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Push It To the Limit… What are Chandra's limits?

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Abstract

After more than 25 years on orbit, the Chandra X-Ray Observatory continues to collect excellent science for the astrophysical community. Though the overall health of the Chandra vehicle remains excellent, operating the spacecraft in recent years has not been without difficulty. Chandra's Flight Operations Team (FOT) has had to develop and deploy operational and software-based workarounds to continue operating the mission within design requirements and limitations. Of most concern to Chandra are rising temperatures as the vehicle's thermal protection has deteriorated over 25 years on orbit. These rising temperatures have impacted various spacecraft subsystems in different ways and require operational changes to ensure spacecraft safety as well as quality science. Chandra's active propulsion system has been most affected by these rising temperatures and has already surpassed original mission design and qualification limits. Thermal model predictions show that the expected heating over the next 5+ years would push Chandra's propulsion subsystem into a potentially unsafe and mission-ending regime without mitigation.

Chandra was launched in 1999 with two propulsion systems in place. Firstly, Chandra's Integral Propulsion Subsystem (IPS) was used for launch and orbit insertion and has since been deactivated, and secondly, Chandra's Momentum Unloading Propulsion Subsystem (MUPS) is still in use today for momentum management. The MUPS consists of four banks of redundant thrusters providing 3-axis control of momentum. Two of these banks of redundant thrusters sit on the sun-facing side of the spacecraft and are often called the "hot side" thrusters. The other two banks of thrusters reside on the cooler side of the spacecraft and are under near constant heater control. As overall spacecraft heating continues, these "hot side" thrusters are rapidly approaching long standing maximum allowed thruster temperatures. Various failure modes exist in Chandra's MUPS thruster performance at these elevated temperatures ranging from a potential catastrophic thruster failure to benign unloading inefficiency. To avoid reaching these limits, Chandra continually maneuvers between different spacecraft sun-pitch angles keeping all subsystems within allowable constraints. The FOT developed thermal models for the two banks of hot side thrusters to help manage temperatures in a predictive manner during the mission's weekly schedule building. The FOT considers both thermal model error and thruster heat soakback from momentum unloading when planning near the maximum allowed temperatures. Additionally, the FOT developed multiple software patches to modify the original flight momentum unloading logic to block thrusters from use if they were predicted to be too hot for momentum unloading. Nevertheless, the continued heating of the MUPS thrusters has caused the need for more frequent maneuvering which increases risk and decreases science efficiency. After 25 years of operations, it was time to begin investigating longstanding thermal limits for these monopropellant thrusters to continue operating in the years to come.

The FOT, in coordination with Northrop Grumman factory support, conducted an extensive literature review of relevant hydrazine systems with the goal of determining if raising long standing design limits could be done safely and determining the source of those original limits. The team ultimately found that the original limits placed on the MUPS thrusters were too conservative and moderate relaxations in allowed temperatures could buy the Chandra mission years of relief in terms of science efficiency. This paper intends to discuss the history of the Chandra X-Ray Observatory's MUPS thrusters, the operational and software workarounds that have been deployed during the 25 years of operations, and the extensive literature review that ultimately led to establishment of higher thermal safety limits which will allow Chandra to continue to collect excellent science for years to come.

Acronyms/Abbreviations

ACA – Aspect Camera Assembly
ACIS – Advanced CCD Imaging Spectrometer
FOT – Flight Operations Team
HRC – High Resolution Camera
IPS – Integral Propulsion Subsystem
IRU – Inertial Reference Unit
LAE – Liquid Apogee Engines
MLI – Multi-layered Insulation
MUPS – Momentum Unloading Propulsion Subsystem
OBC – Onboard Computer
OR – Observation Request
PCM – Pressurant Control Module
RCS – Reaction Control System
USBM – United States Bureau of Mines

1. Introduction

The Chandra X-Ray Observatory, launched aboard the Space Shuttle Columbia on July 23, 1999 serves as a flagship mission as part of NASA’s Great Observatories program. Chandra observes high energy phenomena such as black holes, supernovae, and galaxy clusters, and has helped to shape our understanding of high energy systems. Named after astrophysicist Subrahmanyan Chandrasekhar, Chandra is used to detect X-rays helping to compliment observations from other missions made in infrared, radio, and the visible spectra.

The Chandra Observatory operates in a highly elliptical orbit passing in and out of the Van Allen radiation belts. Its two science instruments, the High-Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS), can only be utilized for collecting science data while outside of the radiation belts to avoid instrument damage. The spacecraft maintains attitude control via 6 reaction wheels and two redundant mechanical gyros contained within the Inertial Reference Unit (IRU) along with a star tracking camera called the Aspect Camera Assembly (ACA). Spacecraft momentum management is conducted via small monopropellant thrusters and careful attitude selection during its orbit’s perigee. In all modes of operation, the sun must be kept on the minus Z side of the spacecraft to avoid sunlight on the observatory’s highly polished mirrors that run down the spacecrafts telescope boresight as well as keep the sun on the two solar arrays for electrical power. The sunlit side of Chandra is often referred to as the “hot” side of the spacecraft as it is always being heated by the sun. (**see Fig 1**)

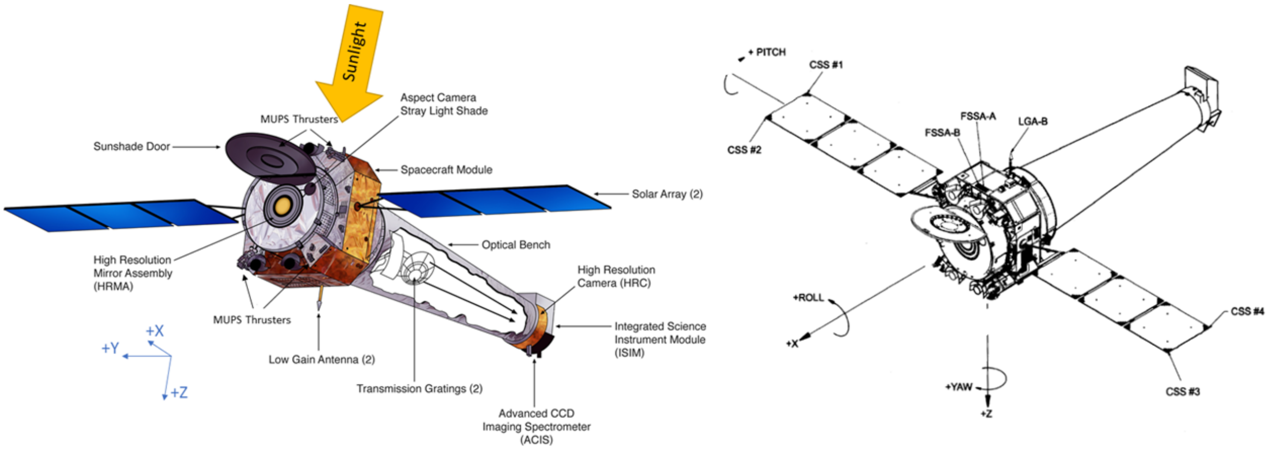

Fig 1: Chandra Coordinate Frame

Chandra’s Momentum Unloading Propulsion Subsystem (MUPS) consists of four banks of redundant monopropellant thrusters located on the exterior of the spacecraft bus, giving 3-axis momentum control. Being that the thrusters, valves, and some portions of propellant lines are on the exterior of the spacecraft, thermal management is critically important to both operation of the thrusters and safety of the spacecraft. Chandra MUPS was originally designed for operations between 40 and 240 degrees F, utilizing thermostats and patch heaters to keep the thrusters well above the freezing temperature of hydrazine (~35 deg F). Maximum temperatures were never a major concern as the original design life of Chandra was only 5 years and it was expected that the thermal protection covering the lines (silverized Teflon multi-layer insulation or MLI) would be sufficient to limit elevated MUPS temperatures. As the mission extended beyond 5 years and the MLI began to degrade, maximum MUPS temperatures began to increase during extended spacecraft dwells at attitudes that placed the MUPS thruster valves in direct sunlight (forward of 130 degrees sun-pitch). The Chandra Flight Operations Team (FOT) began to investigate the original design limits to determine if there was margin that could be reclaimed to allow for increased planning flexibility.

The Chandra FOT maintains several different “limit sets” for safe spacecraft operations. These limit sets include hardware thermal design limits, Caution and Warning limit sets used for telemetry monitoring and trending, and Mission Planning Guideline limit sets used to aid in safely planning observing schedules. The Caution and Warning limit sets are traditionally set conservatively to avoid violating hardware design limits, with the Mission Planning Guideline Limits being set even more conservatively to avoid inadvertent Caution/Warning violations due to thermal model error while the observing schedule is executing. For example, a MUPS thruster valve with a design limit of 240 degrees F might have its Caution and Warning High limits set at 220 and 230 degrees F respectively and a Mission

Planning Guideline limit of 210 degrees F. Setting limits more conservatively than their hardware design limits provides the FOT an opportunity to address a potential issue before it becomes untenable should one arise.

After 25 years on orbit, thermal management of many of Chandra's spacecraft components has become a priority when building observing schedules. The risk to certain spacecraft components varies from relatively low-impact science calibration issues, to extremely high-impact mission ending scenarios like critical electronic failures or explosive propulsion events. Chandra's maneuver profile often employs a "ping-pong" method of pitching between forward and tail sun attitudes to distribute heating across the -Z side of the spacecraft (**see Fig 2**). As the figure shows, there are critical components that will either heat or cool at any given sun-pitch angle. To date Chandra's FOT has been able to manage both thermal and momentum requirements by using science targets during the observing portion of the orbit and carefully selected attitudes or planned momentum unloads through the radiation zone while Chandra is not taking science. Chandra's orbit is divided into two periods, the observing portion when Chandra can safely collect science (around 80% of the orbit), and the radiation zone when Chandra passes through the Van Allen radiation belts where it is not safe to collect science data.

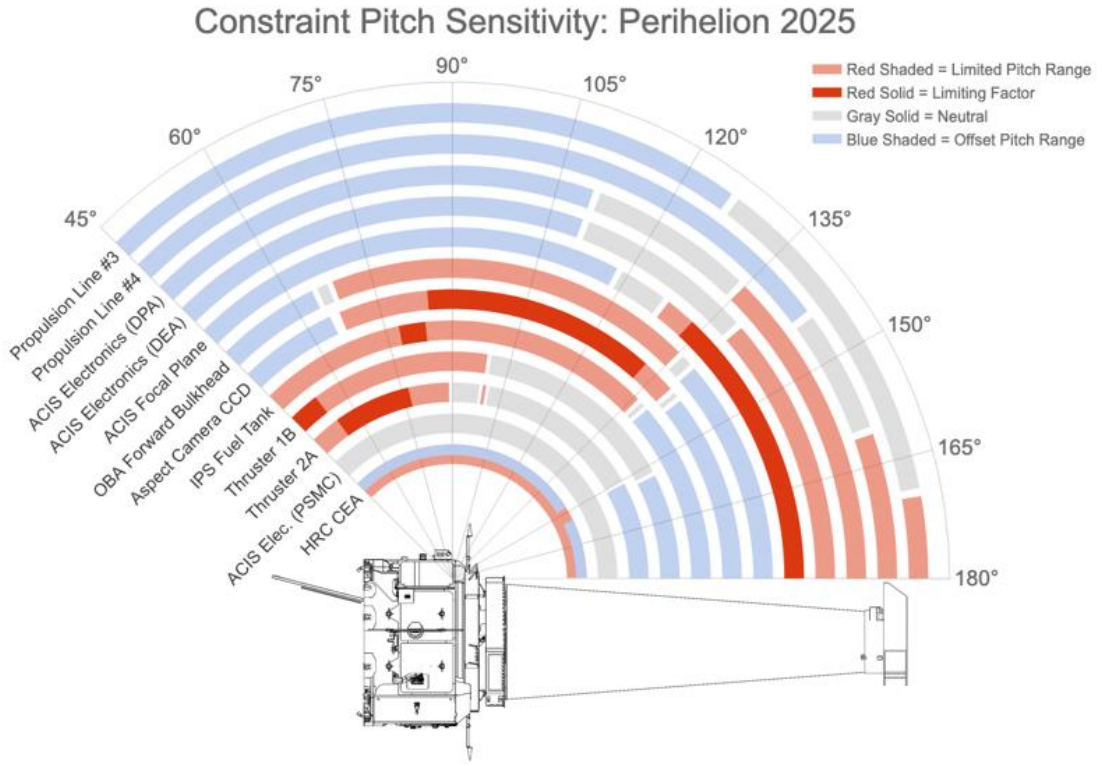

Fig 2: Chandra Sun-Pitch Sensitivity

Chandra's observing schedule is built on a weekly basis driven by Observation Requests (ORs) which have been binned for a specific time of year based on observation requirements and long-term thermal predictions. The Chandra FOT maintains complex thermal models for many spacecraft components that may reach, have reached, or have already surpassed original thermal design limits. These thermal models are incorporated into the FOT's mission planning tools to aid in designing an observing schedule that meets mission requirements. The FOT maintains a secondary set of limits referred to as the Mission Planning Guidelines that govern how the observing schedule can be executed. These guidelines contain thermal restrictions (via mission planning limits), momentum considerations, eclipse handling, and other observing requirements that must be met to safely operate the spacecraft. As the mission has evolved over 25 years the suite of mission planning guidelines has expanded making scheduling more difficult. Despite this, there has yet to be a need to employ "idle" time for thermal management during the science portion of the orbit. Unfortunately, as Chandra continues to age, thermal predictions show that the necessity for idle time will increase. There is no portion of the observable sky that Chandra can take science indefinitely due to spacecraft heating. Fortunately, Chandra can sit at sun pitch angles above ~155 degrees for extended periods of time while not taking science.

2. Thermal Consideration for Chandra MUPS

For the first 24 years of Chandra’s mission, MUPS was operated under the philosophy of keeping the thruster valve temperatures between 40 and 240 degrees F at all times with the understanding that violating these constraints could lead to a mission ending scenario. Momentum unloads were nominally scheduled in the weekly loads at times that were convenient to avoid science and spacecraft maneuver interactions. Chandra has a software capability to autonomously command a momentum unload (an auto-unload) if there are elevated momentum levels. Still, it is generally preferable to manage momentum unloading via mission loads. Early in the mission, this was of little difficulty as the MUPS thrusters were almost always under heater control. As the mission progressed beyond the initial 5 years however, the FOT had to begin managing MUPS differently for an extended mission. The FOT initially incorporated ground system tools to better predict the thermal profile of propulsion related hardware (mainly propulsion lines and MUPS thruster valves) as well as to deploy Mission Planning guidelines that governed both when the thrusters could be used for momentum unloading and how cold certain propulsion line segments were allowed to get.

In 2002, Chandra MUPS experienced a phenomenon called “Thermal Choking” during momentum unloading. Thermal choking occurs when heat from the thruster catalyst bed soaks back into the narrow fuel feed tube and causes the hydrazine to boil before reaching the catalyst chamber. This results in a drop in produced thrust during momentum unloading leading to longer unload durations. Although thermal choking is not an immediate safety concern it is a scenario that should be avoided if possible. Analysis of the conditions surrounding this phenomenon showed that when longer momentum unloads were scheduled (greater than 181 seconds) at elevated MUPS thruster valve temperatures (greater than 170 degrees F) it would be possible to enter a thermally choked regime. To avoid thermal choking the FOT modified the MUPS firing parameters and implemented both temperature and duration limits via Mission Planning Guidelines that governed when momentum unloads could be scheduled. Additionally, to avoid thermal choking during an autonomous momentum unload, the FOT implemented a software update that would halt momentum unloading after 400 seconds of execution. This capability is called the “Momentum Unload Cutoff Monitor” and is nominally executing in all spacecraft modes in which the On-Board Computer (OBC) is providing attitude control.

In 2006, due to concerns with a few cold segments of propulsion line, the FOT created a software patch (“The Prop Temp Monitor”) to monitor several thermistors for temperatures below 40 degrees F. In the event these thermistors fell below this threshold for an extended time the spacecraft would transition to a safing configuration known as “Normal Sun Mode” where the spacecraft body orients its minus Z axis to point to the sun (i.e., 90 degrees sun-pitch) to ensure sunlight on the solar arrays as well as warm the regions of propulsion line that were becoming too cold. A normal-sun attitude early in the mission was not a problem for the MUPS thrusters and would warm the lines and valves well above a point where there would be a risk of freezing hydrazine.

As the mission aged over the next 15 years, Chandra MUPS underwent many modifications to continue operating the mission and provide momentum unloading capability. The FOT had to develop software workarounds to deal with one failed thruster, one thruster with limited remaining life, a failed pressure transducer on the MUPS fuel tank, failing thermistors across the propulsion system, increasing temperatures for the entire propulsion system, and concerns with the number of momentum unloads being used to conserve life for expected high momentum swings during low-altitude perigees in the years 2022 through 2024. All of these modifications were completed assuming the highest allowed operating temperature for the Chandra MUPS thruster valves was 240 degrees F.

In October 2019, due to rising temperatures and the predicted maximum temperatures that the MUPS valves could reach, the FOT had to begin limiting spacecraft dwell capabilities based on thermal modeling with a new Mission Planning Guideline. This would be the first time the rising temperatures on MUPS began to affect Chandra’s observing capability. The initial guideline limited maximum MUPS valve temperatures for the “hot side” thrusters to 210 degrees F. This limit assumed up to 15 degrees F of thermal model error as well as the potential for 15 degrees F of thermal soakback from momentum unloading. During momentum unloading, heat soaks from the catalyst chamber upstream to the thruster valve and can cause over a 15 degree F increase in the valve temperatures. Limiting the MUPS valves to predicted temperatures in the mission loads to 210 degrees F helped to provide a conservative approach to avoid surpassing 240 degrees F. Initially this guideline was not overly restricting but it was predicted that by 2024 a limit of 210 degrees F on the MUPS valves would lead to the need for excessive science idle time to provide cooling for the thrusters.

Due to the rising temperatures for the MUPS valves and the potential need for excessive science idle time to provide much needed cooling, the FOT began investigating potential changes to nearly 24 years of MUPS operational philosophy. In 2024, spacecraft sun-pitch angles forward of 105 degrees were considered thermally hot for the MUPS valves and led to rapid heating of the valves necessitating the need for short dwell times and additional maneuvers to balance the temperature swings. Spacecraft pitch angles between 105 and 150 would not necessarily cool the valves which allow the temperatures to remain at elevated levels. Only sun-pitches above 170 degrees can reliably cool the MUPS valves fast enough to be suitable for momentum unloading. (**see Fig 2**)

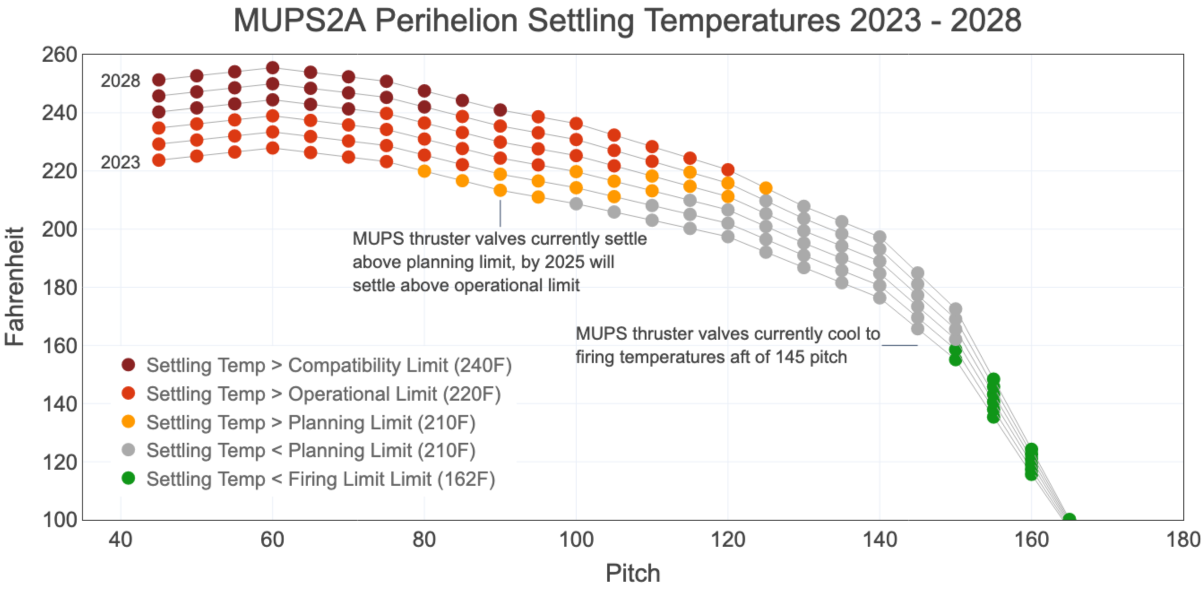

Fig 3: Chandra MUPS Settling Temperature Predictions (as of March 2024)

MUPS thermal predictions for the years 2025 and beyond (**see Fig 3**) presented several major concerns that would need to be addressed to continue operations at useful science efficiency levels. By 2028 the MUPS valves temperatures would settle above 240 degrees F at spacecraft pitch angles below 90 degrees (this was the default safing attitude for several contingency modes).

2.1 Long Term Maximum Settling temperatures at present safing attitudes

When mission loads are running and Chandra is following a planned maneuver profile, the MUPS valve temperatures can be closely predicted. This mitigates the risk of elevated MUPS temperatures while a mission schedule is running. The immediate concern was that Chandra's two main contingency modes, Normal Sun Mode and Safe Sun Mode, result in a 90 degree sun-pitch attitude that is extremely hot for the MUPS valves. As previously mentioned, thermal predictions showed that by 2028 the MUPS valves would settle above 240 degrees F at these attitudes necessitating a modification to default safing configurations. The FOT developed and uplinked multiple software patches to orient the spacecraft at a much cooler 160 degree sun-pitch angle for all autonomous contingency responses to provide much needed cooling for the MUPS valves should a contingency mode be entered.

2.2 Increasingly Short Dwell Times due to Systemic Heating

The mission planning restrictions of limiting maximum MUPS valve temperatures to 210 degrees F were leading to shrinking dwell times over a large portion of the observable sky. Without increasing the limit of 210 degrees F it would be difficult to schedule the mission beyond 2027. Additionally, short dwell times result in more maneuvers which can add additional mission risk due to spacecraft gyro and star tracking issues leading to safing events. Thermal model improvement and flight software workarounds to remove the concern of thermal soakback would allow for increases of this mission planning limit up to 225 degrees F in the very near term. In early 2024, through software updates and thermal model improvements, the FOT was able to begin increasing allowed MUPS valve temperatures up to 220 degrees F with plans to continue increasing up to 225.

2.3 Reaching temperatures safe for planned momentum unloads

The current operations philosophy restricts momentum unloading to below 162 degrees F to prevent thermal choking of the MUPS thrusters. With increasing temperatures across the propulsion system it would be increasingly difficult to reach these temperatures although it should always be possible. There remains the potential to introduce some scheduling inefficiency to reach lower temperatures required for momentum unloading but this was of lower concern when compared to the previously mentioned risks.

2.4 Autonomous Unloads at Hot Temperatures

Lastly the FOT considered the risk of autonomous unloads at hot temperatures. Auto-unloading is a safing feature that allows Chandra to dump excessive momentum autonomously should system momentum violate a threshold. By the end of 2024 it would have been possible for a worst case auto-unload at 90 degrees sun-pitch to result in temperatures exceeding 240 degrees F when accounting for 20 degrees F of thermal soakback from the catalyst chamber to the valve. The FOT considered disabling auto-unloading in both Normal Sun and Safe Sun modes but due to previously mentioned software patches that moved the default safing sun-pitch angle to 160 degrees it was deemed unnecessary as the thrusters would cool in these contingency modes. These software patches were critical in mitigating the risk of exceeding 240 degrees F during an auto-unload.

2.5 MUPS Hardware Risks

Prior to the investigation into raising the MUPS Valve Warning High limit above 240 degrees F it was believed that elevated MUPS temperatures could lead to various undesirable scenarios including:

- Thermal choking during momentum unloading when valve temperatures exceed 162 degrees F
- Momentum Unloading when valve temperatures exceed 220 degrees F could lead to thermal soakback that would raise valve temperatures over 240 degrees F
- Valve temperatures above the design limit of 240 degrees F could lead to component failure when not unloading
- Momentum unloading above 240 degrees F could lead to component failure or explosive hazard
- Valve temperatures exceeding 300 degrees F could initiate runaway thermal decomposition of hydrazine vapor due to catalytic activity between hydrazine and components within the propulsion system

Being that several of the component failures could lead to mission-ending scenarios, the FOT identified the most at-risk propulsion components that are reaching elevated temperatures. These components included:

- The MUPS-1 and MUPS 2 Thruster Valves
- The Exposed Stainless Steel Fuel lines leading to the MUPS thruster valves
- The hot side (-Z side) LAE/RCS Thruster assemblies (while no longer in use, still contain trapped fuel)
- The Pressurant Control Module (PCM) mounted on the hot side of the spacecraft which includes many propulsion components including filters, check valves, pressure transducers and regulators

Fortunately, the mission planning guidelines placed on the MUPS valves effectively eliminates the concerns with all of these components, as the valves are the most conservative limiting factor.

2.6 Options to provide thermal relaxation

To continue operating at high science efficiency and avoid excessive idle time to cool the MUPS thrusters, the FOT began considering additional options that would allow operating closer to 240 degrees F. The FOT investigated the following options:

- Improve thermal modelling to reduce MUPS Valve model error which would allow building schedules that approach 240 degrees F
- Allow scheduling closer to 240 degrees F by preventing the possibility of thermal soakback from momentum unloading
- Passivate MUPS in a manner that would eliminate the risk of exceeding 240 degrees F
- Raising the Warning High limit above 240 degrees F and accept the risk of potential hardware failure

2.6.1 Improved Thermal Modelling

The Chandra FOT maintains predictive thermal modelling for the MUPS Thruster valves. These models are used when building mission schedules to predict thruster valve temperatures one week in advance. The FOT has fine tuned the thermal models to accurately predict the hottest temperatures within several degrees. These thermal models have an error of up to about 15 degrees F during rapid heating or cooling as Chandra maneuvers from one sun-pitch angle to another. The Chandra Thermal models go through routine updates and refits and this error of about 15 degrees has remained consistent since their inception. It was unlikely that thermal model improvements would lead to the required thermal relief. Due to this, the FOT would need to retain a 15 degree F backoff from 240 degree F to avoid model error being the cause of component failure.

2.6.2 Preventing thermal soakback from unloading

In addition to 15 degrees F of backoff from thermal model error, the FOT maintains an additional 15 degrees F to account for thermal soakback from momentum unloading. By preventing hot side thruster use at times when the thrusters were known to be hot, the FOT could remove the assumed 15 degrees F from thermal soakback from the Mission Planning Guideline limits. In the years 2022-2024, the FOT developed software patches that would allow hot side thruster use to be blocked based on thermal predictions. These patches were ultimately deployed and select MUPS thrusters are being blocked from use at known hot times. The only exception for this is in a potential mission-ending loss of attitude control scenario in Safe Mode when the thrusters are required for momentum control. The FOT agreed that in a critical fault scenario the MUPS thrusters should be utilized to maintain attitude control regardless of their temperature to avoid certain mission-ending scenarios. With these software patches in place, the FOT was able to remove the 15 degree F backoff that was built into the Mission Planning Guideline, reducing it from 30 to 15 degrees F. Following this update to the guideline the FOT began increasing the Mission Planning limit towards 225 degrees F in mid-2024 providing significant thermal relief to the observing schedule.

2.6.3 Passivating MUPS

The main concern with exceeding 240 degrees F is the potential for a catalytic reaction between hydrazine and the components used across the propulsion system. It would be possible to completely ignore the 240 degree F thruster valve limit if the MUPS valves were void of hydrazine. This could be achieved by venting MUPS by closing several fuel isolation valves and then firing the MUPS thrusters until all fuel was expelled downstream of those isolation valves. Although eliminating the MUPS Valve Planning Guideline would provide much in terms of dwell time capability at sun-pitch angles below 135 degrees, it would mean that momentum management would have to be completely attitude based. This could potentially lead to the need for idle time during the science orbit to balance momentum and eliminate any of the science gains from thermal relaxations. Passivating MUPS would also mean the MUPS thrusters would not be available during contingency scenarios placing Chandra at greater risk for a loss of attitude control. Repriming the system from a near-vacuum state would need to be analyzed for peak waterhammer pressures before considering opening the fuel isolation valves. Additionally, the passivation process itself would be operationally complex due to the boiling and freezing of hydrazine that can occur during the firing process with the upstream isolation valves closed. It would most likely require a series of unloads (possibly 10 or more), all with thermal and communication requirements separated by many hours. The FOT briefly investigated the potential of this and quickly ruled this out as a feasible option due to both complexity in passivating the system and potential long term mission risks.

2.6.4 Raising the MUPS Valve Warning High Limit Above 240 Degrees F

Due to the concerns identified previously, the FOT began considering whether it was possible to raise the MUPS Valve Warning High limit above 240 degrees F to provide much increased science observing time and additional life to the Chandra mission. The FOT formed a tiger team comprised of several members from the Chandra FOT, Northrop Grumman Propulsion Factory support personnel, and several NASA representatives, and began investigating the potential of allowing MUPS valve temperatures above 240 degrees F.

3. Investigation into Raising Allowed Temperatures

The investigation into raising the MUPS Thruster Valve limits initially had a multi-faceted approach. Very early on in the investigation the team discussed whether it would be possible to conduct ground testing using spare ground hardware to test thruster valve operation at temperatures above 240 degrees F. After analysing total cost, the potential time it would take to complete ground testing, and the difficulty in recreating a realistic scenario (Chandra has had nearly 25 years on orbit with hydrazine wetted valves) the team decided it would not be feasible to conduct such testing. As a result, the team would focus its investigation on hardware component capabilities and conduct and extensive literature review of similar hydrazine monopropellant systems.

The primary focus of the investigation was to identify the source of the 240 degree F maximum operating temperature limit as well as prove that it would be safe to operate above this limit. Hardware specifications and requirements for the MUPS Thruster Valves state that the valves are capable of operating between 40- and 240-degrees F with no indication as to where these limits came from. Initial qualification testing of the thruster valves only reached 164 degrees F including thermal soak back from the catalyst beds while firing. It was believed that the initial 40/240 degree F limits were based upon the freezing/boiling temperatures of hydrazine at atmospheric pressure which is well below the MUPS operating pressures. (~14.7 psi vs MUPS pressure of near 190 psi) Northrop Grumman has had a legacy of setting do not exceed temperature restrictions on its monopropellant hydrazine systems at 240 degrees F dating back to the 1960’s.[1]

Northrop Grumman Factory experts conducted an extensive literature review and identified seven key documents[1] with relevant information pertinent to the investigation. The review not only provided ample evidence that it would be safe to increase the limit above 240 degrees F, but also revealed the potential source of the 240 degree limit. Additionally, the investigation identified limits for several of the most limiting hardware component materials.

The investigation concluded that a 1949 United States Bureau of Mines (USBM) study that analyzed the explosive properties of hydrazine was used to establish conservative limits for early monopropellant systems. The study found that when hydrazine vapor reached 38% or higher by volume mixture with Nitrogen at a total pressure of 14.6 psia with temperatures between 228- and 234-degrees F that it would be detonatable via spark. The Chandra investigative team noted,

> “The 38% by volume hydrazine vapor concentration versus temperature threshold curve was in fact the basis for TRW (now Northrop Grumman) propulsion engineering establishing as far back in time as the late 1960’s that monopropellant hydrazine systems should never operate above 240 °F temperature . . . as per the referenced curve, 240 °F is conservatively (about 10 °F) below the threshold temperature associated with an absolute hydrazine pressure of about 50 psia, which is about the lowest operational pressure considered for earlier monopropellant hydrazine blowdown propulsion systems. Setting a not-to-exceed “stake in the ground” at the single empirically-based maximum operational temperature of 240 °F insured conservatism in operating temperature margin for all operating thruster feed pressures above 50 psia based on this extrapolated 38% hydrazine vapor concentration curve.” [1]

Gas bubbles that have evolved in the MUPS fuel lines contain 38% volume hydrazine vapor with 62% Nitrogen but at a much higher pressure of 190 psia. This data suggests that detonation on Chandra would not be expected below 338 degrees F at 190 psia as seen in **Fig 4**.

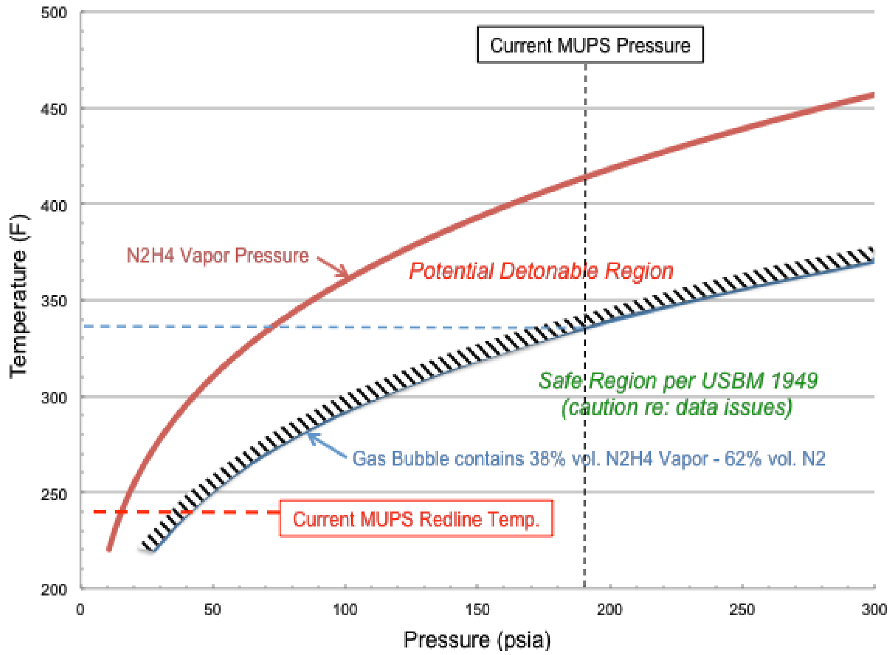

Fig 4: Hydrazine Potentially Detonable Region

As noted in **Fig 4**, the FOT needed to consider that "There is an absence of independent empirical data the either supports or refutes the validity of the above-cited extrapolations of the single, USBM empirically-established 38% vol. hydrazine-62% vol. nitrogen vapor concentration flammability/detonability threshold to higher pressures (i.e., greater than ~14.7 psia) and higher temperatures." [1]

The investigation also identified the most limiting hardware component that should be considered when raising the MUPS thruster valve maximum operating temperatures. An industry-standard rubber used in the propellant valve soft seat was found to have a maximum operating temperature of 314 degrees F. Other hardware components, such as several of the stainless-steel alloys, were found to have maximum operating temperatures much higher near 399 degrees F. With this information in hand the team was confident that there was ample margin to increase the MUPS Valve Limit above 240 degrees F and maintain mission safety.

4. Results of Literature Analysis

The key findings from the literature review concluded that:

- The lowest maximum temperature for materials of relevance to the Chandra MUPS Thruster valves is 314 degrees F for the valve soft seat seal with evidence of other thrusters with identical seals operating at temperatures greater than 350 degrees F
- Literature review revealed that Chandra's hydrazine compatibility is safe up to 338 degrees F
- Increasing the operating limits on the MUPS Thruster Valves up to 260 degrees F would retain a conservative margin of greater than 50 degrees from material capabilities while providing much needed thermal relief for planning the mission

5. Go forward plan for operations

The FOT concluded, in coordination with NG Factory support, that it would be safe to increase the MUPS Valve Warning High Limit from 240 to 260 degrees F and continue to operate the mission as it had been for most of the mission. The 260 degree F limit would strike a balance between providing mission scheduling relief as well as retain ample conservatism in material limits. Increasing the limit by only 20 degrees would set the clock back 4-5 years in terms of thermal dwell capability and effectively remove the MUPS Thruster Valves as a limiting constraint in the near term. The limit increase would also provide an effective solution for science operations in the years 2027 and beyond.

The FOT will continue to operate MUPS in a similar manner as it had over the previous 24 years of the mission with a few exceptions. The FOT would retain all restrictions on thermal requirements for scheduled momentum unloading but would allow MUPS thruster valve temperatures to increase over 240 degrees when not in use and accept the risk that an auto-unload could occur at elevated temperatures. The increase to 260 degrees F would mean that there will be long periods of time where the MUPS thruster valves will sit at elevated temperatures before cooling (Chandra maneuvers to a cooler thruster attitude).

This raised a minor concern of excess gas bubble formation in the valves. It has been known for much of the mission that decomposed hydrazine gas bubbles collect on the MUPS Valves inlet filter due to the large surface-to-area ratio of the filter screen. Though not a health and safety concern these bubbles cause unload inefficiency and are being tracked. It is believed that the bubble formation in the thruster valve is self-limiting in that once all hydrazine around the inlet filter has decomposed to gas the phenomenon halts. Since hydrazine gas bubble formation follows Arrhenius scaling (rate of decomposition doubles for every 10 degrees C) it was deemed necessary to consider the potential for runaway gas formation as more time is spent at elevated temperatures should it not be self-limiting. The FOT developed several methods for tracking gas bubble formation using the relationship between thruster efficiencies and time at temperature, and it continues to monitor gas bubble formation. Should the FOT find that bubble formation is not self-limiting, there may be a need to potentially require periodic momentum unloads to flush the thruster valves of gas bubbles.

The final go-forward plan for the Chandra MUPS Thrusters included increasing the MUPS Valve Warning limits from 240 to 260 degrees F, continuing to increase the MUPS Mission Planning guideline limit in 5 degree increments until no longer limiting for mission scheduling, retaining a backoff from 260 degrees F to account for thermal model error, and continue to track MUPS thruster bubble formation for changes and reconvene with NG factory support if required.

Additionally, the FOT would continue to investigate modifications to Safe Mode to delay Safe Mode momentum unloads as long as possible to facilitate cooler thruster valves.

6. Conclusions

For over 24 years Chandra MUPS was operated under original design assumptions. As Chandra aged and its thermal protection deteriorated, it became necessary to revisit these original assumptions and decide if continuing the mission with these restrictions was possible. When designing mission requirements, it is important to have a clear and thorough understanding of both operating and hardware limitations to not unnecessarily limit the scope of the mission. When possible, it would be beneficial to test hardware to failure limits and maintain accessible documentation as to where the source of these limits originated. When operating an extended mission like Chandra, over 5 times the original design life, the FOT may want to push it to the limits, and often wonder… what are the limits?

Acknowledgements

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