo, PLT	C	OV 105 OMDP
15	432	622	70	Jul-95	10.5	2,994	1,011	0.34	L2L	0.0070	Type I	Water Mo, Met	C	OV 103 OMDP
16	451	672	83	Apr-97	11.3	70	54	0.77	F3F	0.0033	Type I	PLT, Met	C	IFA-Fail Off
17	476	703	67	Feb-95	7.7	1,278	375	0.29	R3R	0.0075	Type I	GN2 Mo, PLT, Met	I	IFA-Fail Leak
18	497	744	63	Feb-95	5.8	5,252	1,008	0.19	R1U	0.0055	Type I	Met	I	IFA – Fail Leak
19	571	893	77	May-96	5.2	3,147	477	0.15	F3U	0.0065	Type I	GN2 Mo, Met	I	OV 105 OMDP
20	574	895	72	Jan-96	3.7	26	69	2.65	L1A	0.0034	Type I	GN2, Mo, PLT, Met	I	IFA-Fail Off
21	601	806	77	May-96	5.7	145	68	0.47	F3F	0.0073	Type I	GN2 Mo, Met	I	OV 105 OMDP
22	603	803	77	May-96	5.7	637	310	0.49	F2F	0.0045[a]	Type I	GN2 Mo, PLT	I	OV 105 OMDP
23	628	832	91	Jun-98	7.0	2,780	387	0.14	R2U	0.0075	Type I	PLT, Met	I	IFA-Fail Off
24	108	679	70	Jul-95	7.6	2,614	456	0.17	F3U	0.0020	Type II	GN2 &water Mo, Met	C	OV 103 OMDP
25	125	604	76	Mar-96	12.1	4,476	993	0.22	L2D	0.0011	Type II	GN2 Mo, PLT, Met	C	PM
26	126	263	77	May-96	15.7	1,109	249	0.22	L2D	0.0017	Type II	GN2 & water Mo, Met	C	OV 105 OMDP
27	229	552	86	Sep-97	14.7	4,193	770	0.18	L1U	0.0000[a]	Type II	GN2 Mo, PLT	C	OV 104 OMDP
28	237	543	86	Sep-97	15.9	1,249	418	0.33	L4L	0.0000[a]	Type II	GN2 Mo, PLT	C	OV 104 OMDP
29	317	584	86	Sep-97	13.8	1,515	1,373	0.91	R3A	0.0025[a]	Type II	GN2 Mo, PLT	C	OV 104 OMDP
30	332	569	86	Sep-97	13.4	1,230	608	0.49	R1R	0.0000[a]	Type II	GN2 Mc, PLT	C	OV 104 OMDP
31	335	575	70	Jul-95	11.1	5,659	1,719	0.30	R3R	0.0000[a]	Type II	GN2 Mo, PLT	C	OV 103 OMDP
32	411	637	81	Jan-97	13.9	2,181	736	0.34	F3L	0.0017	Type II	GN2 & water Mo, Met	C	PM
33	421	582	80	Nov-96	13.8	3,791	725	0.19	R4D	0.0012	Type II	GN2 Mo, Met	C	OV 105 OMDP
34	422	586	77	May-96	11.7	205	163	0.80	L4D	0.0000[a]	Type II	PLT	C	OV 105 OMDP
35	437	600	81	Jan-97	13.1	1,702	655	0.38	R4R	0.0000[a]	Type II	GN2 Mo, PLT	C	PM
36	616	823	77	May-96	5.4	929	728	0.78	R3A	0.0015[a]	Type II	PLT	I	IFA-Heater Fail Off
37	133	255	77	May-96	15.7	2,044	754	0.37	L3L	ND	Unknown	GN2 Mo	I	OV 105 OMDP
38	220	516	70	Jul-95	13.7	6,720	1,229	0.18	R3D	ND	Unknown	GN2 Mo	C	OV 103 OMDP
39	330	714	70	Jul-95	7.2	3,752	818	0.22	R1U	ND	Unknown	GN2 Mo	I	OV 103 OMDP
40	332	714	92	Oct-00	2.4	105	58	0.55	R2R	ND	Unknown	GN2 Mo, PLT	I	PM
41	427	630	93	Jul-99	14.4	1,839	610	0.33	L4U	ND	Unknown	GN2 Mo	C	OV 102 OMDP
42	428	711	70	Jul-95	7.4	311	130	0.42	R2D	ND	Unknown	Water Mo	I	OV 103 OMDP
43	430	588	77	May-96	11.5	2,979	443	0.15	L3D	ND	Unknown	GN2 & water Mo	C	OV 105 OMDP
44	463	646	93	Jul-99	10.6	989	1,089	1.10	F4R	ND	Unknown	GN2 Mo	C	OV 102 OMDP
45	488	208	81	Jan-97	8.4	3,557	617	0.17	F3U	ND	Unknown	Water Mo	C	PM
46	498	762	95	Oct-98	6.3	309	141	0.46	L3L	ND	Unknown	GN2 Mo	I	IFA-Fail Off
47	615	814	93	Jul-99	8.5	378	385	1.02	R1A	ND	Unknown	GN2 & water Mo	I	OV 102 OMDP
48	617	836	93	Jul-99	8.3	257	291	1.13	L1A	ND	Unknown	GN2 & water Mo	I	OV 102 OMDP
49	627	831	93	Jul-99	8.3	3,785	636	0.17	L2D	ND	Unknown	GN2 & water Mo	I	OV 102 OMDP

[a] Proud height (height of PTFE seal inner diameter above downstream metal) inferred from pilot poppet versus armature travel

Abbreviations used: S/N=serial number, STS=Space Transportation System Flight, ND=not determined, GN2=gaseous nitrogen, Met.=Metrology, Mo=main valve opening time, Mc=main valve closing time, PLT=poppet lift test, C=circumferential, I=intermittent, IFA=in-flight anomaly, OV=Orbiter Vehicle, OMDP=Orbiter Maintenance Down Period, PM=preventative maintenance flush, KSC=Kennedy Space Center, Ox=oxidizer (N_2O_4)

Table 2

PRCS Thruster Fuel Valve Failure Distribution from 1981 through 2000[a]

Year	Number Of Flights	Flight/Ground/OMDP Extrusion Failures	Total Extrusion Failures	Total Fuel Valve Failures	Number of Thrusters Submitted	Ship Set OMDP
1981-1990	38	--	--	34[b]	–	–
1991	6	–	--	0	1	0
1992	8	–	--	2	14	0
1993	7	–	--	1	14	0
1994	7	1 / 0 / 0	1	3[c]	39	0
1995	7	2 / 1 / 6	9	12	56	1
1996	7	2 / 3 / 1	6	6	27	1
1997	8	3 / 4 / 12	19	20	71	1
1998	5	1 / 0 / 4	5	5	28	0
1999	3	2 / 1 / 5	8	8	53	1
2000	5	0 / 1 / 0	1	1	8	0
10-yr Totals	63	11 / 10 / 28	49	58	311	4

[a] Numbers based on date thruster submitted to WSTF Depot

[b] Includes gypsum intrusion (STS-3) and FRC2 Power-On anomaly (STS-61C flow) failures

[c] Consists of STS-68 extrusion failure plus two other fuel valve failures that occurred before STS-68

NOTE: -- = no data available or data not applicable

Table 3

Firing History Data Status through June 2001 STS-105

Data Status	STS Flights (chronological order)	Number of Flights
Final data	26, 34, 36, 39, 53, 55, 51, 60	8
Raw data	6, 7, 8, 41A, 41C, 41D, 41G, 51A, 51C, 51D, 51B, 51G, 51F, 51I, 51J, 61A, 61B, 61C, 29, 30, 33, 32, 31, 41, 38, 35, 37, 40, 43, 48, 44, 42, 45, 49, 50, 46, 47, 52, 54, 56, 57, 61, 62, 59, 65, 64, 68, 66, 63, 67, 71, 74, 76, 77, 78, 79, 80, 81, 82, 83, 84, 94, 85, 86, 87, 89, 89, 90, 91, 95, 88, 96, 93, 103, 101, 106, 92, 98, 102, 105	80
Gaps in data	1, 2, 3, 4, 5, 41B, 27, 28, 58, 70, 69, 73, 72, 75	14
No data (being processed)	99, 97, 100	3

Table 4

Service Histories of OEM Fuel Valves[a]

Service History Parameter	OEM Fuel Valves Still in Use	OEM Fuel Valves w/ Extruded Seal	Other Fuel Valves w/ Extruded Seal	All Fuel Valves w/ Extruded Seal
Number of cases	120	36	13	49
Years in service	12.2 (5.1)	11.0 (3.8)	7.2 (3.2)	10.0 (4.0)
Number of burns	1668 (1994)	2334 (1873)	1980 (2675)	2240 (2091)
Cumulative ontime (s)	497 (414)	640 (387)	460 (477)	592 (415)

[a] The number in each parenthesis is the standard deviation

Table 5

Relative Incidence of Fuel and Oxidizer Valve R&Rs through 2000

Type of R&R	Type I Extrusion	Type II Extrusion	Extrusion Type Unknown	All Extrusion Cases	Other Fuel Valve Failures Pre-STS-68	Other Fuel Valve Failures Post-STS-68	All Other Fuel Valve Failures
Simultaneous Fu & Ox valve R&R	11	8	10	29	27	4	31
Fu valve R&R	12	5	3	20	12	0	12
Total Fu valve R&Rs	23	13	13	49	39	4	43
Other Ox valve R&Rs[a]	7	7	3	17	2	2	4
Total Ox valve R&Rs	18	15	13	46	19	6	25
Percentage of Fu valve R&Rs requiring simultaneous Ox valve R&R	48 (11 of 23)	62 (8 of 13)	77 (10 of 13)	59 (29 of 49)	69 (27 of 39)	100 (4 of 4)	72 (31 of 43)
Ox valve/Fu valve R&R ratio	0.78 (18/23)	1.15 (15/13)	1.00 (13/13)	0.94 (46/49)	0.74 (29/39)	1.50 (6/4)	0.81 (35/43)

NOTES: R&R = Repair and replacement; Fu = fuel; Ox = oxidizer

[a] Other oxidizer valves replaced on same thruster prior to fuel valve failure

Table 6

Incidence of Oxidizer Leakage during Fuel Valve R&R and Maintenance since STS-68[a]

Type of Valve R&R	Type I Extrusion	Type II Extrusion	Recent or Unknown Extrusion Type	All Extrusion Cases	Other Fu Valve Failures	Active Fu Valves
Total number of cases	23	13	13	49	4	130
Ox leakage during Fu valve R&R	9 (39)	2 (15)	1 (8)	12 (24)	2 (50)	····
Ox leakage during previous service	3 (13)	7 (54)	4 (31)	14 (28)	0 (0)	49 (38)
Total number of Ox valve leakage cases	12 (52)	9 (69)	5 (39)	26 (52)	2 (50)	49 (38)
No indication of Ox leakage	11 (48)	4 (31)	8 (61)	23 (48)	2 (50)	81 (62)

NOTES: R&R = Repair and replacement; Fu = fuel; Ox = oxidizer

Numbers in parentheses are percentages out of the total number of cases.

[a] Data valid for valves submitted for R&R after STS-68, but with a history of Ox leakage as early as July 1988.

[b] ···· denotes no fuel valve R&R (not applicable)

Table 7

Effect of Oxidizer Leakage during Last Shuttle Flow on Valve Longevity[a]

Service History Parameter	Valves with Most Leakage	Valves with Moderate Leakage	Valves with No or Negligible Leakage
Number of cases	7	23	8
Avg. Desiccant Tube Changeouts per Flow	28 (5)	7 (4)	< 1 (<1)
Years in service	9.6 (4.6)	10.2 (4.1)	11.3 (2.8)
Number of burns	1150 (1037)	1808 (1383)	4788 (1973)
Cumulative ontime (s)	477 (442)	506 (326)	1036 (411)

NOTE: The numbers in parentheses are standard deviations

[a] Data good for the 38 extrusion cases known as of June 1998.

Table 8

WSTF Vacuum Bakeout Histories of OEM Fuel Valves[a]

Service History Parameter	No Extrusion (Still in Use)		With Extrusion (Failed)	
	OEM Fuel Valves	Active Fuel Valves	OEM Fuel Valves	Other Fuel Valves
Number of cases	120	83	36	13
WSTF vacuum bakeout hours at 130 +20 –10 °F per thruster[b]	24.4 (15.4)	23.4 (11.2)	18.5 (11.1)	21.6 (10.3)
Total number of returns to Marquardt[c]	240	55	73	15
Average number of returns to Marquardt per thruster	2.0	0.7	2.0	1.2

NOTES: OEM = Original Equipment Manufacturer

[a] The number in each parenthesis is the standard deviation.

[b] Estimated total bakeout time per thruster at WSTF between 1991 and 2000.

[c] Total number of thruster returns to Marquardt between 1981 and 1993.