The ACIS Contamination and a Proposed Bakeout

CXC SOT & FOT, ACIS Instrument Team and MSFC Project Science

Contributors to the Bakeout Effort

The``ACIS Contamination Working Group'' has been studying the ACIS contamination issue for the last two years. This presentation is a summary of that work. Those contributing directly to this presentation:

CXC: P. Plucinsky, A. Vikhilin, H. Marshall, N. Schulz, R. Edgar, D. Schwartz, S. Wolk, H. Tananbaum, J. DePasquale, S. Virani, D. Dewey, L. David

MIT: M. Bautz, C. Grant, W. Mayer, R. Goeke, P. Ford, B. LaMarr, G Prigozhin, S. Kissel, E. Boughan

PSU: G. Garmire, L. Townsley, G. Chartas, D. Sanwal, M. Teter, G. Pavlov

MSFC: S. O'Dell, D. Swartz, M. Weisskopf, A. Tennant, R. Elsner

NGST: M. Mach, P. Knollenberg, D. Shropshire, L. McKendrick, R. Logan, R. Giordano, T. Trinh, K. Chen, K. Henderson, F. Cottrell, J. Lamb, D. McGregor, H. Tran, D. Lindemann, L. Harper, L. Ryan, A. Tao

LMA: N. Tice

McMaster University: A. Hitchcock

Many others have contributed directly or indirectly.

Brief Description of the Problem and Introduction

Problem: **A layer of contamination is building up on the ACIS Optical Blocking Filter (OBF).**

Impact: **The contamination layer reduces the transmission of X-ray photons through the OBF, thereby reducing the number of photons which reach the CCDs. This decreases the effective area of the *High-Resolution Mirror Assembly* (HRMA) and ACIS system. The ``effective area'' is defined as the combination of the collecting area of the HRMA, the transmission of the OBF, and the detection efficiency of the CCDs. The ``detection efficiency'' is defined as the probabilty of detecting a photon which strikes the detector.**

This effect is energy-dependent, affecting low energies most. The decreased sensitivity results in:

- **longer observing times to achieve the same science objective (~ 15%)**
- **loss of some science programs because they are no longer feasible (~15%)**

Comparison to Level 1 Requirements (Detection Efficiency)

- **Level 1 requirements on the ACIS instrument detection efficiency are greater than 5% between 0.4 – 0.7 keV, 20% between 0.7-1.0 keV, and 50% between 1.0-8.0 keV**
- **The decrease is due solely to the additional absorption of the contamination layer**
- **At the current rate of increase in the thickness of the contamination layer, the level 1 requirement will not be met at 0.4 keV around November 2005**

Bandpass	Level 1 Req.	Launch Value	6/2004 Value
0.4- 0.7 keV	> 5 %	>29%	>7%
0.7-1.0 keV	> 20%	>59%	>35%
1.0-8.0 keV	>50%	>50%	>50%

Comparison to Level 1 Requirements (Spectral Resolution)

- **Level 1 requirement for the ACIS instrument spectral resolution is a resolving power ($R = E/\Delta E$) larger than 7 at 0.5 keV and larger than 45 at 8.0 keV**
- **ACIS has not met this requirement since the radiation damage early in the mission**
- **Based on on-orbit and ground test experience, we expect some further degradation in the spectral resolution of the FI CCDs**

Energy	Level 1 Req.	Pre-Launch I3	I3 aim 2000	I3 aim 2004	S3 middle
0.5 keV	**71 eV**	**50 eV**	**100 eV**	**104 eV**	**100 eV**
8.0 keV	**178 eV**	**170 eV**	**370 eV**	**390 eV**	**175 eV**

Contamination, Bakeouts & CTI Increase

- **Contamination was expected on ACIS during the mission since ACIS contains the coldest surfaces internal to the spacecraft**

- **The pre-launch plan was to bake ACIS out at regular intervals to minimize the buildup of contamination**

- **There have been two ACIS bakeouts to room temperature in the mission, both early in 1999. The first bakeout was part of the ACIS door opening procedure. The CCDs were functioning nominnally before and after this bakeout.**

- **The CCDs suffered radiation damage from low-energy protons (~100 keV) in August and September 1999. Further damage has been minimized by moving ACIS out of the focus of the HRMA during radiation belt passages.**

- **The second room temperature bakeout was an attempt to ``anneal'' the CCDs (to reverse some of the effects of the radiation damage). Unfortunately, the CCD performance got worse after the second room temperature bakeout (CTI increased by 30%).**

- **This leads to the expectation of increased CTI for another bakeout.**

Mitigation Options

1) **Accept degradation, relax the level 1 requirements on detection efficiency**

2) **Bakeout to remove the contamination**

Proposed Bakeout Scenario

- **Heat the ACIS detector housing (DH) from -60 C to +20 C**
- **Heat the ACIS focal plane (FP) from -120 C to +20 C**
- **Heat the Science Instrument Module (SIM) surfaces surrounding the ACIS aperture from -10 C to +10 C**
- **Maintain the hot phase of the bakeout for ~ 1 orbit (150,000 s)**

Risks Associated with Bakeout

Definition: **Risk to the spacecraft or instrument health & safety, and/or to the science mission.**

1) **Thermal cycling results in a HW failure in the ACIS instrument**
2) **Damage to the OBF**
3) **CTI increases by a larger than anticipated amount**
4) **Unexpected change in contamination**
   - 4a) **contamination increases in thickness**
   - 4b) **contamination returns quickly**
   - 4c) **contamination migrates to another spacecraft system**
5) **Thermal cycling has a negative impact on the spacecraft**

Risk Assessment

RISK	MITIGATION	IMPACT	PROBABILITY
1. HW failure due to thermal cycling	Assessment by ACIS engineering team, HW design, previous bakeouts	Moderate Possible degradation	Very low
2. OBF Damage	Ground tests at NGST on spare flight OBFs	Moderate Loss of science	Very low
3. Larger than anticipated CTI increase	Ground irradiation tests on spare flight CCDs	Low Loss of science	Very low
4. Undesirable change in contamination	Simulations of bakeout, materials testing	Moderate Loss of science	Low
5. Thermal cycle has adverse effect on spacecraft	Assessment by Chandra FOT and NGST	Low Possible misalignment	Very low

Benefits of the Bakeout

- Restore the HRMA+ACIS effective area to close to launch values and restore the original margin against the level 1 requirements
- Provide an additional *2.8 Million seconds* of observing time per AO, which will be ~54 additional *Chandra* observations per AO
- Restore classes of targets with soft spectra which are not currently feasible (such as supersoft sources, neutrons stars with soft spectra)

Costs of the Bakeout

- The bakeout and calibration observations will take ~ 1 Million seconds. Given that the contaminant accumulation is slowing in time and we have gone 5 years without a bakeout, we expect that we would not desire another bakeout for at least another 5 years.

- The likely CTI increase of the FI CCDs will impact observations of extended objects on the I array through degraded spectral resolution

- The delay in some analyses until updated calibration products are available

Recommendation

- **The ACIS contamination working group has evaluated the risks of the proposed bakeout against the benefits and recommends to the *Chandra* project that a bakeout of the ACIS instrument is the appropriate response to the contamination buildup.**

- **The proposed bakeout should be done to ensure the maximum scientific return of the *Chandra* mission and before the ACIS detection efficiency drops below the level 1 requirements**

Outline of the Presentation

1. Impact of Contamination Layer on Science
2. Characterization of the Contaminant and Identification Attempts
3. Description of the ACIS HW
4. Thermal models of ACIS
5. Thermal models of the ISIM and plan for using the ISIM abort heaters (Dan Shropshire)
6. Simulations of the Bakeout (Steve O'Dell and Doug Swartz)
7. Operational plan of the bakeout
8. Risk Assessment (Mark Bautz and Dan Shropshire)
9. Post Bakeout Calibration Plan
10. Conclusions

1. Impact of Contamination Layer on Science Observations

- The contamination layer introduces additional absorption at low energies which reduces the combined effective area of the High-Resolution Mirror Assembly (HRMA) + ACIS system. ``Effective Area'' is the product of the collecting area of the HRMA, the transmission through the filter and the detection efficiency of the CCDs.
- This additional absorption depends strongly on energy, low energies are severely affected while high energies are unaffected.
- Exposure times are increased, on average, by ~15% to compensate for the contamination layer
- Some projects are not affected at all
- If the growth of the contamination layer is truly leveling off, the above statements will remain true. However, if the contamination layer continues to increase then more science projects will become infeasible and the adjustment to the exposure times will get larger.

Impact of Bakeout on Observing Configurations

- There are three main instrument configurations for ACIS:

1) ACIS-S with no grating, for narrow-field imaging on S3(BI)
2) ACIS-I with no grating, for wide-field imaging on the I array
3) ACIS-S with the gratings, for high resolution spectroscopy

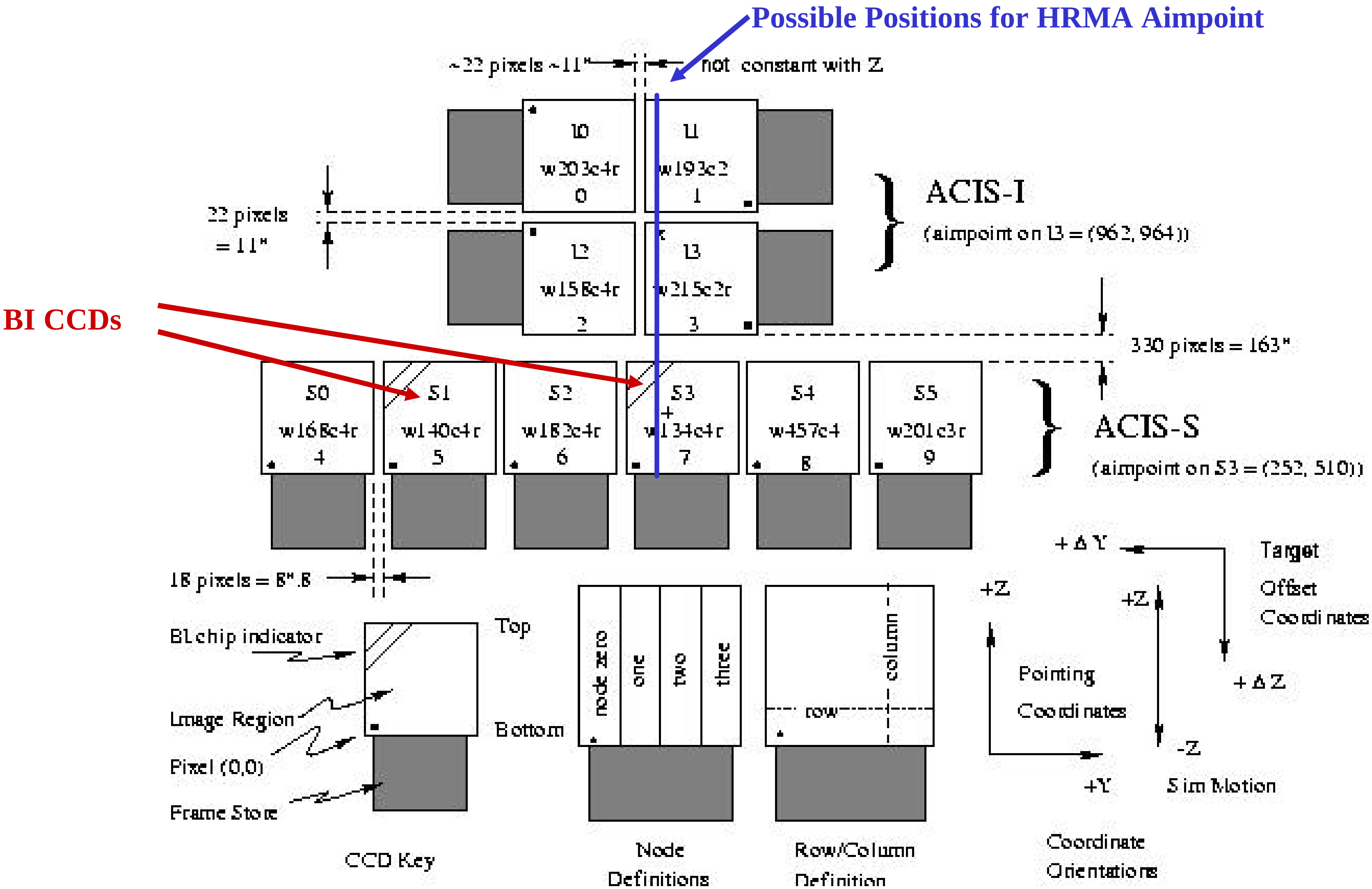
- The percentage of time in each configuration for AO1-AO5 is listed below for GO/GTO/DDT/TOO observations

	Configuration	%	Impact of Bakeout
1.	ACIS-S/NONE	42.2%	Net benefit on S3(BI), more photons
2.	ACIS-I/NONE	27.0%	Mixed, more photons, degraded E resolution
3.	ACIS-S/Gratings	21.9%	Net benefit, more photons
4.	HRC	8.9%	No effect

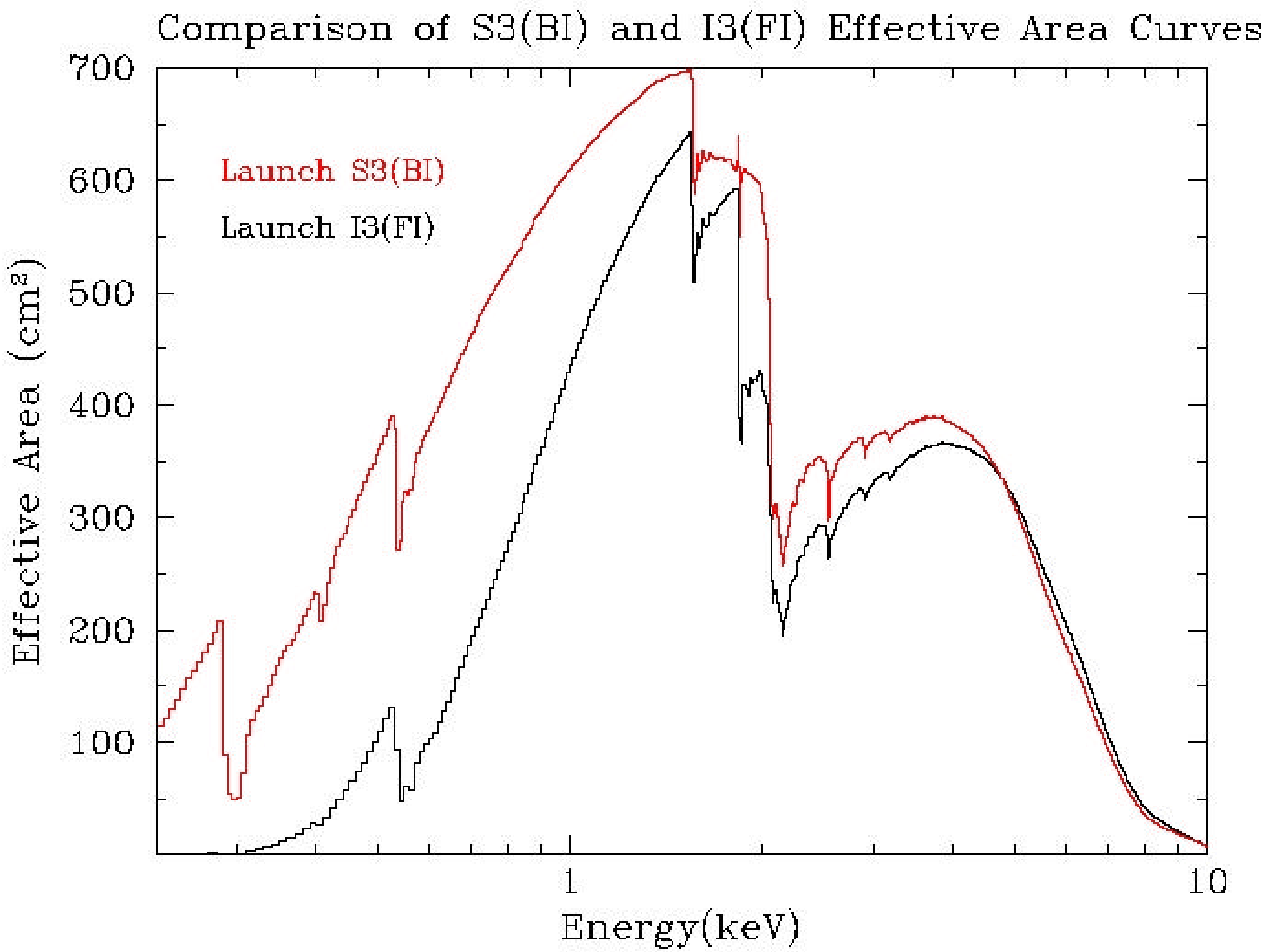
- 2/3 of *Chandra's* science observations will benefit from the bakeout (40% strong benefit, 25% low-moderate benefit)

- The percentage of time in the ACIS-S/None configuration has increased in every AO and has reached a mission-high of 51.6% in AO-5

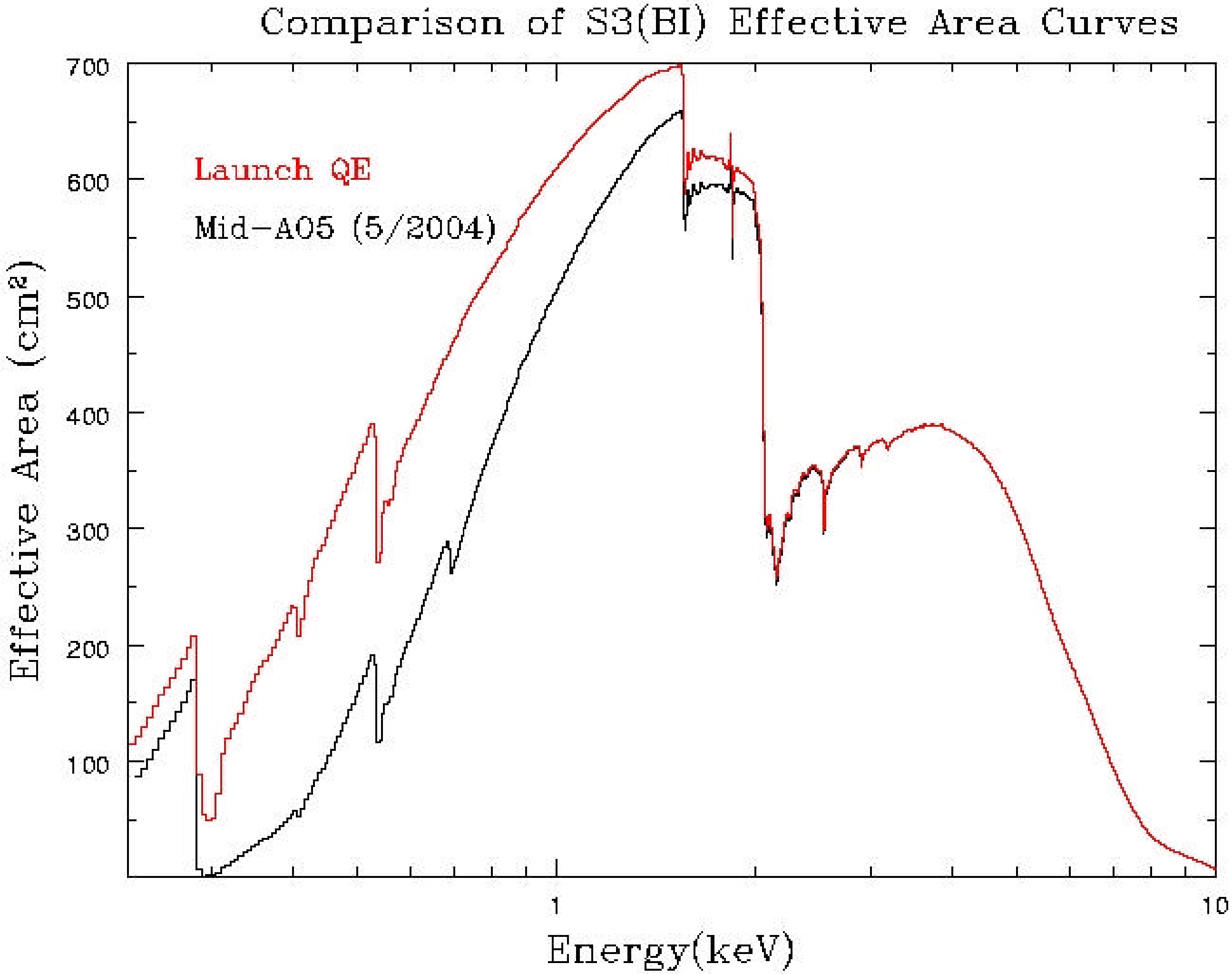
ACIS FLIGHT FOCAL PLANE



BI vs. FI CCD Effective Area

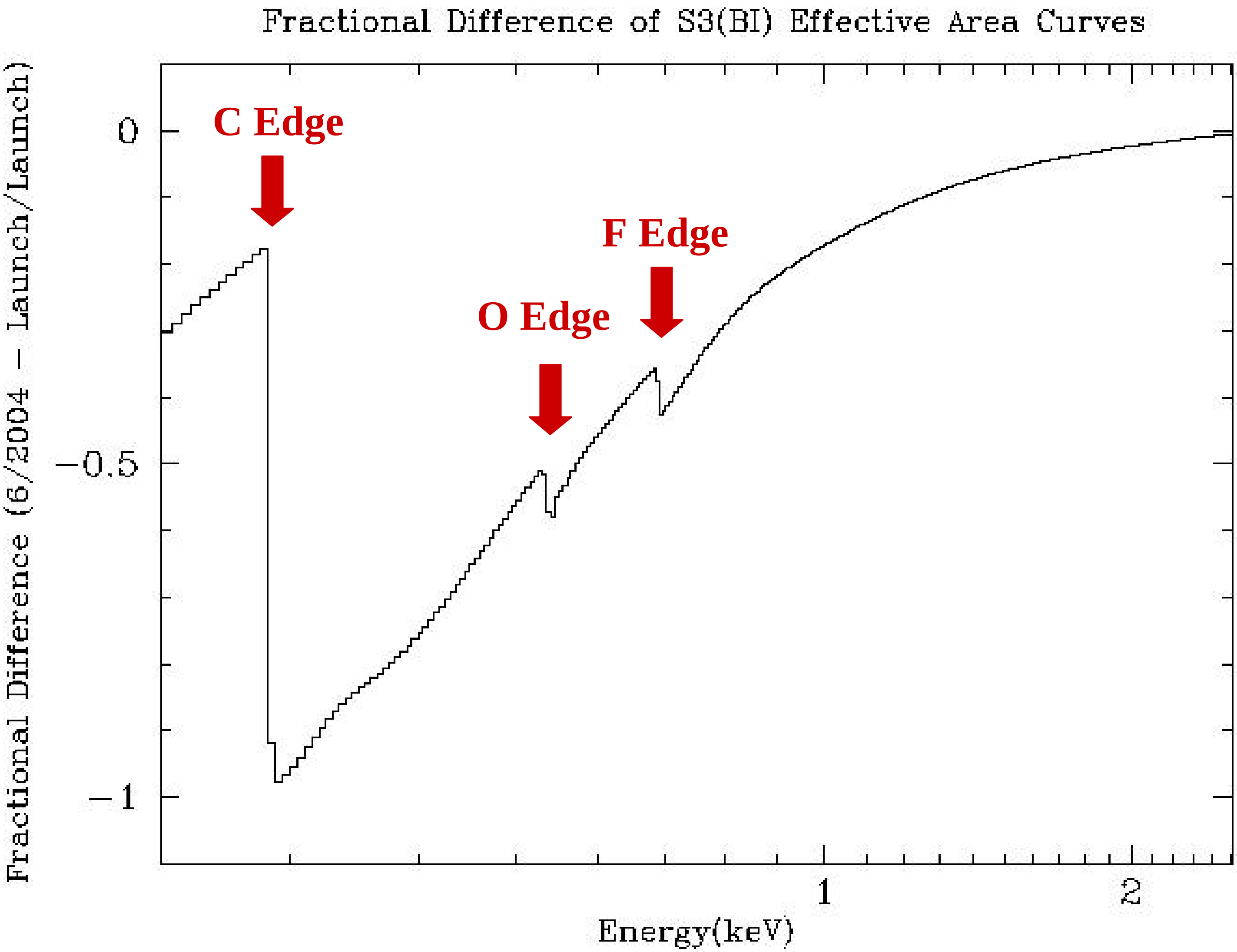


Decrease in Effective Area vs. Time



S3 (BI)

CCD


Fractional Difference of S3(BI) Effective Area Curves
Fractional Difference (6/2004 - Launch/Launch)
Energy(keV)
0
−0.5
−1
1
2
C Edge
O Edge
F Edge

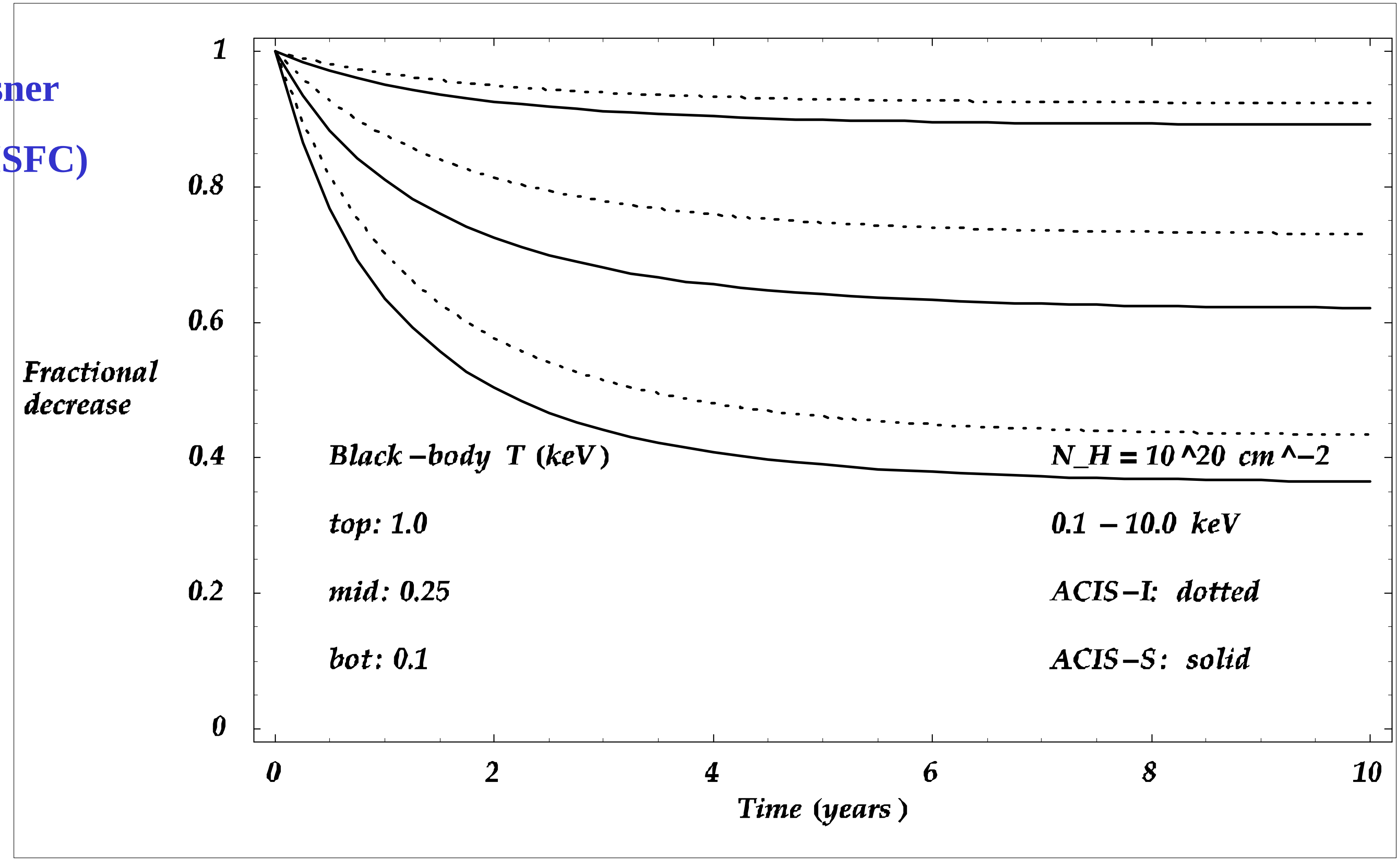
S3 (BI)

CCD

Impact on Count Rates for Typical Spectra (Blackbody)

Elsner

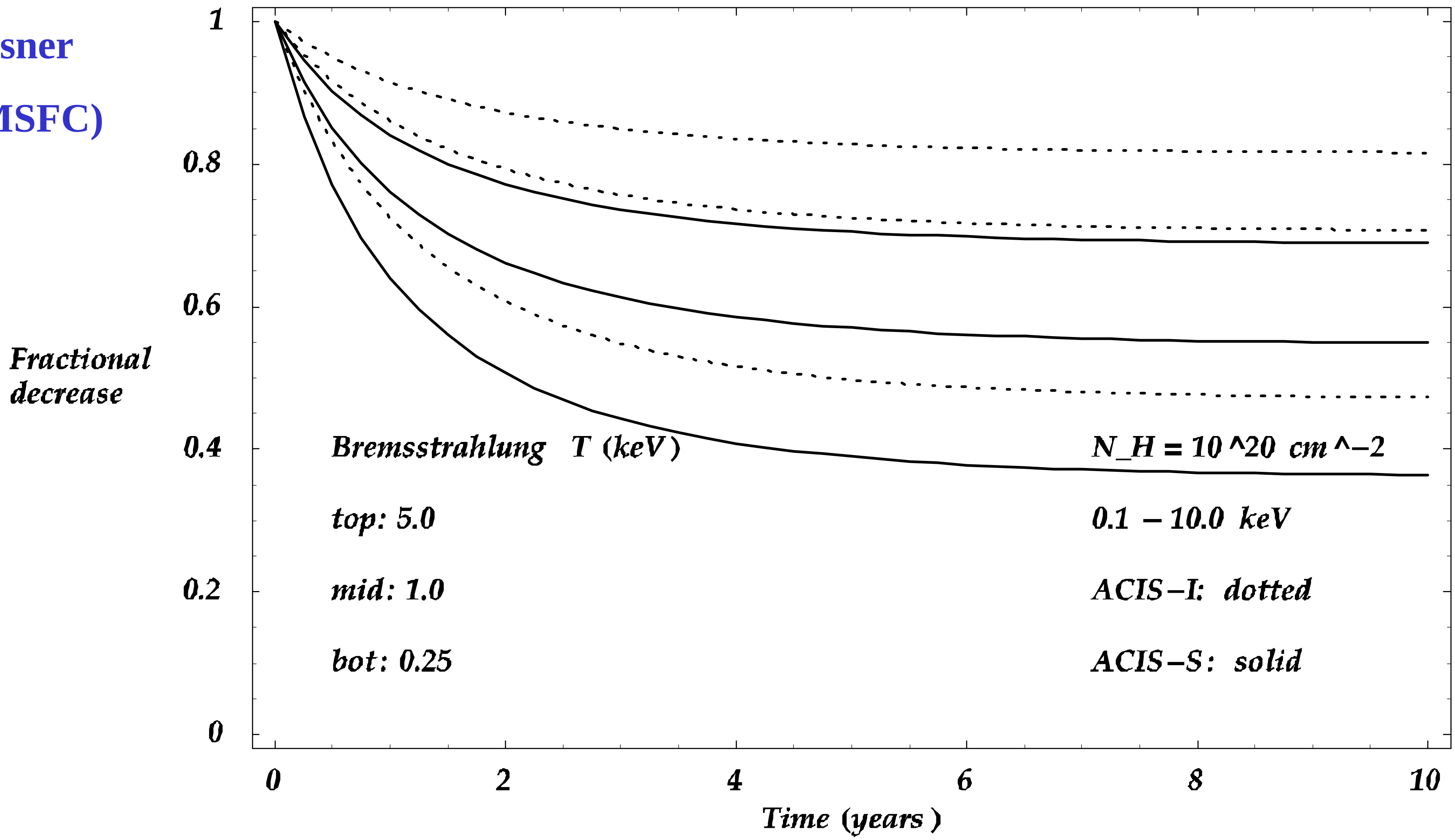
(MSFC)



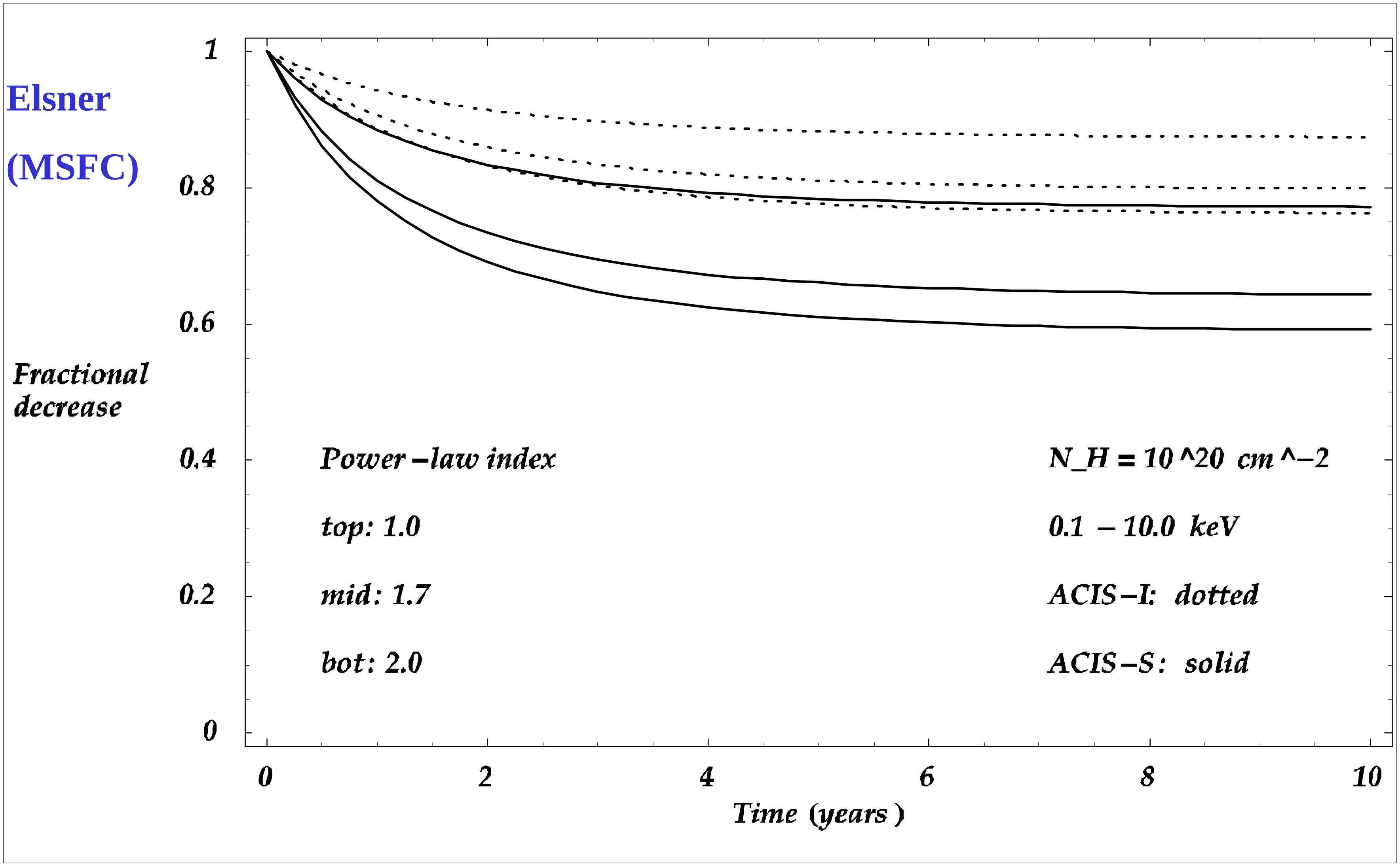
Impact on Count Rates for Typical Spectra (Bremsstrahlung)

Elsner

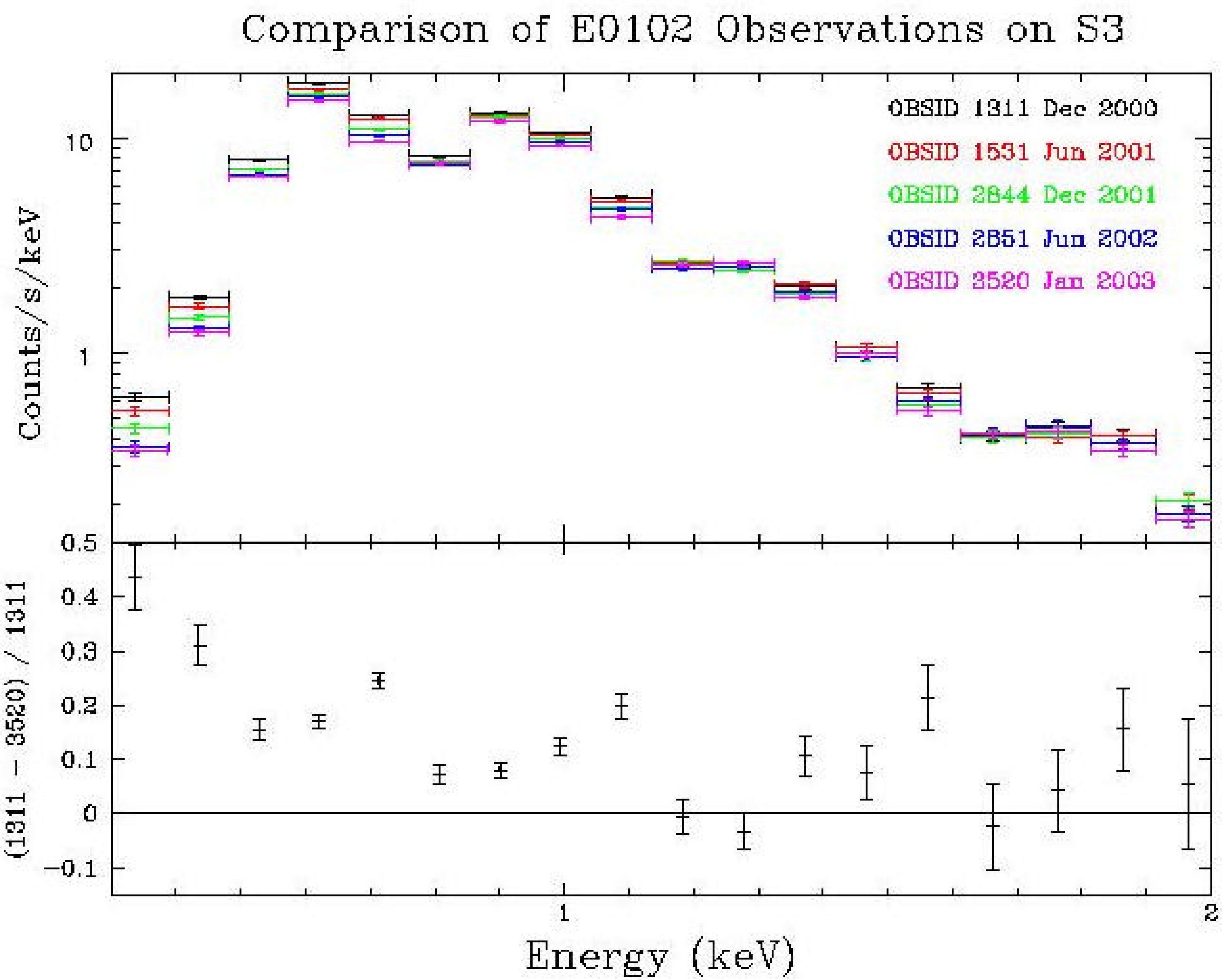
(MSFC)



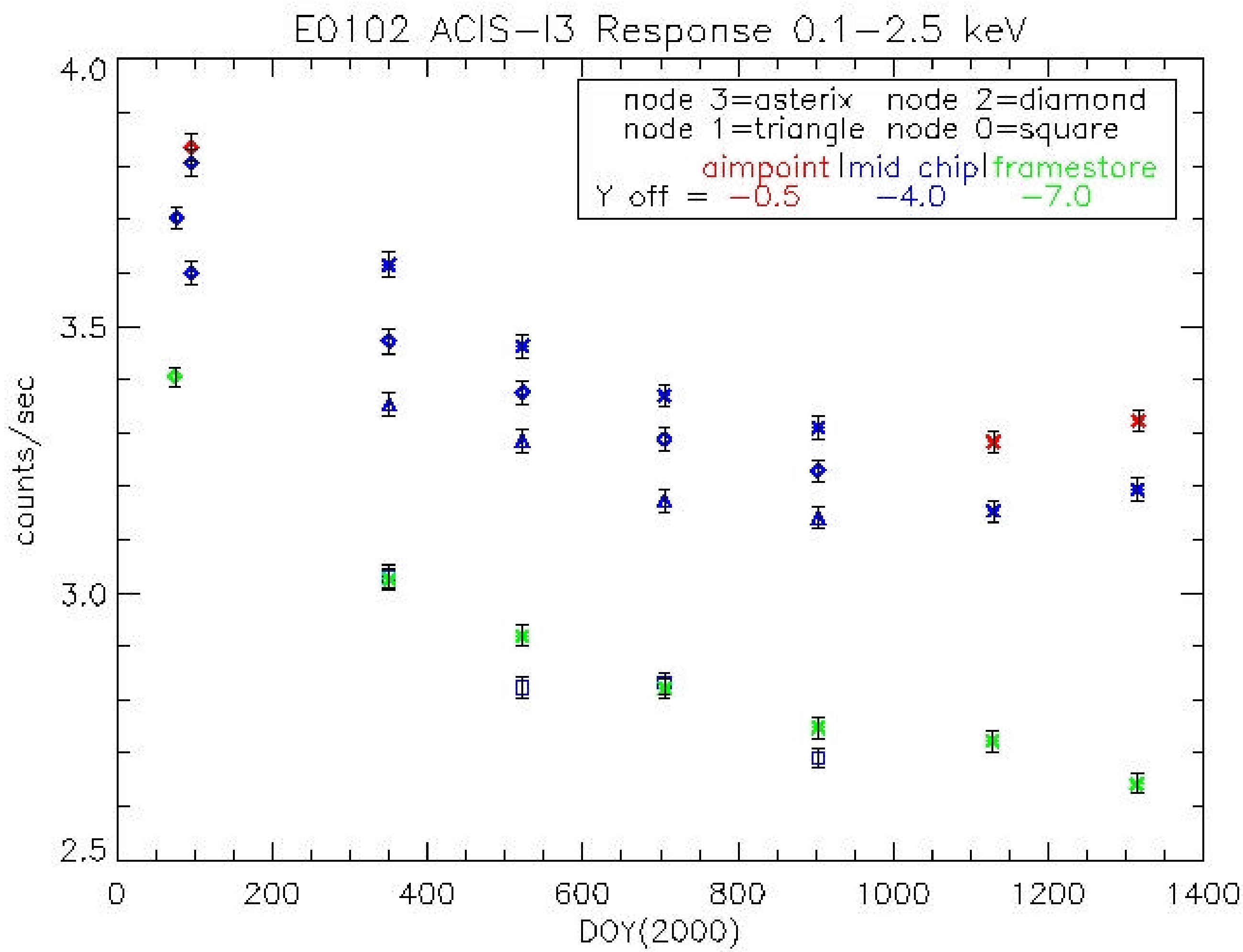
Impact on Count Rates for Typical Spectra (Power-Law)



E0102: Spectrum vs. Time



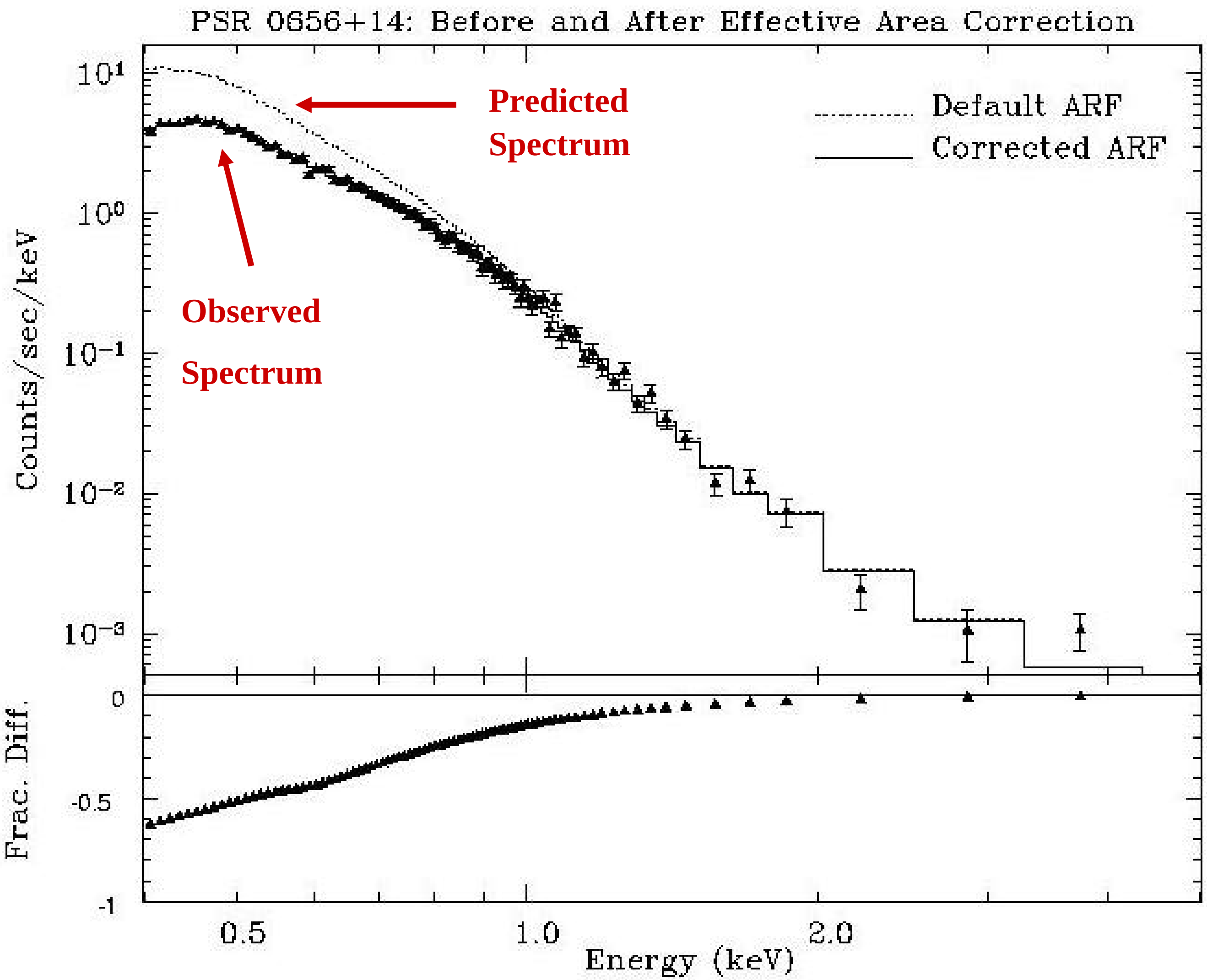
E0102 Count Rate vs. Time



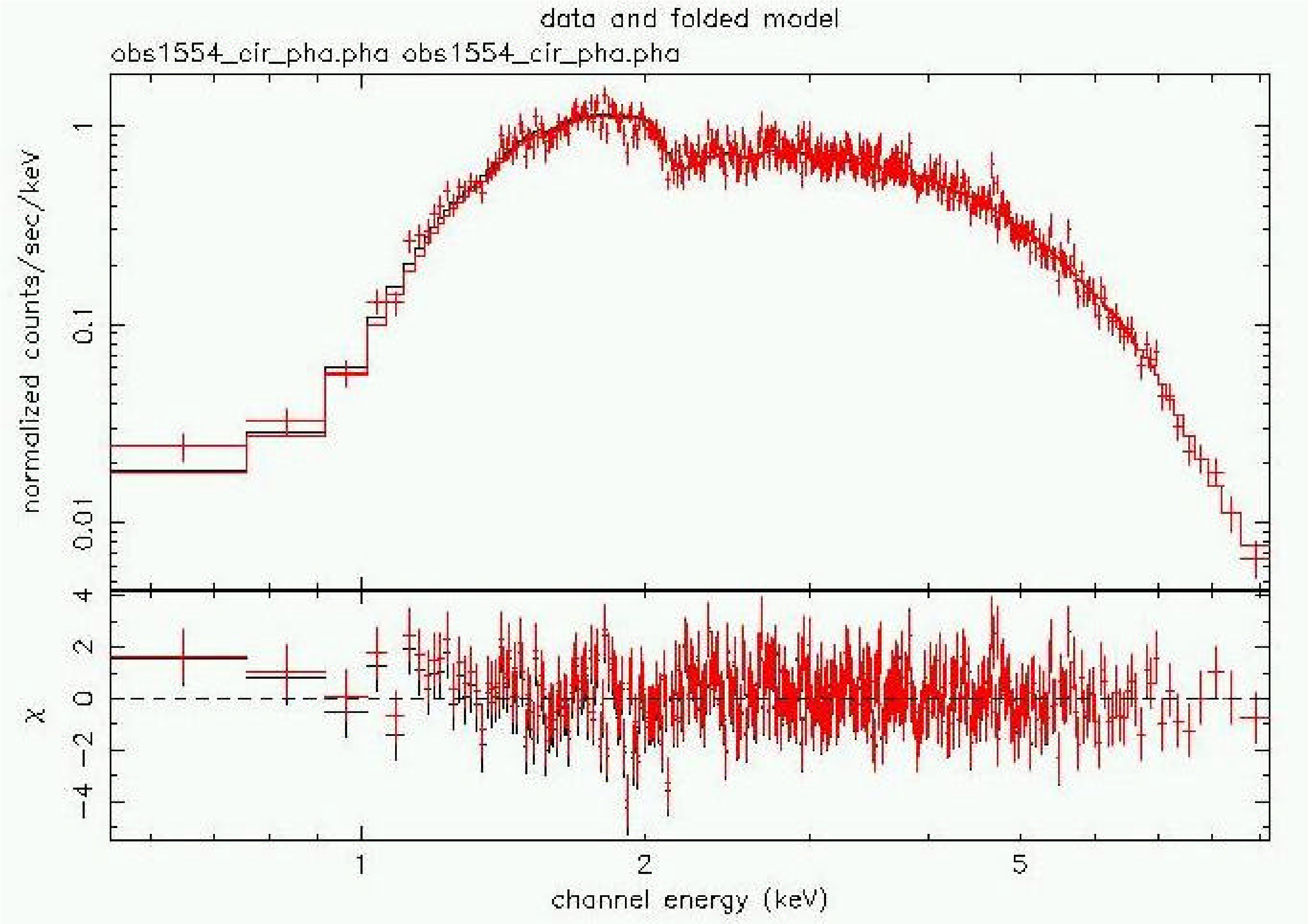
DePasquale

(SAO)

PSR 0656+14: Soft Spectrum (2002)



G21.5-0.9: Hard Spectrum (2002)



Impact on GTO AO-5 Proposals

Question 1: **Were there any targets for which you wanted to propose but did not because the observation was no longer feasible ?**

Question 2: **Were there any targets for which you increased the exposure time due to the contamination layer ? If yes, how many and by how much ?**

Question 3: **How many targets were unaffected ?**

~700 ks for each GTO team in AO-5

	#1	#2	#3
ACIS GTO Team	5 targets	13 targets, 16% of total exposure time	24 targets
HRC GTO Team	0 targets	0 targets	All, 30 targets
HETG GTO Team	0 targets	2 targets, 28% of total exposure time	2 targets

Comparison Between GTO and GO AO-5 Proposals

1) Comparison between GTOs' and GOs' instrument configurations
2) Comparison between GTOs' and GOs' observing categories

AO-5 Distribution of Instrument Configurations

Instrument Configuration	GTOs (%)	GO/GTO/ DDT/TOO (%)
ACIS-S/NONE	22.5	51.6
ACIS-I/NONE	37.2	24.2
ACIS-S/Grat	34.2	18.0
HRC	6.0	6.2

AO-5 Distribution of Science Classes

Category	GTO(%)	GO/GTO/DDT/TOO (%)
Solar System Misc.	0.0	0.8
Normal Stars & WDs	12.6	10.6
WD Binaries & CVs	0.0	5.7
BHs & Neutron Stars	4.9	9.6
SNe, SNRs, & Isolated NSs	15.6	19.2
Normal Galaxies	4.4	11.2
AGNs	28.4	14.8
Clusters of Galaxies	34.2	17.6
Extragalactic Diffuse Emission & Surveys	0.0	10.7
Galactic Diffuse Emission & Surveys	0.0	0.5

Science Impact Summary

Severely Impacted - In general these observations are no longer done with *Chandra*

- Supersoft sources

- Neutron stars with soft thermal spectra

Somewhat Impacted – Observations are done with longer exposure times

- Any galactic or extragalactic object for which the absorbing column is less than 5.0×10^{21} cm^{-2}

- This includes all classes of objects which *Chandra* observes

- All gratings observations with lines below 1.5 keV, particularly the O lines

- Deep surveys, sensitivity to soft sources changing throughout the mission

- For example, 1Ms observation of M101, search for absorption edges from intergalactic medium

No Impact

- Any galactic or extragalactic object for which the absorbing column is larger than 5.0×10^{21} cm^{-2}

- In general, absorbed X-ray binaries, absorbed AGNs

Science Impact Summary (continued)

Observations Which May Suffer Because of the Bakeout – in general these are observations of extended sources on the ACIS-I array which need the moderate resolution provided by the I array CCDs

- Supernova Remnants

- Clusters of Galaxies

Chandra's Strengths

High Resolution Imaging – benefits from the increased effective area, more photons

High Resolution Spectroscopy – benefits from the increased effective, more photons

Given the choice between increasing the effective area of *Chandra* or preserving the moderate spectral resolution of the ACIS-I CCDs at their current value, we should choose to increase the effective area since that benefits the majority of *Chandra's* User community. This maximizes *Chandra's* strengths and provides the greatest benefit to the community.

Community Concurrence

Chandra Users Committee briefed June 2003 and Jan 2004 and gave initial concurrence. Final briefing on June 28, 2004.

Science Working Group will also be polled for final feedback in late June, 2004.

2. Characterization of the Contaminant and Identification Attempts

Initial Symptoms – Counting rate of constant sources decreasing in time, the ratio of the Mn L line complex (~0.7 keV) to the Mn K line complex (~6.0 keV) from the ACIS external calibration source is decreasing in time

Energy Dependence – The effect is clearly energy dependent, consistent with contamination

Time Dependence – Layer is increasing with time, but the rate of increase is decreasing, consistent with a source of contamination which is finite

Thickness – layer is about 80-120 *m*g/cm^2, about as thick as the OBF itself

Spatial Dependence – Affects all 10 CCDs, contaminant varies in thickness with temperature gradient on the OBFs. Majority if not all of the contaminant on the OBFs and not on the CCDs because the CCDs are uniform at -120 C (no temperature gradient) and a small layer of any contaminant in the volume which houses the CCDs would change the emittance properties such that it would be impossible to maintain -120 C on the FP.

Chemical Composition – High resolution spectroscopy of the contaminant identifies, C, O, and F edges. The ratios of these elements is C:O = 11.5:1 and C:F=14:1. In addition, fine structure around the C edge indicates that most of the contaminant is an aliphatic* hydrocarbon.

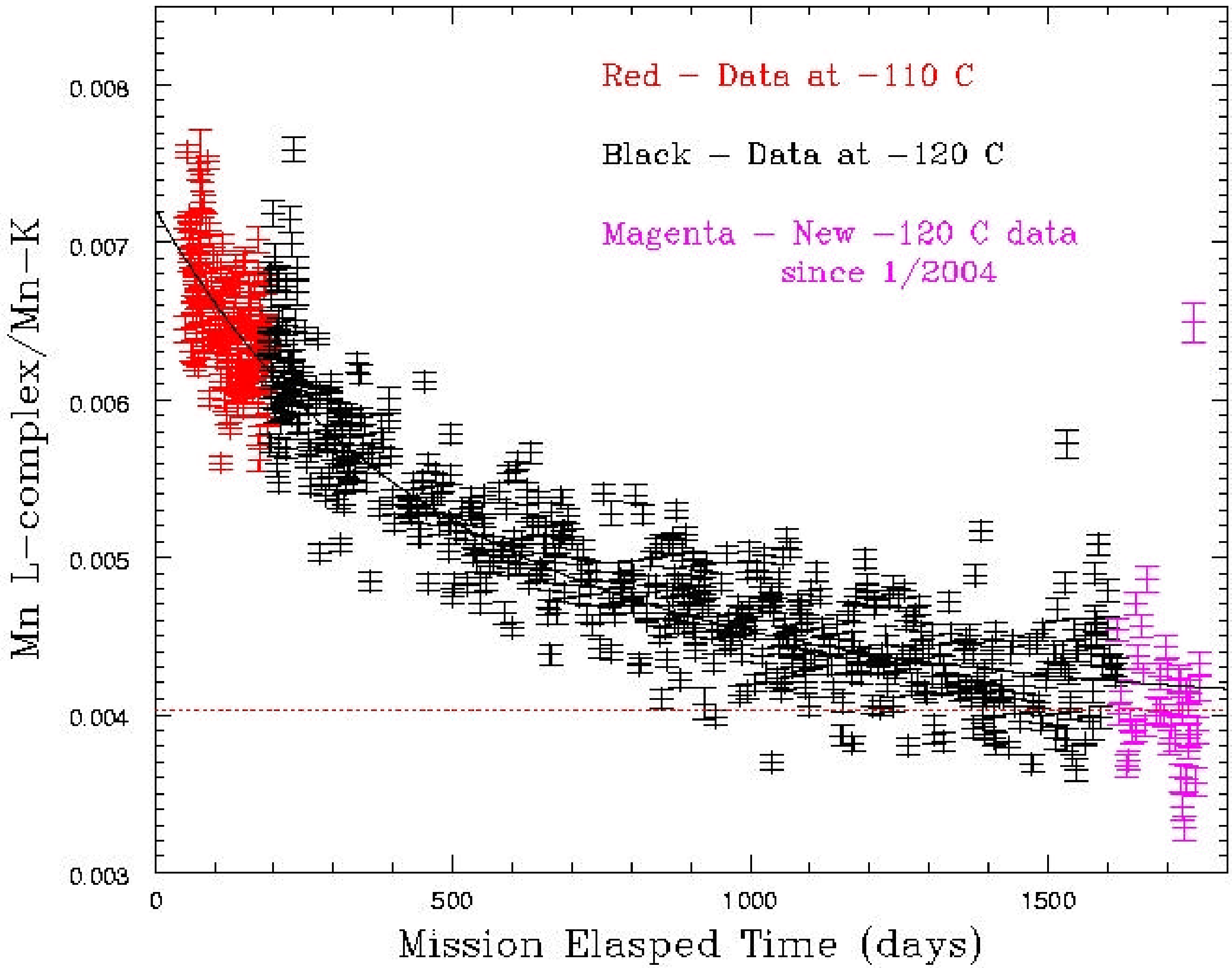
Detector Effects Not Credible – No change in the detectors or the detector electronics could have produced the energy-dependent decrease in sensitivity

*``aliphatic" = molecules with single C bonds

Chandra X-Ray Observatory

CXC

External Calibration Source: Mn-L complex/Mn-K vs Time



Grant (MIT)

Analysis

Tennant,

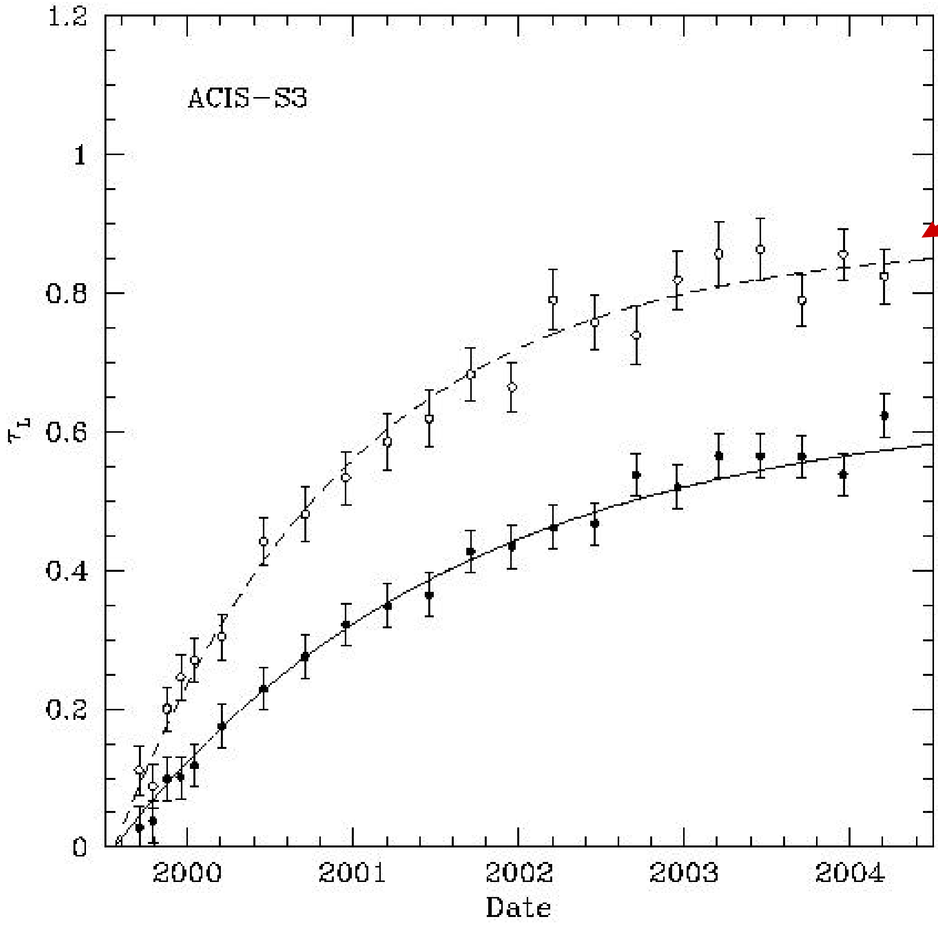
O'Dell

(MSFC)

Functional

Form

Optical Depth vs. Time based on the Mn-L complex/Mn-K



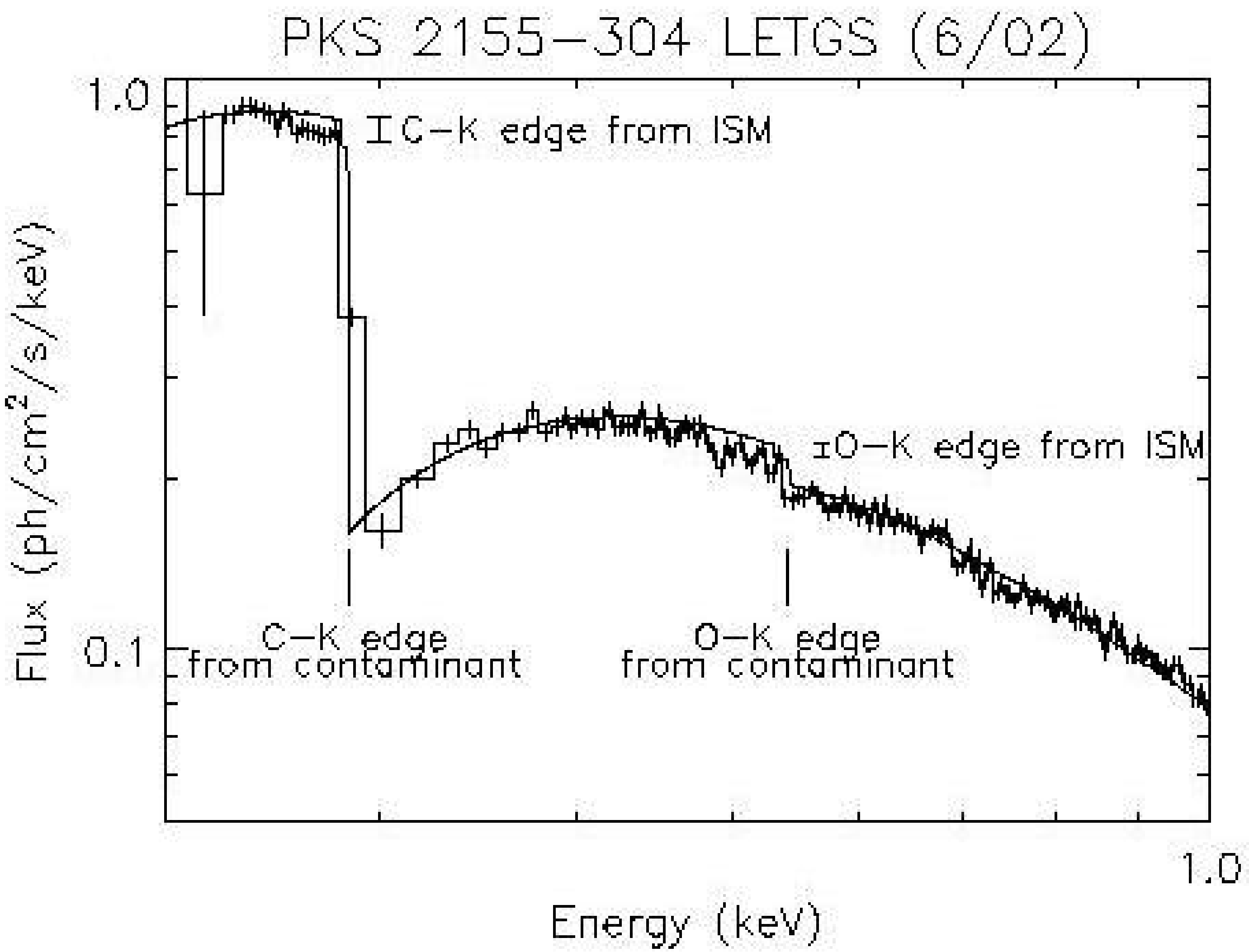
Bottom of S3 CCD

Middle of S3 CCD

Vikhlinin (SAO)

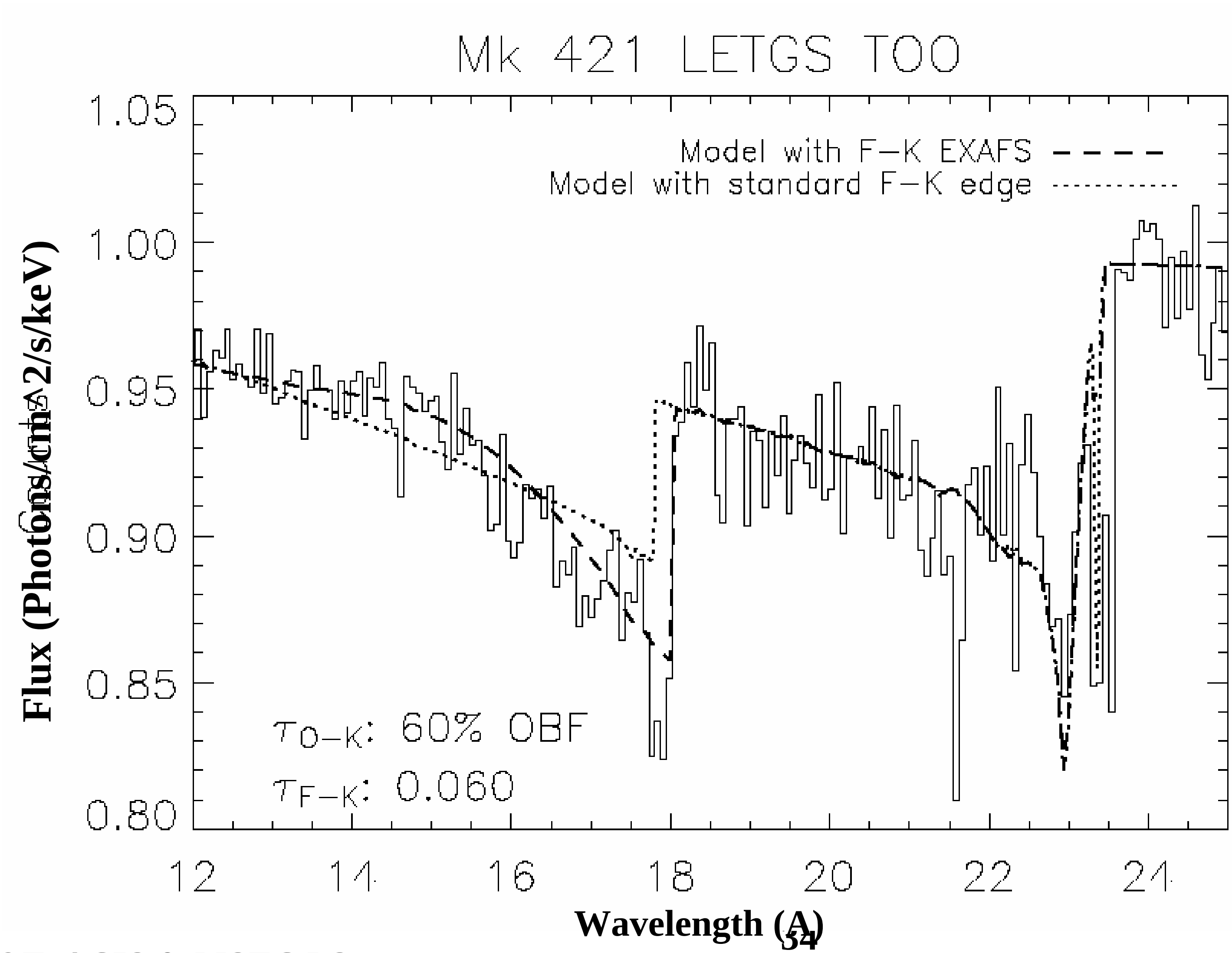
Contaminant is thicker along the edges of the I and S array OBFs, thinnest in the middle. Contaminant has reached over 80% of its maximum depth.

LETG/ACIS Characterization of the Edges



Marshall (MIT)

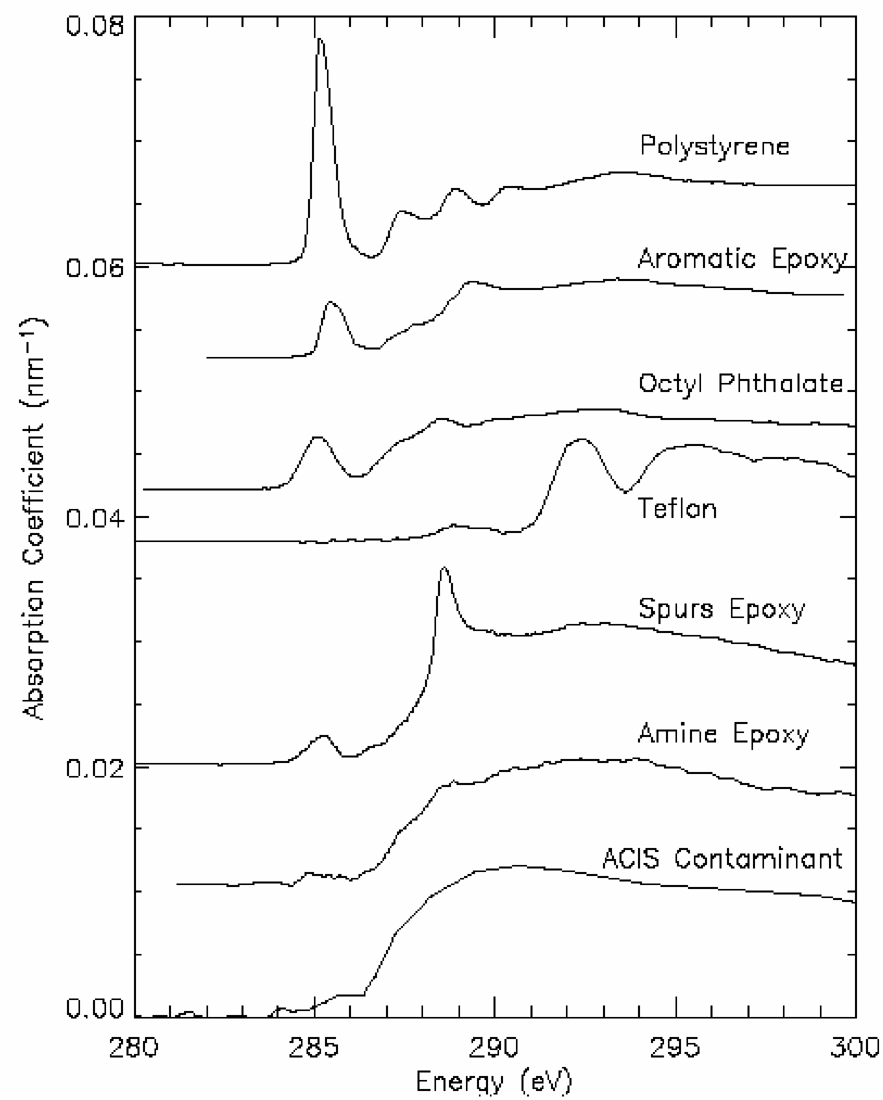
LETG/ACIS Characterization of the Edges



Nicastro (SAO)

Marshall (MIT)

Synchrotron Measurements from Herman Marshall and Adam Hitchcock



Fine structure around the C-K edge provides information on the types of bonds and hence the molecular structure of the contaminant. From the lack of a peak at 285 eV, we conclude that the contaminant on ACIS is composed mostly of an aliphatic hydrocarbon. There is no evidence of C=C bonds in the contaminant.

Material Investigation (from Kelly Henderson and Marty Mach)

- **Several materials were tested in an attempt to identify the contaminant**
- **GCMS was performed to determine the elemental ratios of the outgassing products for materials used on Chandra**
- **None of the materials tested had ratios similar to that of the ACIS contaminant**
- **None of the materials tested indicated fluorocarbons in the outgassing products, except Braycote, which evolved a very small amount**
- **It was suggested that radiation could enhance the outgassing rate of Braycote and other materials**
  - **Braycote 601 grease irradiated w/ 27Co60 gamma radiation was more volatile and the only material that liberate fluorocarbons per GCMS and VODKA tests**
  - **Most of the materials tested spanned the retention time (similar boiling point range) of the Braycote 601 grease. It was therefore chosen as the *"model compound"***

CONCLUSION: The contaminant is most likely a mixture of several materials and not just one material.

Materials Tested (from Kelly Henderson and Marty Mach)

Description	Usage
Braycote 601VB+3%MoS2AB,MIT450731,8/19/96,PO M9393	Translation table lubricant
C258905, Emerson Cumings lot 108169, exp11-7-01-->ext 2-15-02	Epoxy used to stake nuts, bolts, wires, etc.
MT5-20-1, RFC1120 A/B,lot22795,EVRoberts11865,RT Cure Mix 11-6-02	As above, but lower strength
MT5-20-1,Tra-Bond 970-3,lot0335,exp11/30/01,RT cure mix 11/6/02	As above – used in the ACIS
Black Urethane (black flakes)	Cushioning material from translation table. Also used to bond light shades and install tantalum shielding
C600505-II tape, TRW stores,1/4"w, roll 010712005,7/12/01	Bonds MLI insulation
O-ring, Viton, TRW NAS1593-018	Seals, etc
Panel: Fiber M55J/Resin 954-3, cured 021203	Optical bench

3. Description of the Relevant ACIS HW

Purpose: In order to model and understand the bakeout, one must know the locations, sizes, and viewfactors of all the surfaces the contaminant might encounter.

Four important pieces of the HW to define:

Detector Housing (DH) – sometime referred to as the "Camera Body"

Focal Plane (FP) – location of the CCDs

Optical Blocking Filter (OBF) – prevents optical and UV light from reaching the CCDs

ACIS Collimator – 18 inch tall Ti structure

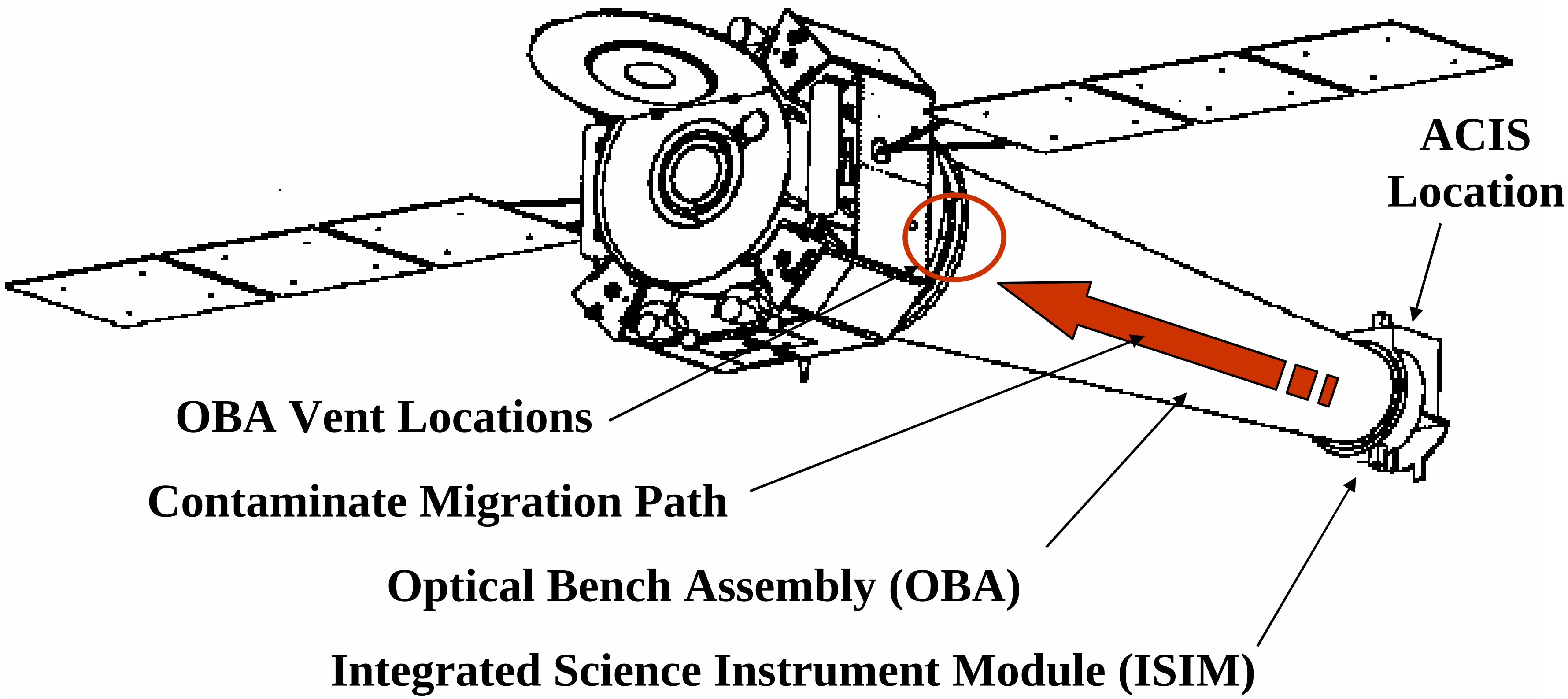
Only two heaters, Focal Plane and Detector Housing, no direct means of heating the OBF

Problem: contamination layer is building up on the OBF surface facing the mirror assembly. We conclude this based on two facts:

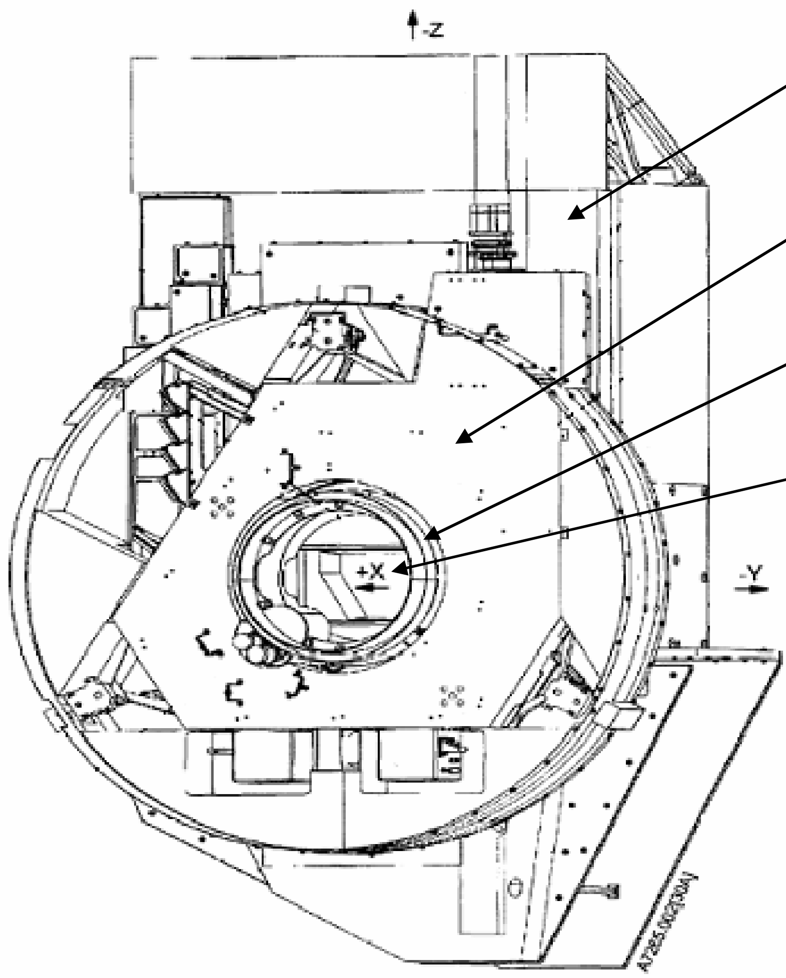
-the variation in thickness of the contaminant follows the temperature distribution of the OBF

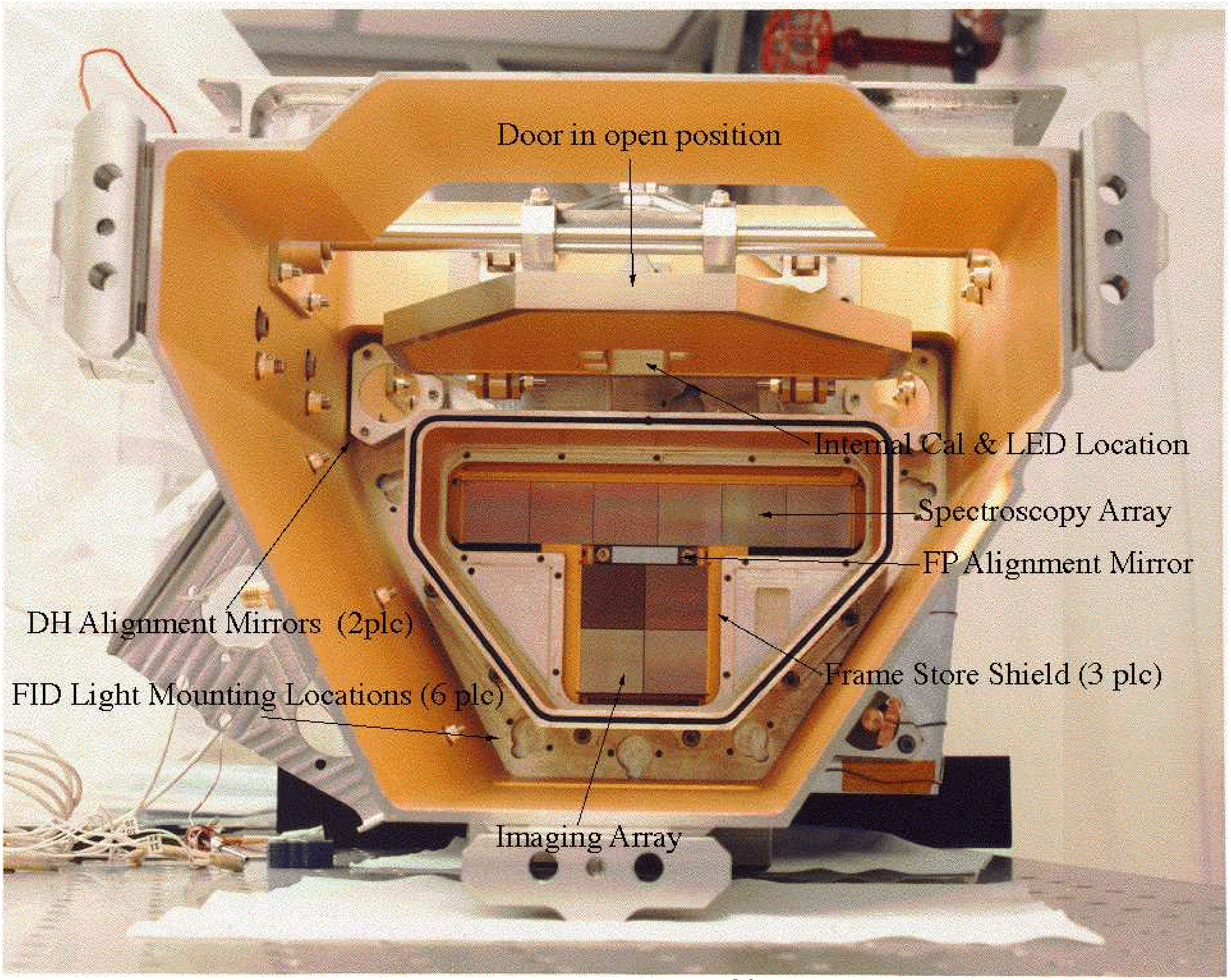
- the thermal properties of the FP cavity have not changed with time

Chandra X-Ray Observatory

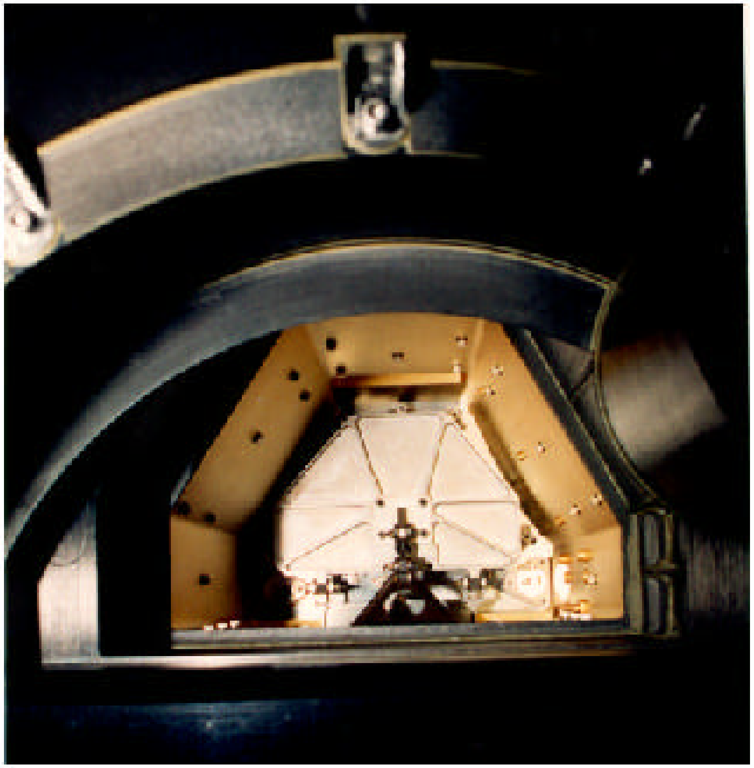


Integrated Science Instrument

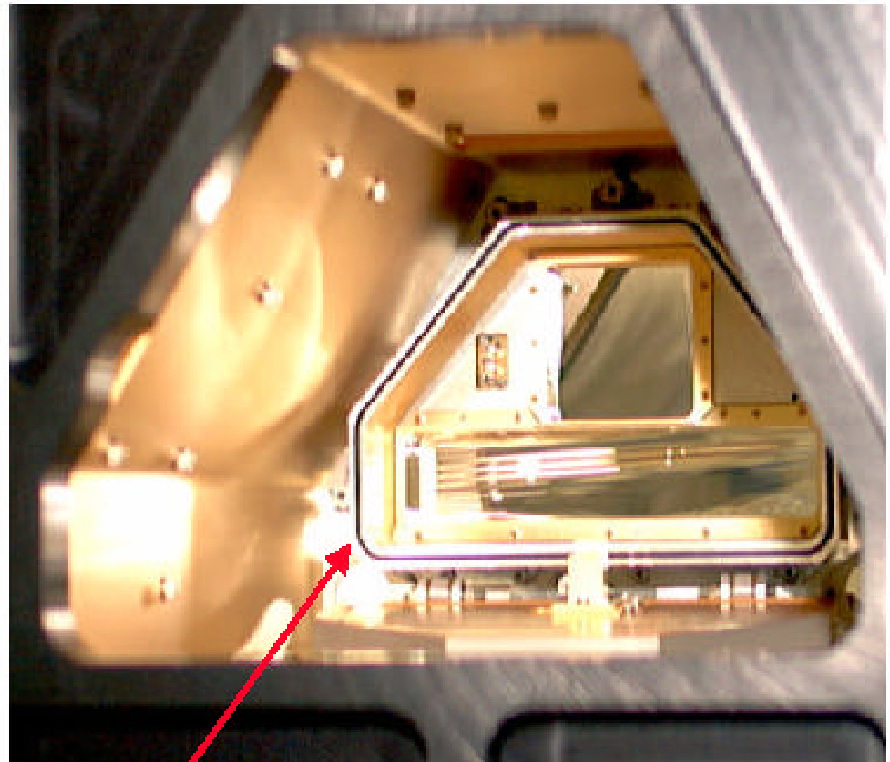



Door in open position
Internal Cal & LED Location
Spectroscopy Array
FP Alignment Mirror
DH Alignment Mirrors (2plc)
Frame Store Shield (3 plc)
FID Light Mounting Locations (6 plc)
Imaging Array

X-Ray View of ACIS Door and Detector



Door Closed while Mounted to ISIM

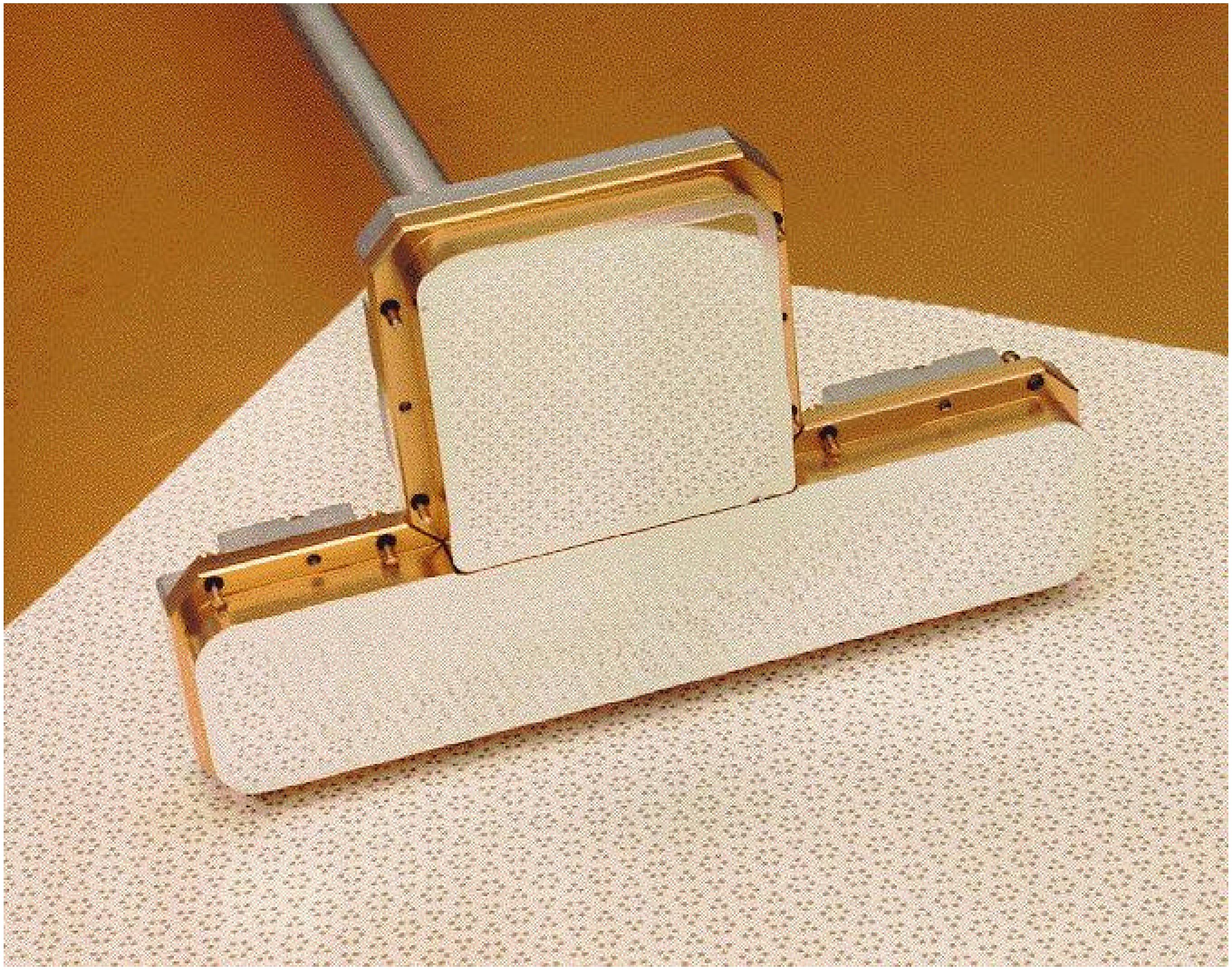


Door Open at LMA

Viton O-ring

1

ACIS Optical Blocking Filter



ACIS-I OBF

Al/Polyimide/Al

1200A/2000A/400A

ACIS-S OBF

Al/Polyimide/Al

1000A/2000A/300A

4. Thermal Models of the ACIS Instrument

Purpose: In order to model and understand the bakeout, one must know the temperatures of all the surfaces the contaminant might encounter.

Modeling – provided by Neil Tice at LMA, ACIS thermal engineer pre- and post-launch

Collimator – primary surface which the contaminant will interact with on its way out of the instrument during the bakeout

Detector Housing – upper portion probably contains the majority of the contaminant by mass and the OBFs are installed in the DH

OBFs – significant temperature gradient across the filters

In order to model the bakeout, the temperatures of the relevant surfaces in ACIS must be known for:

1) Normal operations, FP= -120 C, DH=-60 C

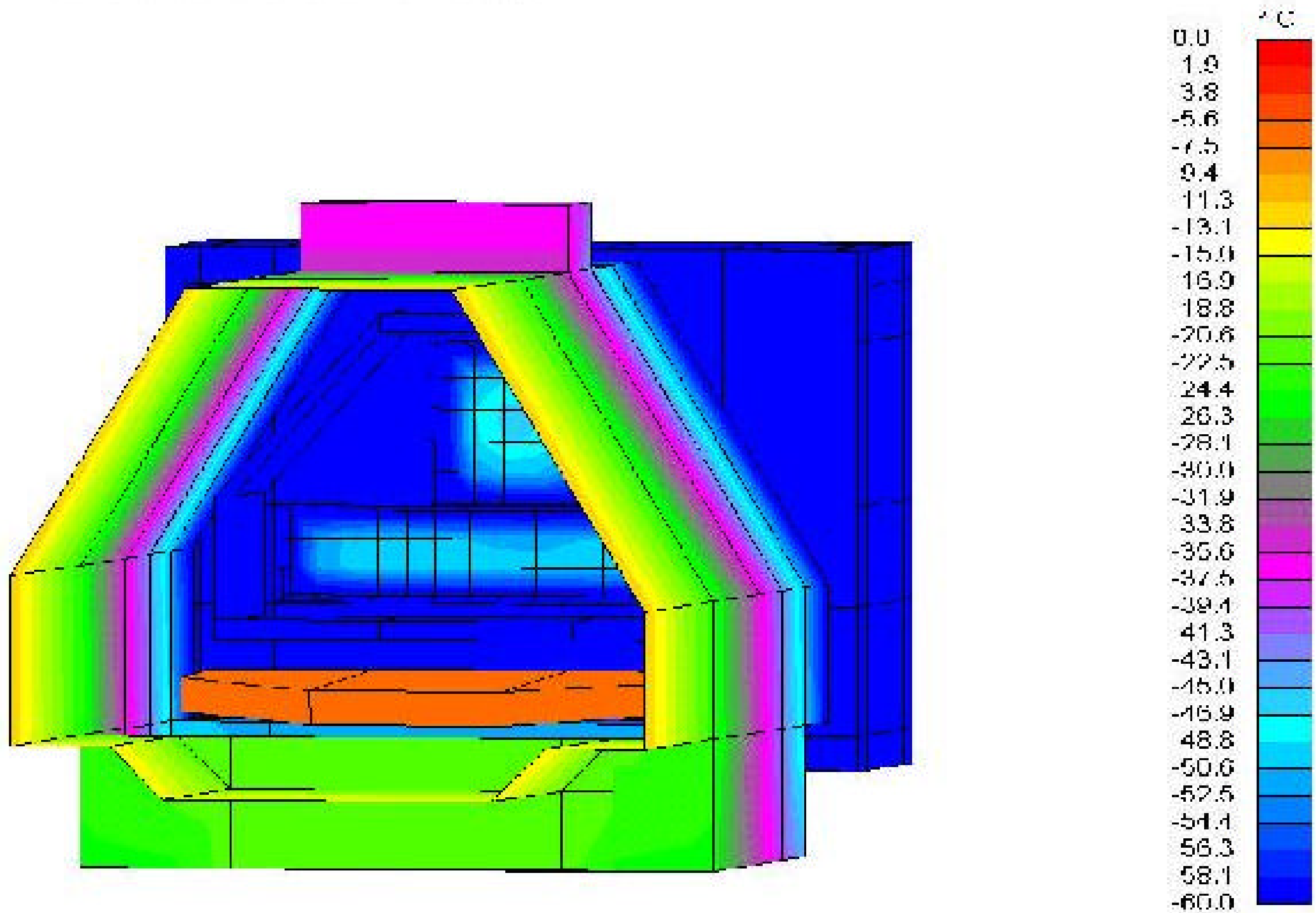
2) Bakeout conditions, FP= +20 C, DH=+20 C

Tice

(LMA)

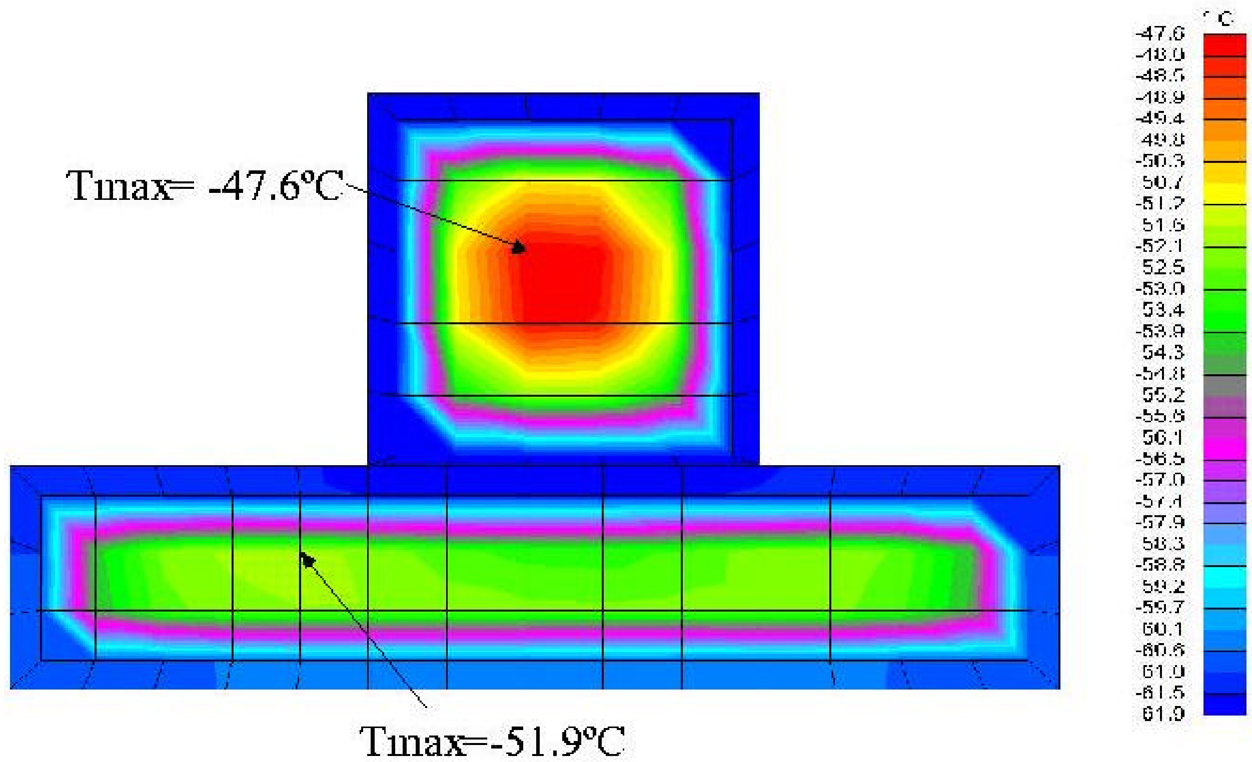
ACIS Temperatures During Nominal Operation

Focal Plane is a –120°C



ACIS Filter Temperatures for Standard Conditions

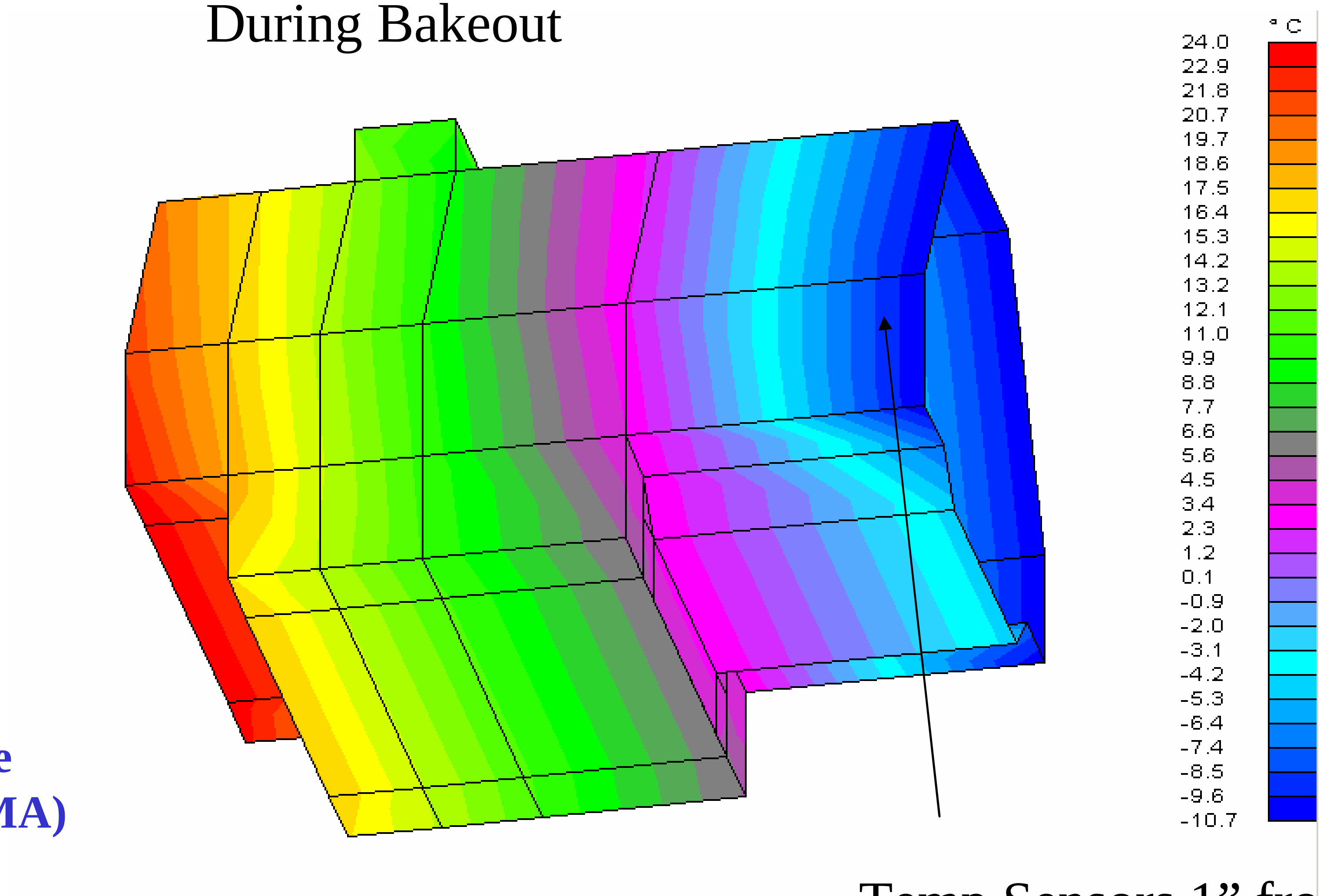
ACIS Housing -60°C, FP -120°C



Tice

(LMA)

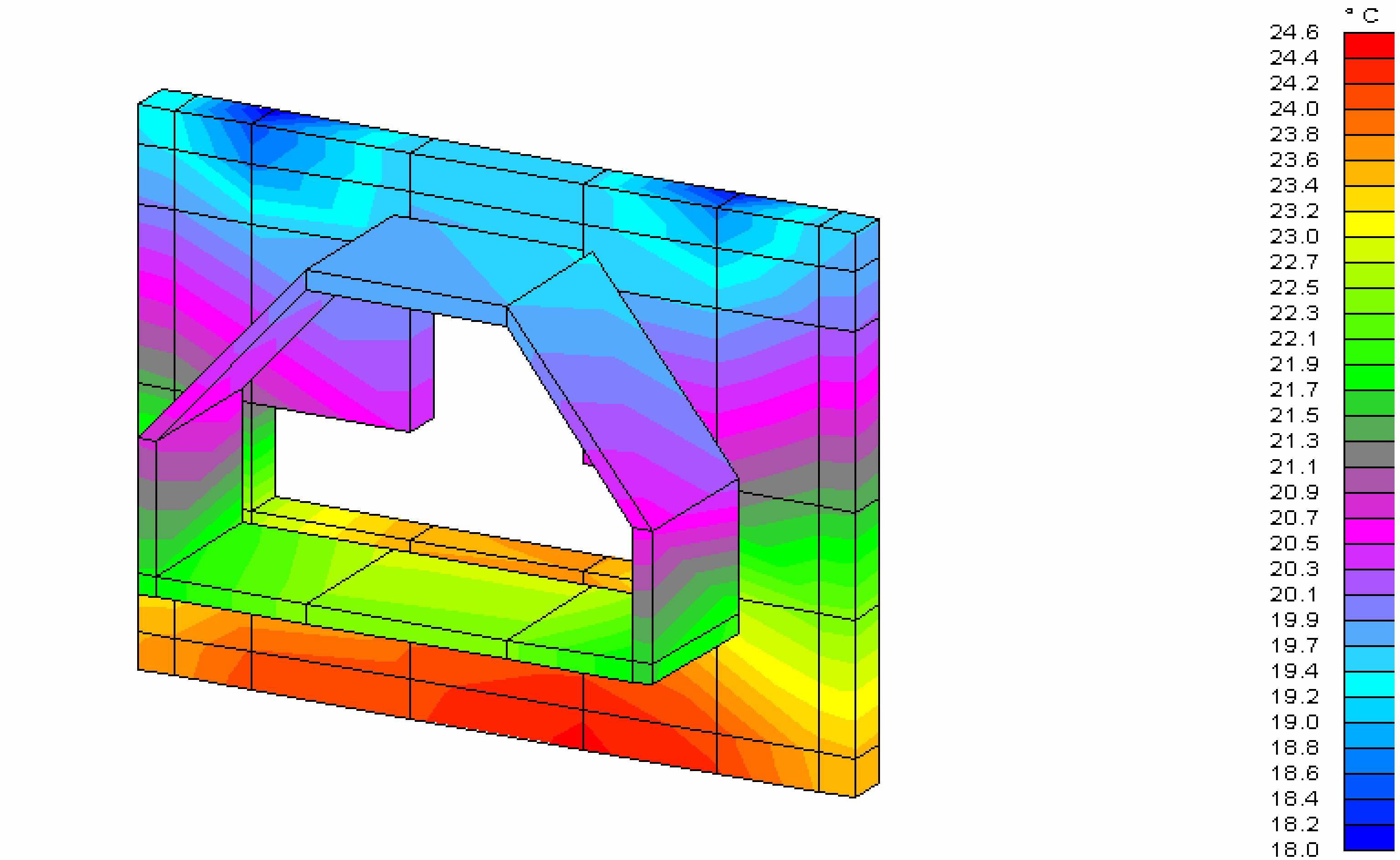
Collimator Temperature Gradients During Bakeout



Tice (LMA)

Temp Sensors 1” from SIM I/F

Camera Top and Snoot



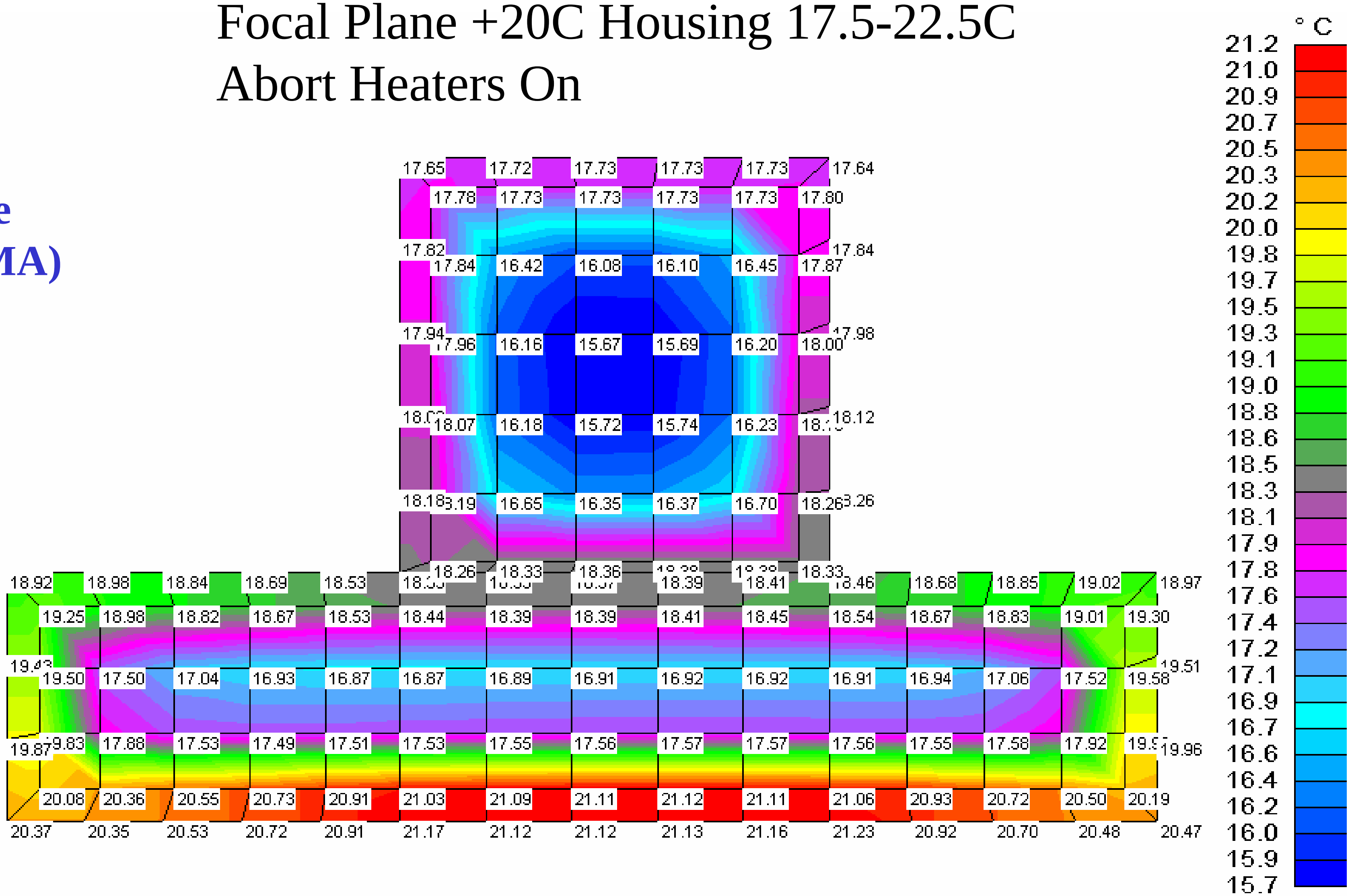
Tice (LMA)

Chandra X-Ray Observatory

CXC

Focal Plane +20C Housing 17.5-22.5C
Abort Heaters On

Tice (LMA)



5. Thermal Model of ISIM & Use of Abort Heaters

Dan Shropshire

Northrop Grumman Space Technology

ISIM Heater Investigation

- **Detailed modeling of the expected ACIS OBF contamination migration revealed a strong dependence on ACIS collimator temperature.**

- **A review of the ISIM heaters was done at the request of the ACIS instrument team to see if there was any way to heat the top of the collimator assembly and other SIM structures forward of the collimator.**

- **The TSC1 abort heater was found to be in close proximity to the desired area and could provide some conductive heating of the collimator.**

- **The abort heaters were designed for use while in the shuttle bay only. They provided extra margin to the ISIM compartment structural integrity for the abort landing scenario.**

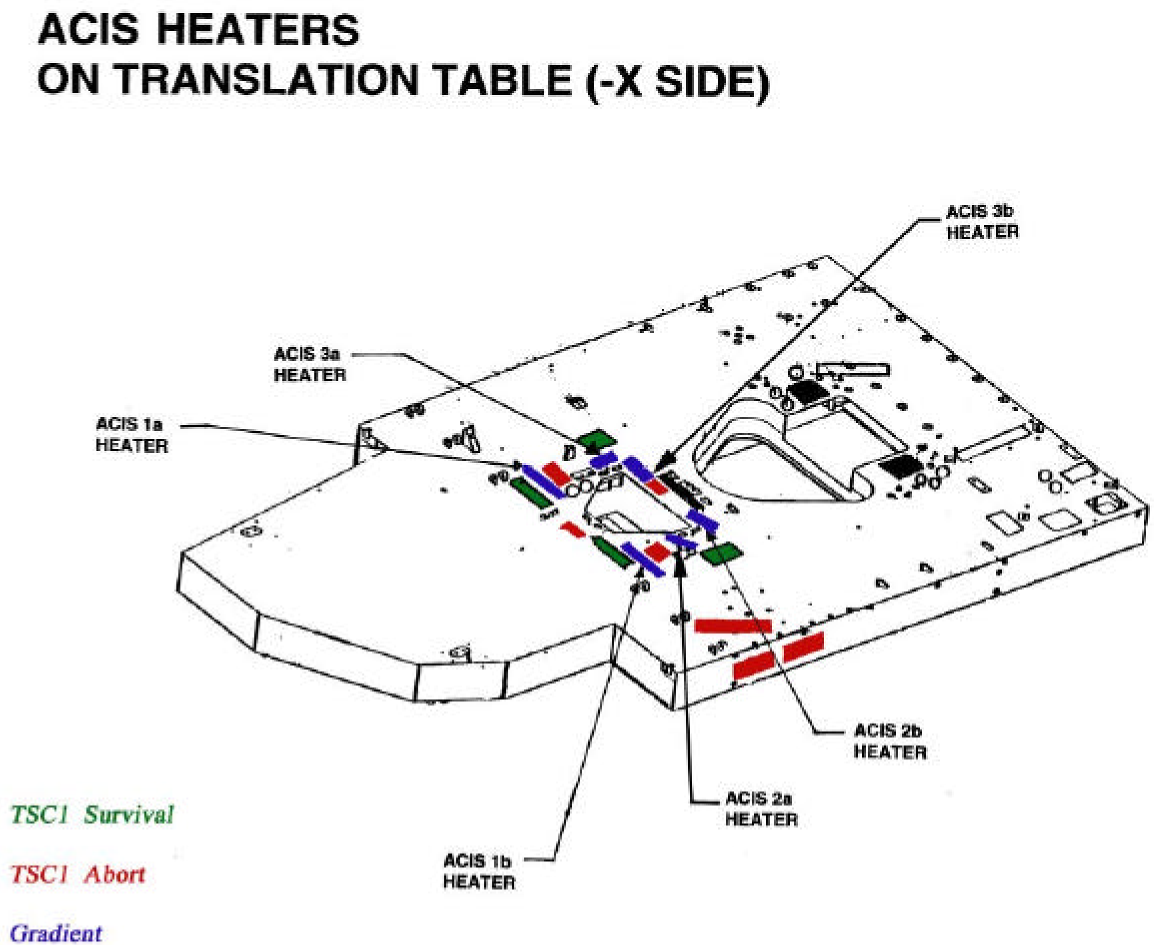
NGST ISIM Thermal Model

- **Goal: To provide predicted temperatures during an ACIS bakeout at the ACIS collimator interface to the SIM translation table with and without the TSC1 abort heaters enabled**

- **ISIM Thermal Math Model (TMM) created pre-launch for prediction of on-orbit temperatures**
  - **End of Life thermal surface properties**
  - **Solar constant = 450 BTU's/hour/per square foot**
  - **Earth albedo = 0.35 Percent reflected solar**
  - **Earth IR = 84.5 BTU's/hour/per square foot**
  - **Sun at 90 degrees pitch, 0 roll**
  - **No eclipses**
  - **Includes Simplified Instrument Models**
  - **All Normal operational heaters enabled**
  - **All prime abort heaters enabled, where specified**
  - **Model was correlated to Thermal Vacuum data but not to On-orbit data.**

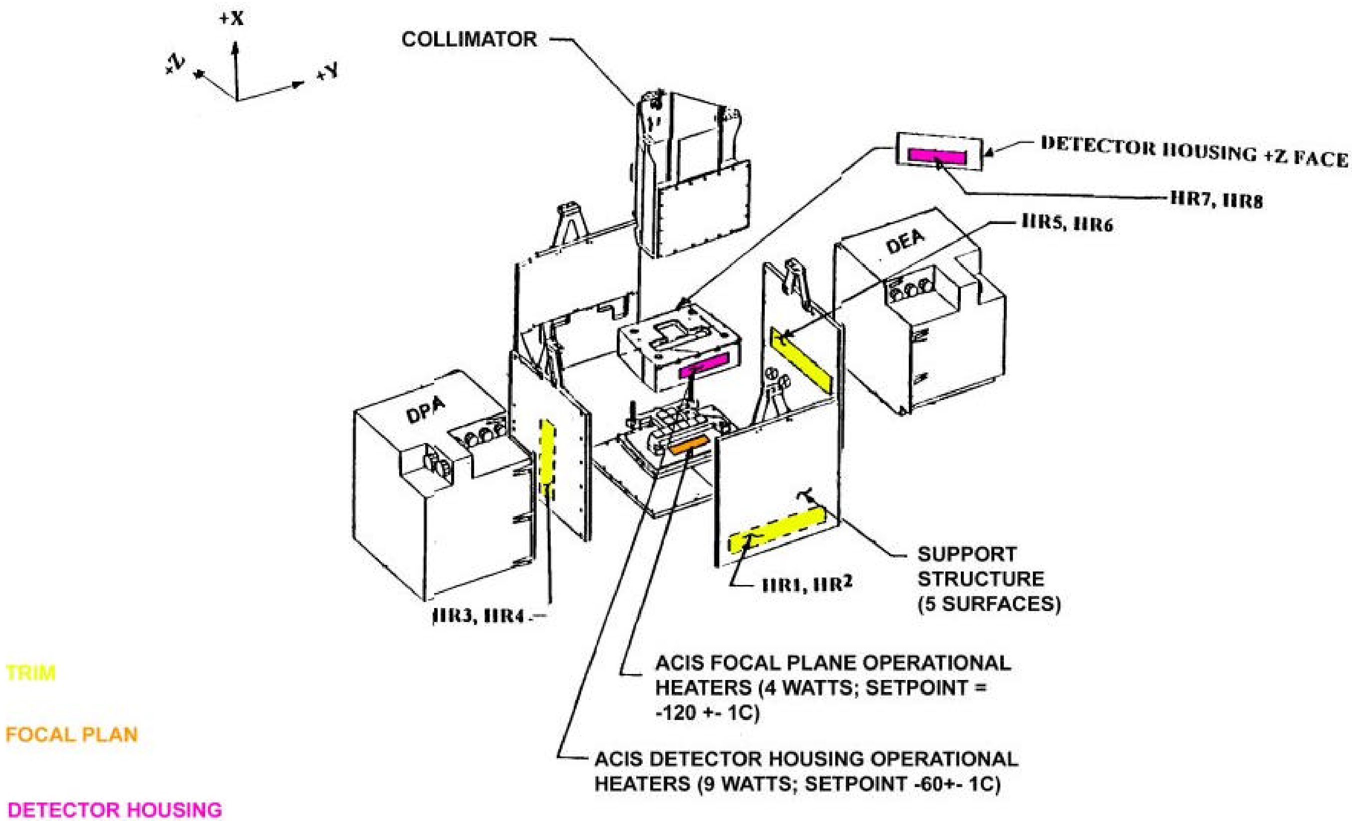
Translation Table Abort & ACIS Gradient Heater Locations

- TSC1 Abort heaters to be enabled at beginning of ACIS bakeout (red patches)
- ACIS Gradient 3 heater to be disabled for ACIS bakeout (blue patches)



Translation Table Abort & ACIS Gradient Heater Locations

- **ACIS Trim heater to remain enabled for ACIS bakeout (yellow patch)**

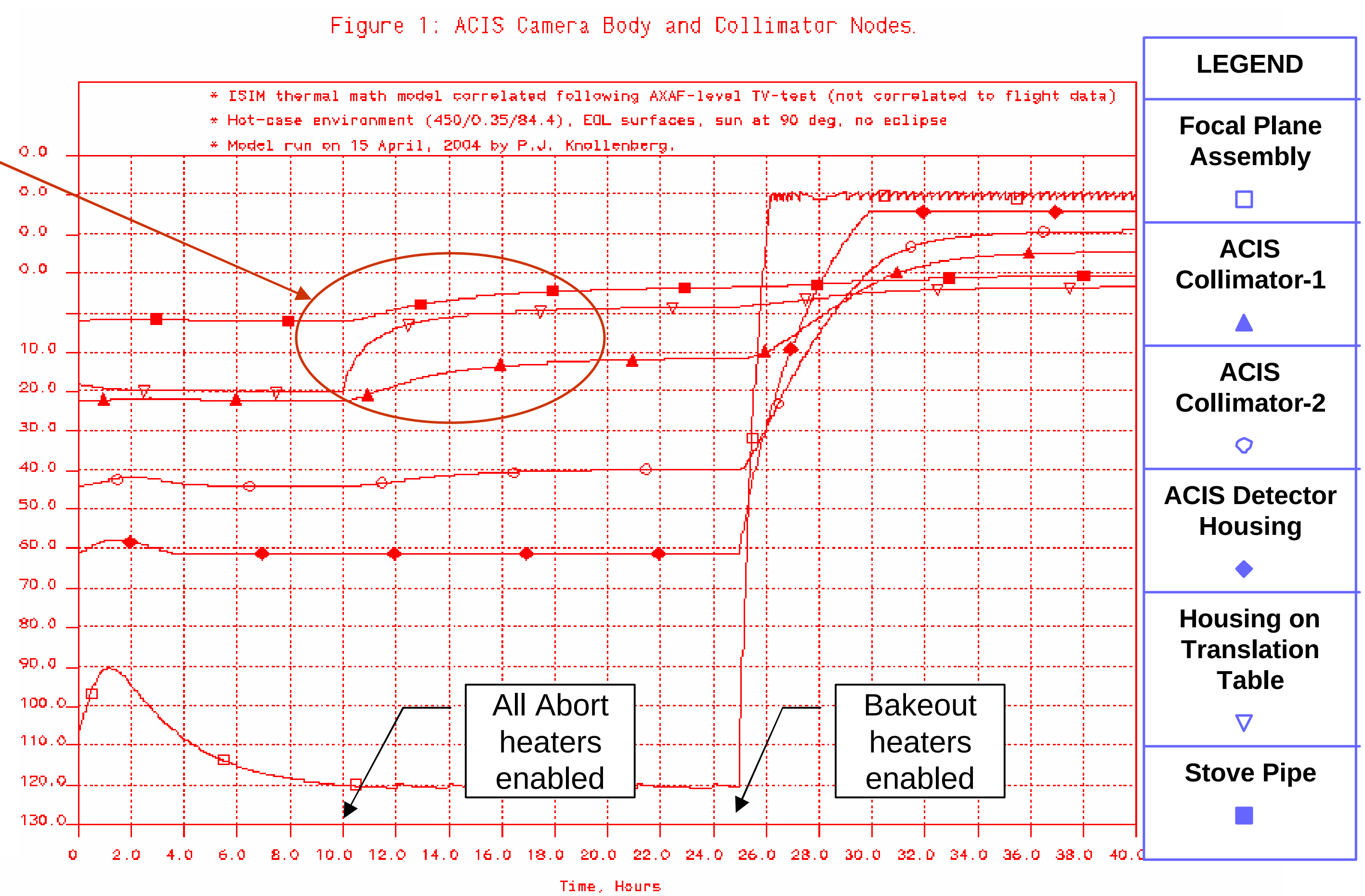


Chandra X-Ray Observatory

CXC

ACIS Detector and Collimator Temperature Predictions

- Enabling of TSC1 abort heater adds +10 deg C at the ACIS collimator / translation table interface
- Temperatures at collimator / translation table interface expected to reach 12 +/- 5 deg C



Use of the Shuttle Abort Heaters

- Use of the TSC1 shuttle abort heaters was not intended after release from the Space Shuttle cargo bay
  - Intended only for use in the event of a shuttle abort landing
- Therefore, prior to use, a thorough study was performed to ensure their suitability for use in the current operational environment
  - NGST Thermal engineers contacted
  - All constraints, restrictions, and limitations reviewed
  - Thermal vacuum data reviewed
- Two issues were raised regarding fuse stress and heater watt density
  - Both issues addressed in OP05, the Constraints, Restrictions, and Limitations document
    - CARD SIM-C-004
    - CARD SIM-C-008

Fusing and Heater Watt Density

- **The Chandra Constraints Restrictions and Limitations Document (CARD) states that:**
- **Heater watt densities are such that, if both prime and redundant abort heaters are enabled simultaneously, heater burnout may occur**
- **Fuse stress is possible if the operational trim and gradient heaters are enabled while the associated abort heaters are enabled on the same heater bus**
  - **The fuse stress possibility depends on specific heater combinations and bus voltage**

Fusing and Heater Watt Density

- **Technically, waivers of CARDs SIM-C-004 and SIM-C-008 are required, however, the operational intent of the CARD will still be met:**
  - **At no time will both prime and redundant abort heaters be enabled, only the prime heater will be exercised**
  - **It is proposed that the ACIS 3 gradient heater also be disabled prior to enabling the abort heater**
    - **This is a 51 watt heater that rarely operates on orbit but disabling it provides margin against fuse stress**
  - **The ACIS trim heater should be left on, so as not to make the support structure a heat sink for the abort heater**

Fusing and Heater Watt Density

Heater	State	Set point °C	Resistance Ω	Watts @ 30v	Amps @ 30v	Closest Thermistor	On-Obit Temp Range
Primary TSC1 Abort	Disa	14	34.8	25.9	0.86	3TTVALVT	-40 to –5
Primary TSC3 Abort	Disa	14	67.8	13.3	0.44	3TTRALAT	-43 to –20
Primary TSC4 Abort	Disa	14	125.3	7.2	0.24	3TTBRGBT	-25 to 10
Primary ACIS Gradient 3	Enab	-11	17.5	51.4	1.71	3TTACS1T	-12 to -2
Primary ACIS Support Structure +Y Trim	Enab	11.7	14.5	62.1	2.07	1SSPYT	11 to 13
ACIS Support Structure +Y Survival	Bus 1	-19	14.5	62.1	2.07	1SSPYT	11 to 13
Primary TSC1 Survival	Bus 1	-34.5	10.7	84.1	2.80	3TTACS1T	-12 to -2
Enabled Heaters TOTAL Amps					8.65		
Operating Heaters TOTAL Amps					3.78		
Operating Heaters + TSC1 Abort heater TOTAL Amps					4.64		
ACIS SS +Y Trim & Abort Heater Only					2.93	De-rated Amps = 7.0	

Conclusion

- **Enabling the TSC1 abort heaters will increase the ACIS collimator / translation table interface temperature +10 deg C to 12 +/- 5 deg C**
- **Following the recommended approach, there is no added risk to the spacecraft with the use of the TSC1 abort heaters to support the ACIS bakeout**

6. Simulations of contamination migration

Steve O'Dell & Doug Swartz (MSFC/ Project Science)

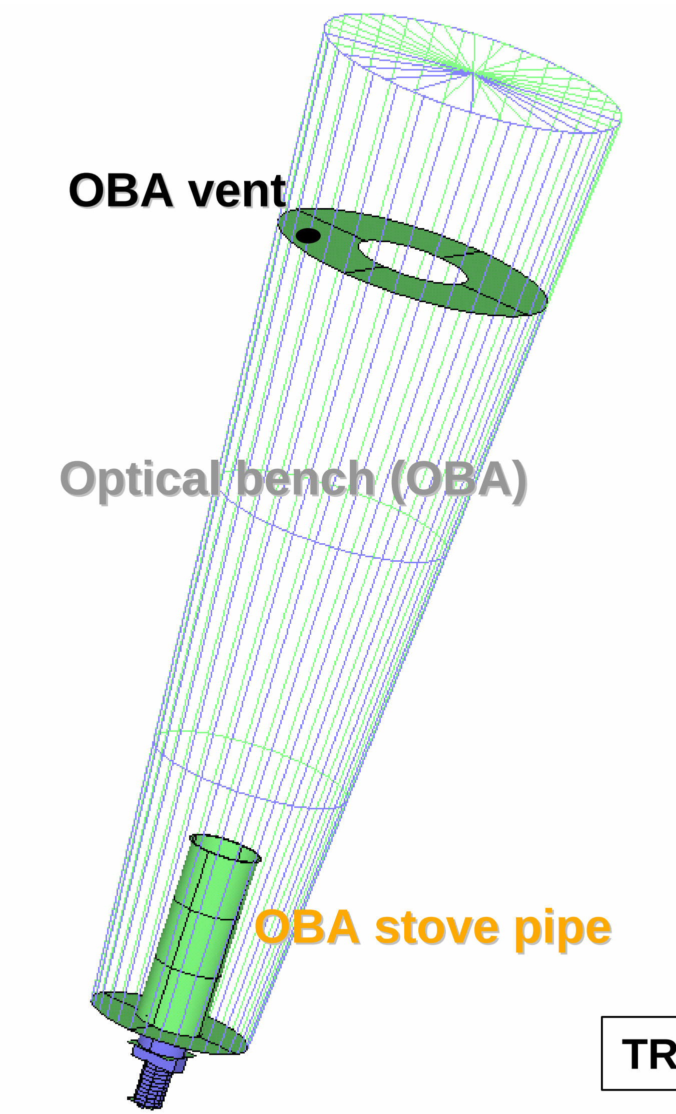
Simulation methodology

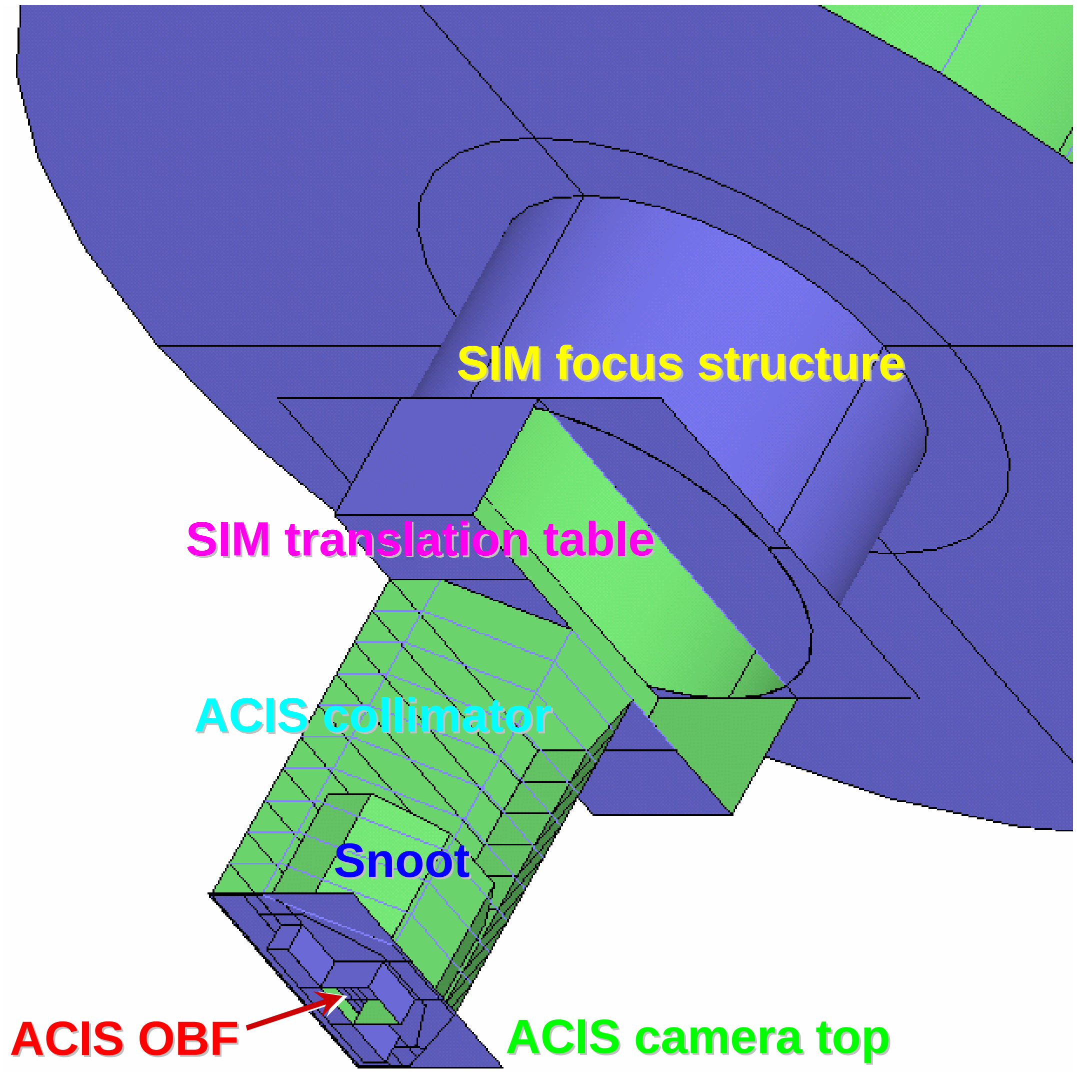
- **Developed code to simulate numerically contamination migration within CXO.**
  - **If present on a surface, contaminant vaporizes at a temperature-dependent rate.**
    - **Use Clausius–Clapeyron scaling of temperature dependence — ≈ *factor of 2 per 5°C*.**
  - **Contaminant deposits from other surfaces based on their view factors and rates..**
- **Need area, view factor, and temperature of each node in CXO model.**
  - **Use NGST's TRASYS output for geometry — area and view factor of each node.**
  - **Use LMC's thermal predictions for temperature of each node in ACIS cavity.**
  - **Use NGST's thermal predictions for temperature of each node elsewhere on Observatory.**

Mass vaporization rate (vapor pressure) of contaminant

- **Observed column gradient on OBF constrains vaporization rate of contaminant.**
  - **If caused by OBF temperature gradient, deduce a "measured" vaporization rate at -60°C.**
    - **7.1×10^{-8} μg cm^{-2} s^{-1} ($P_v \approx 1.3 \times 10^{-15}$ atm, 350 amu) @ T_1 = -60°C.**
  - **Extrapolate to other T using a reasonable effective vaporization enthalpy (90 kJ $mole^{-1}$).**
    - **6.4×10^{-2} μg cm^{-2} s^{-1} ($P_v \approx 1.3 \times 10^{-9}$ atm, 350 amu) @ T = +20°C.**
  - **If not caused by OBF temperature gradient, have only an upper limit to vaporization rate.**
- **Alternatively, assume a "bad-player" contaminant as a "worst case".**

Geometric model



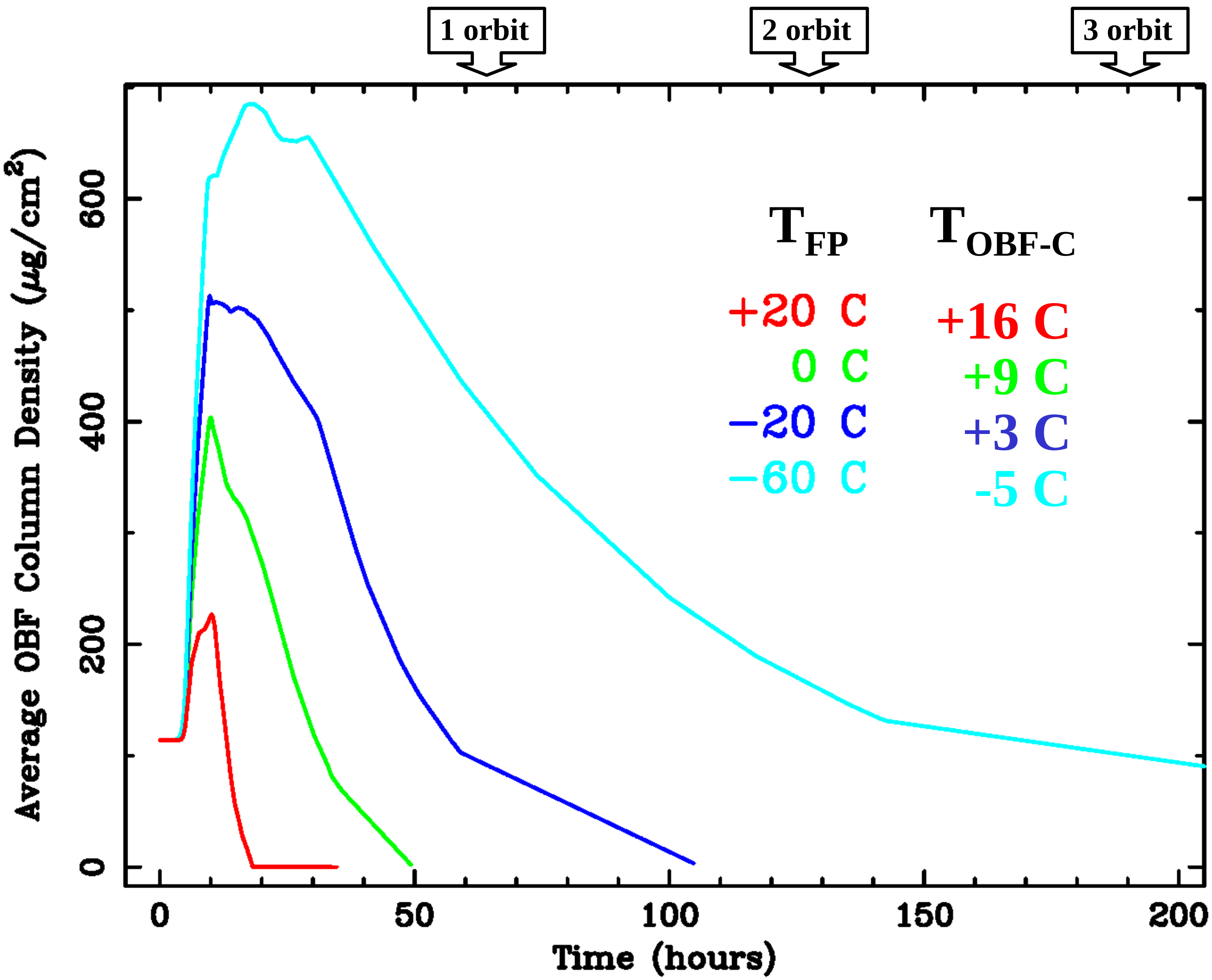


TRASYS model by NGST/ H. Tran et al.

Initial conditions for bake-out

- Group NGST TRASYS 243 nodes as 9 elements (for display only).
  - 24 nodes are hidden — on focal plane (behind OBF) or outside collimator.
  - ACIS model has 9 OBF-I nodes; 27 OBF-S nodes; and 60 collimator nodes (10 axial zones).
- Initial column is 80 μg cm^{-2} at OBF centers; 150 μg cm^{-2} on surfaces < –57.5°C.
  - ACIS contaminant mass ≈ 0.28 g accumulated (≈ 6 × 10^{-8} CXO); ≈ 0.07 g vented.

ID	Nodes #	Area [cm^2]	Area-weighted temperature [°C]				Mass [μg]	Name
			Operate	AH off	Nominal	Sub-nom		
1	36	68	-54	+17	+17.9	+15.4	7726	ACIS OBF
2	32	244	-60	+20	+20.0	+17.5	36620	ACIS camera top
3	12	1335	-60	+21	+21.1	+18.6	200200	Snoot (inner+outer)
4	60	2416	-36	+5.3	+16.3	+13.8	36240	ACIS collimator
5	10	1814	-9.1	-9.1	+10.0	+7.5		SIM translation table
6	4	2839	+3.7	+3.7	+5.0	+2.5		SIM focus structure
7	24	54096	+10.0	+10.0	+10.0	+7.5		OBA stove pipe
8	41	634688	+12.5	+12.5	+12.5	+10.0		Optical bench (OBA)
9	5	476	—	—	—	—		OBA vent



Dependence on focal-plane temperature

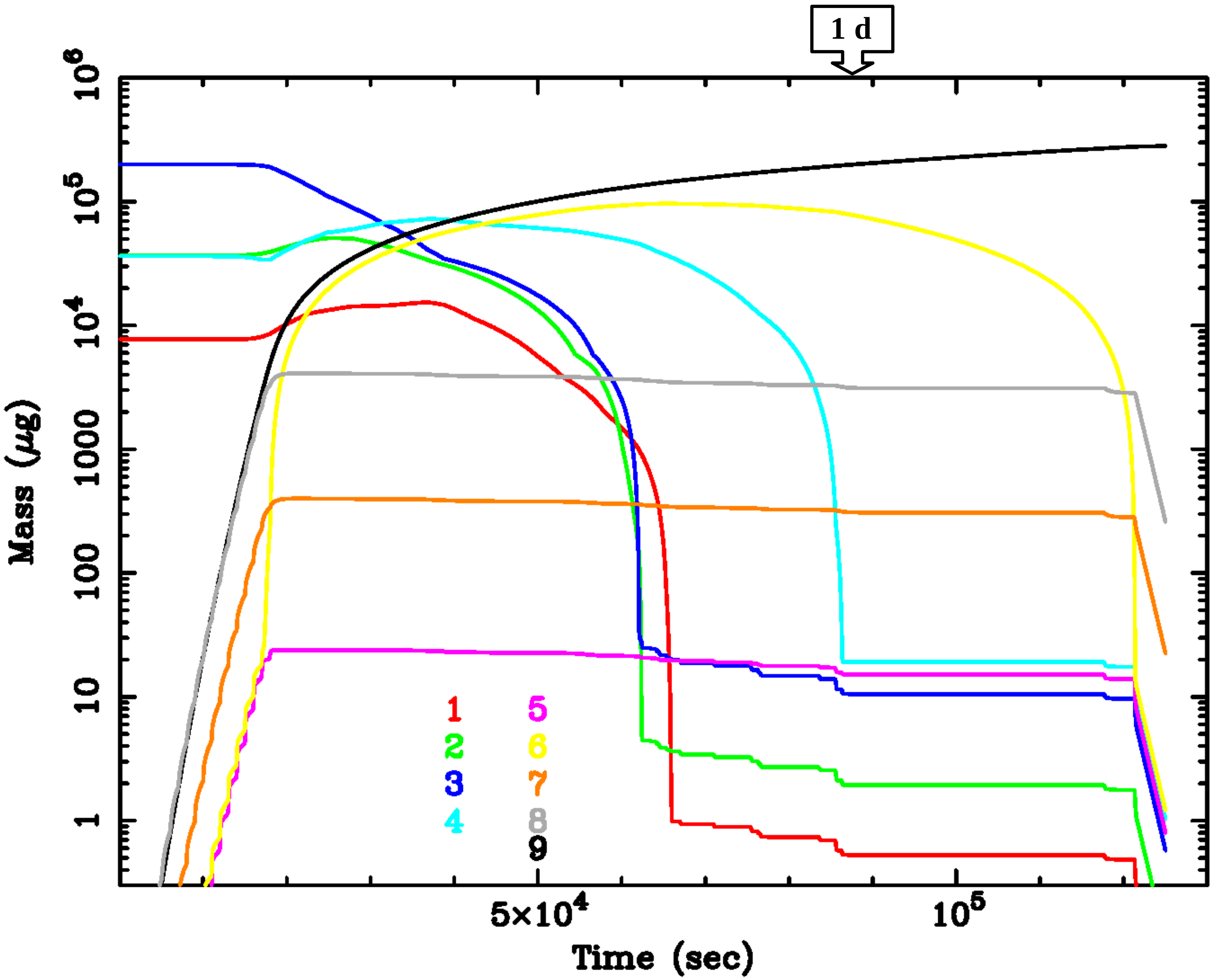
Cold bake-out (T_{FP} << +20°C):

Contamination on OBF shows large initial increase.

Timescale is very long to clean OBF.

Timescale to vent all contamination is even longer.

The warmer, the better.

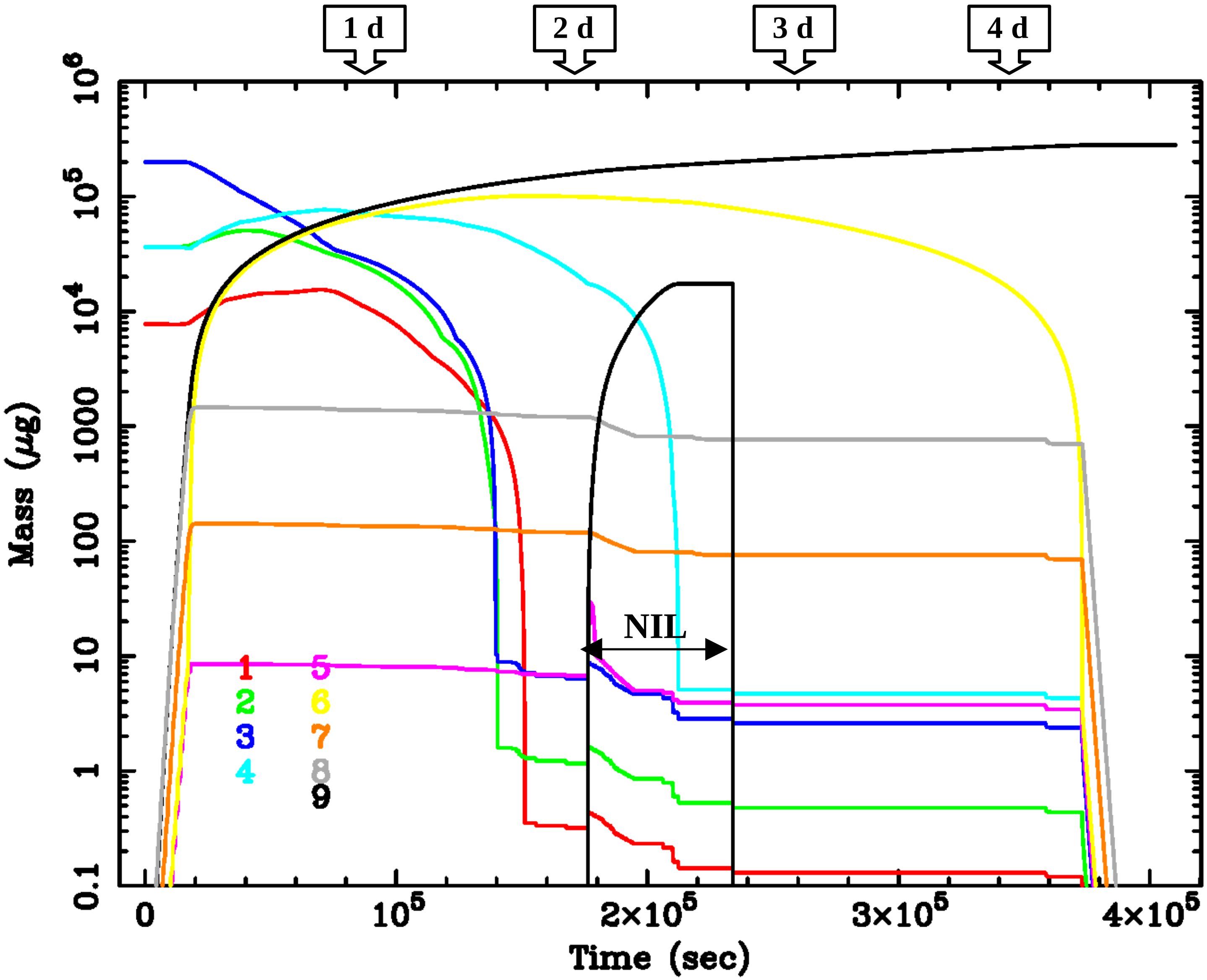


Nominal bake-out

Temperatures:
T_{FP} = +20°C
T_{DH} =+25°C
Abort heat “on”

Vapor pressures:
1.3´10^{-15} atm @-60
1.3´10^{-9} atm @+20
(6´10^{-2} mg cm^{-2} s^{-1})

1: ACIS OBF
2: Camera top
3: ACIS snoot
4: ACIS collimator
5: SIM transl table
6: SIM focus struct
7: OBA stove pipe
8: Optical bench
9: OBA vent



Sub-nominal bake

Temperatures:
De-rate all -2.5°C.

Vapor pressures:
De-rate by another factor of 2.

Net de-rating is factor of 3.

1: ACIS OBF
2: Camera top
3: ACIS snoot
4: ACIS collimator
5: SIM transl table
6: SIM focus struct
7: OBA stove pipe
8: Optical bench
9: OBA vent
NIL FS bottom 0°C

Uncertainties in the simulations

- If column gradient on OBF is due to temperature gradient, compare sub-nominal case.
  - Vaporization rates are 0.35 of nominal vaporization rates
    - De-rate all temperatures by –2.5°C, to account for temperature uncertainty.
    - De-rate vapor pressure, to account for “measurement” uncertainty at –60°C.
  - Uncertainty due to geometric model is probably less than the above uncertainties.
  - Vaporization enthalpy of 90 kJ mole^{-1} is sensible for “measured” vaporization rate.
    - If contaminant is liquid down to –60°C, vaporization enthalpy cannot be much lower.
      - This would lead to higher vaporization (sublimation) rates near room temperature.
    - If contaminant is solid, vaporization (i.e., sublimation) enthalpy could be higher.
  - A mixture of contaminants, some with lower vaporization rates, is likely.
- If OBF column gradient is not due temperature gradient, have just upper limit to rate.
  - “Worst case” is “bad player” with order-of-magnitude lower vaporization rate.
    - If polymerized, contaminant might never vaporize.

A 1-2-orbit warm bake-out is likely, but not certain, to be successful in cleaning OBF.
Primary source of uncertainty is incomplete knowledge of properties of contaminant(s).
A bad-player contaminant would require a substantially (>10´) longer bake-out.
Baking-out with the focal plane warm limits initial contamination growth on OBF.

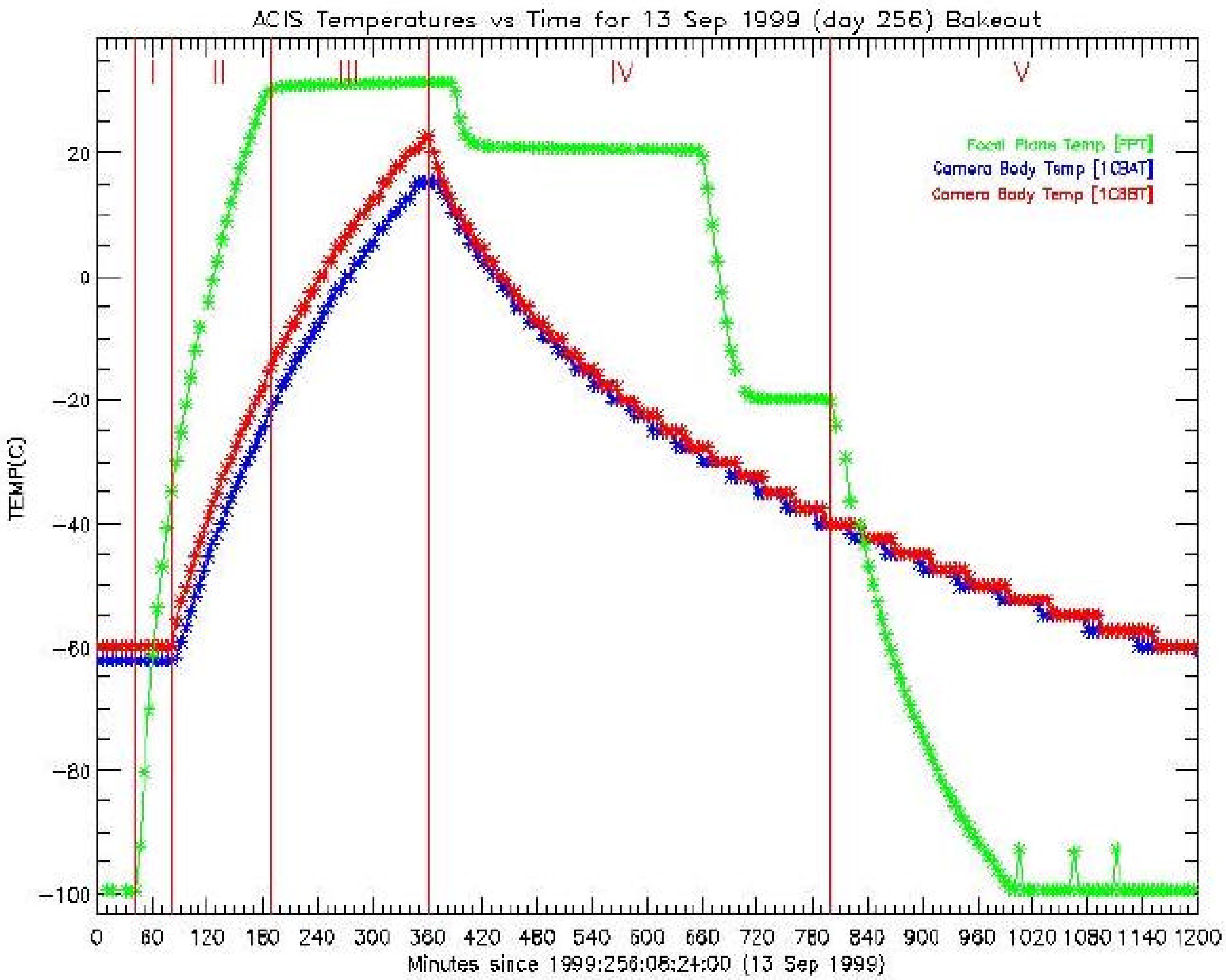
7. Operational Plans for a Bakeout

Bakeout History:

- **The instrument was designed to be baked out. It was thermally cycled from FP < -100 C to +30 C over 40 times on the ground**
- **The pre-launch contamination control plan included regular bakeouts of the ACIS instrument to remove the contaminants.**
- **There have been 4 bakeouts performed in flight, two with the FP to +30 C and two with the FP to -60/-50 C. All four of these bakeouts were executed in 1999.**

Description	Date	Max FP Temp	Duration	Max DH Temp	Duration
Door Opening	Aug 9, 1999	+31.6 C	5.5 hr	+22.8 C	2.5 hr
ACC Opening	Aug 11, 1999	-49.4 C	5.0 hr	-60.0 C	NA
Reverse Annealing	Sep 13, 1999	+31.6 C	3.0 hr	+22.8 C	2.5 hr
-60 C Measurements	Sep 18, 1999	-59.5 C	7.0 hr	-60.0 C	NA

Sep 13, 1999 Bakeout Profile



Proposed Bakeout

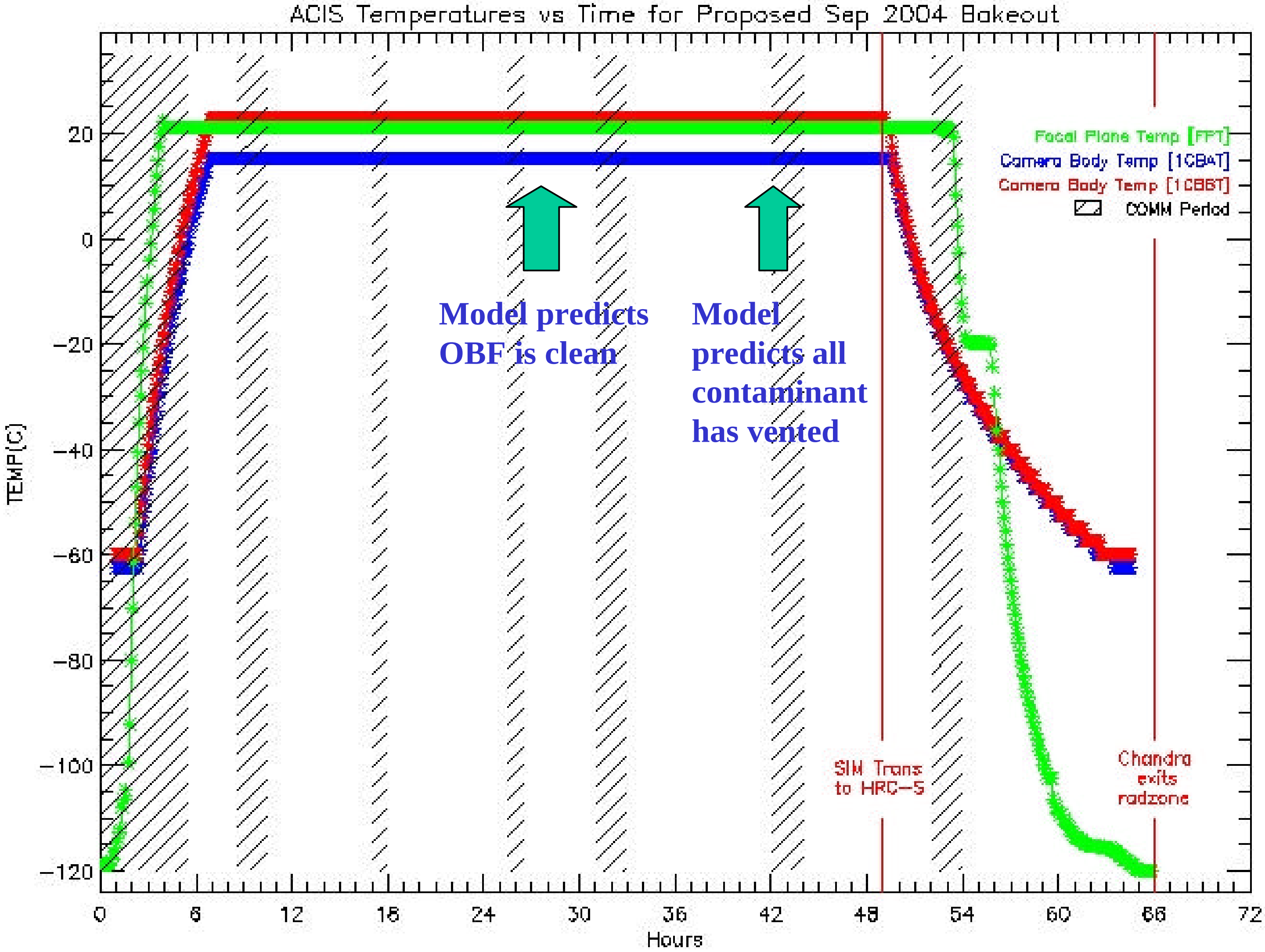
Differences:

- The FP temperature will be set to +20 C instead of +30 C
- The hot phase of the bakeout will last for 50 hr instead of 8 hr
- The SIM abort heaters will be used

Similarities:

- The same ACIS heaters will be used
- Every ACIS command will be a command which has been used previously
- Existing procedure will be modified to change set point for the FP temperature

Possible FP=+20 C, DH=+20 C Bakeout Profile



Contingency Plans

There are two main contingencies to be planned for:

- **Bakeout achieves lower than expected temperatures on the ISIM, the ACIS DH, or the ACIS FP**
    - **We are planning to turn on the FP heater and the SIM abort heaters before the bakeout activity to verify that they still work as expected.**
- **Bakeout results in higher than expected temperatures**
    - **Turn off the heaters and terminate the bakeout.**

8. Risk Analysis

Risks Associated with Bakeout

1) Thermal cycling results in a HW failure in the ACIS instrument
2) Damage to the OBF
3) CTI increases by an unacceptable amount
4) Unexpected change in contamination
   - 4a) contamination increases in thickness
   - 4b) contamination returns quickly
   - 4c) contamination migrates to another spacecraft system
5) Thermal cycling has a negative impact on the spacecraft

Risk Assessment

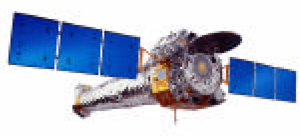
RISK	**MITIGATION**	**IMPACT**	**PROBABILITY**
1. HW failure due to thermal cycling	Assessment by ACIS engineering team, HW design, previous bakeouts	Moderate Possible degradation	Very low
2. OBF Damage	Ground tests at NGST on spare flight OBFs	Moderate Loss of science	Very low
3. Larger than anticipated CTI increase	Ground irradiation tests on spare flight CCDs	Low Loss of science	Very low
4. Undesirable change in contamination	Simulations of bakeout, materials testing	Moderate Loss of science	Low
5. Thermal cycle has adverse effect on spacecraft	Assessment by Chandra FOT and NGST	Low Possible misalignment	Very low

RISK #1: Thermal cycling results in a HW failure in the ACIS instrument

- The instrument was designed to be thermally cycled
- The instrument was thermally cycled from -100 C to +30 C over 40 times on the ground during calibration and thermal vac tests
- The instrument has been thermally cycled to +30 C twice in orbit
- The ACIS engineering team evaluated the risk and considered it to be very low
- The types of failures considered were breakage of bond wires to the CCDs, damage to the flexprint connectors, on-chip amplifier, etc. If some failure were to occur, it would most likely result in the loss of one output node on a CCD. It would not be a catastrophic failure of the entire FP.

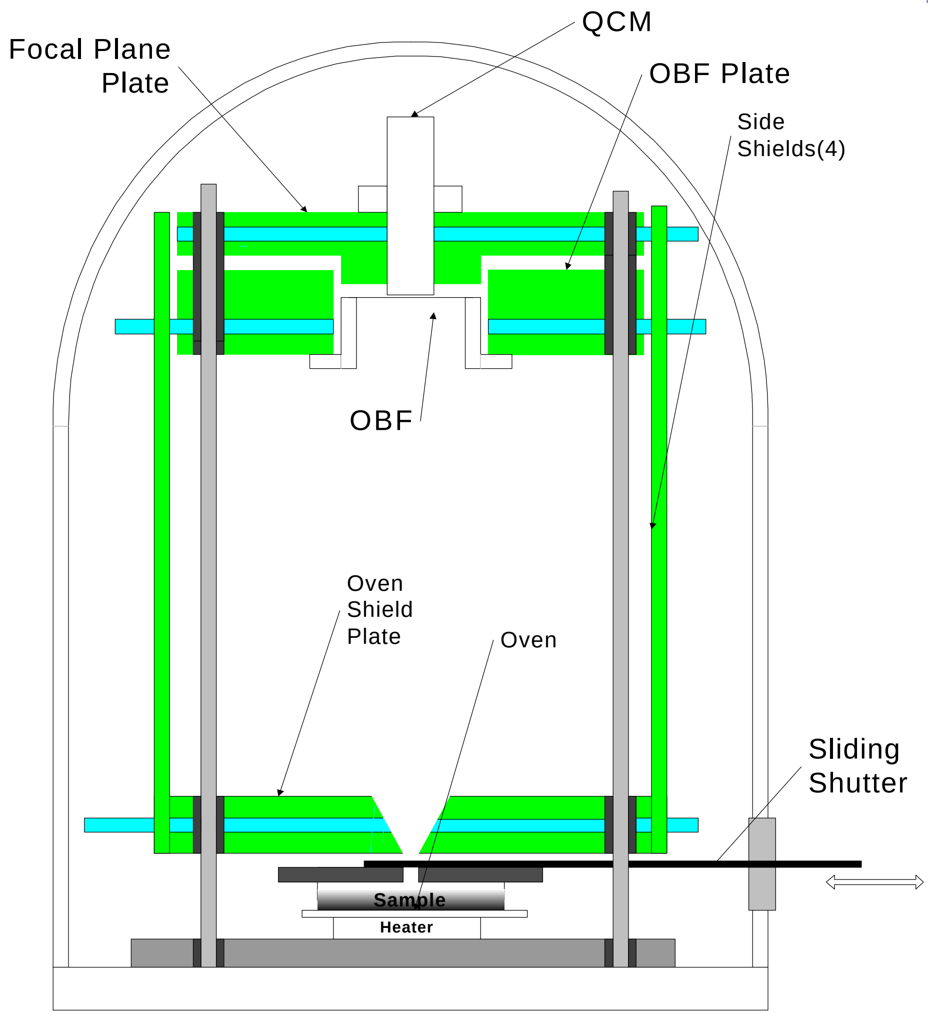
RISK #2: Thermal cycling results in Damage to the ACIS OBF

- **The threat to the ACIS OBF was the one new issue which was uncovered during the ACIS engineering team review**
- **The concern is that the filter, with a thick layer of contaminant on it, is mechanically different than the filter which was thermally cycled in the ground tests (the contaminant is about as thick as the filter)**
- **To address this concern, a series of tests on spare flight filters were commissioned at NGST, overseen by Marty Mach**
- **Two ACIS spare flight filters (one ACIS-I and one ACIS-S) were intentionally contaminated and then thermally cycled**
- **The candidate contaminant was a paraffin wax (Calwax 160) since it provided a large mismatch in CTE with the Al and polyimide of the filter and it desorbed slowly at +25 C but reasonably quickly at +50 C**
- **The tests were designed to be more stressing than the flight bakeout: a thicker layer of the contaminant was deposited, temperature ramp rates were larger than in flight, 40 thermal cycles were executed, the contaminant would not come off at +25 C (this was considered a worst case)**

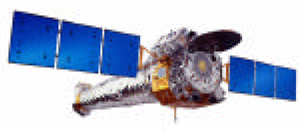


OBF Test Setup

CXC



- **Details**
  - **Focal Plane and OBF Plates create X-Y temperature gradient across OBF membrane**
  - **Individual temperature controlled zones**
    - **Helps duplicate on-orbit conditions**
    - **Computer controlled heating and cooling**

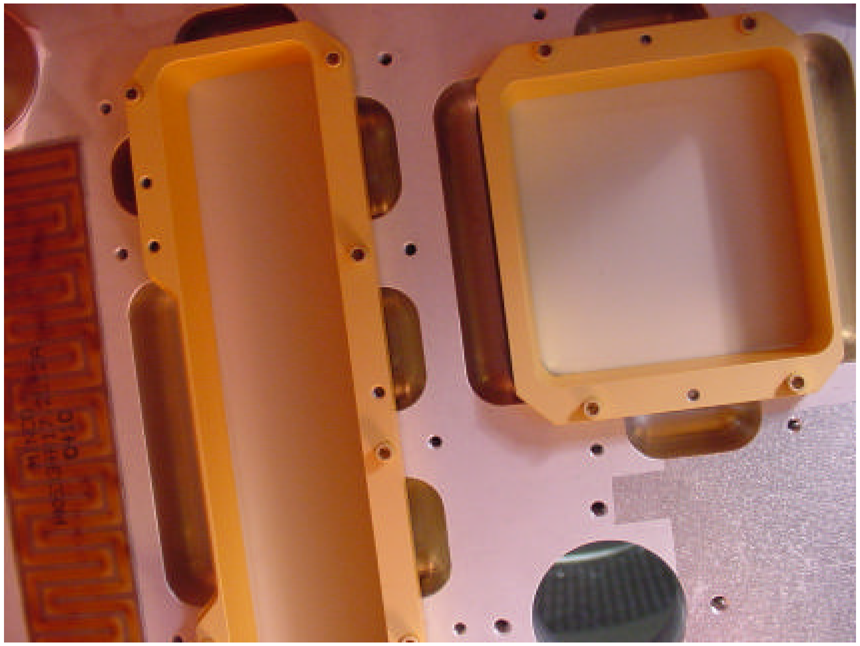
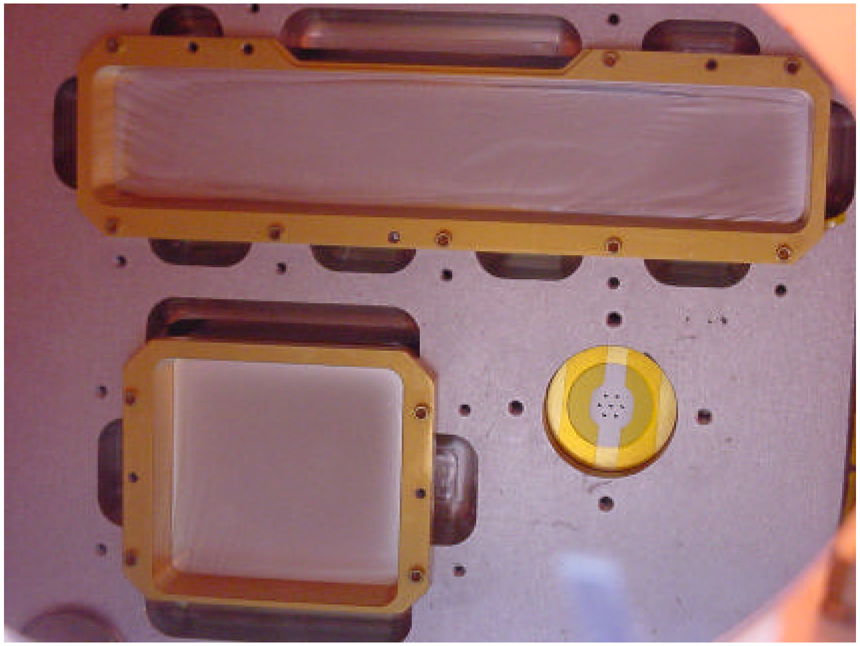


OBF Tests

CXC

Test #	Description	Comments
0	Trial runs of temp controls, computer, etc.	
1	Calibrate QCM response for 300 ug/cm^2 deposition	Aperture plate and witness samples
2	Calibration of surrogate filter response to varying FPP temperatures	Use NGST-fabbed thermocouple-instrumented OBFs
3	“Room Temp” OBF cycles	Deposit 118 ug/cm^2, 40 temp cycles.
4	Contaminant removal	5 cycles after 50C bakeout of OBFs
5	Cold FPP bakeout	Deposit 180 ug/cm^2, 40 temp cycles
6	Contaminant removal, temp cycle	5 cycles after 60C bakeout of OBFs

RISK #2: Before and After Pictures of the OBF Tests (Part III)

OBFs with thick layer of contaminant	OBFs at the completion of the tests
	

RESULT: There was no damage to the OBFs at any point during these tests.

RISK #3: Larger Than Expected Increase in CTI

- **The ACIS instrument team expects that the charge-transfer inefficiency (CTI) of the FI and BI CCDs will increase if the FP temperature is raised to +20 C. This expectation is based on the room temperature bakeout of Sep 13, 1999, ground irradiation tests, and theoretical arguments.**

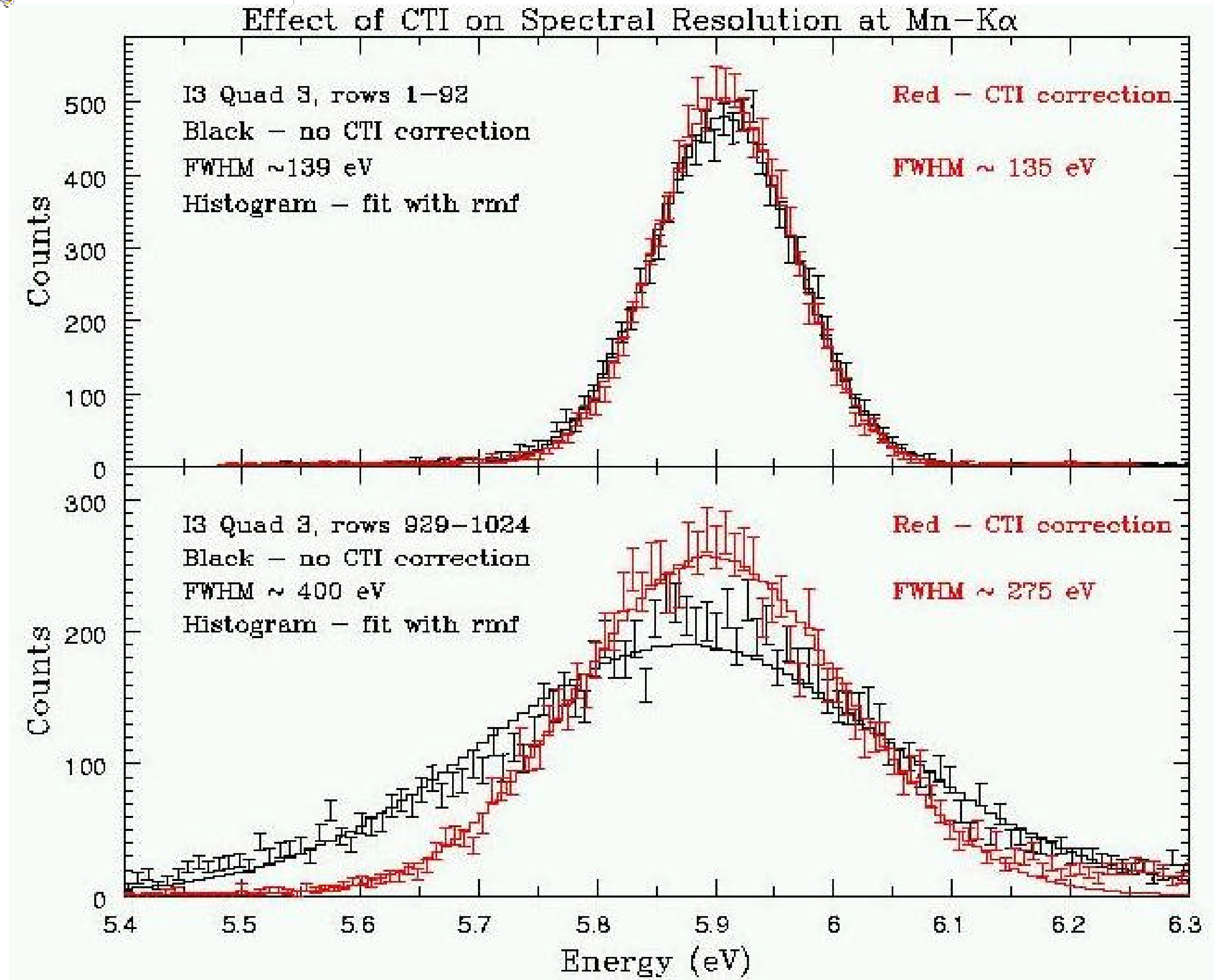
- **The instrument team expects that the FI CCDs will exhibit a range of increases from 5-30% and the BI CCDs will increase between 0-10 %. The relevant quantity for the observer is the FWHM or spectral resolution. The FWHM of the FI CCDs is expected to increase by 3-20% and of the BI CCDs by 0-2%.**

- **CTI increases of this magnitude do *not* impact the 15 year lifetime of the *Chandra* mission.**

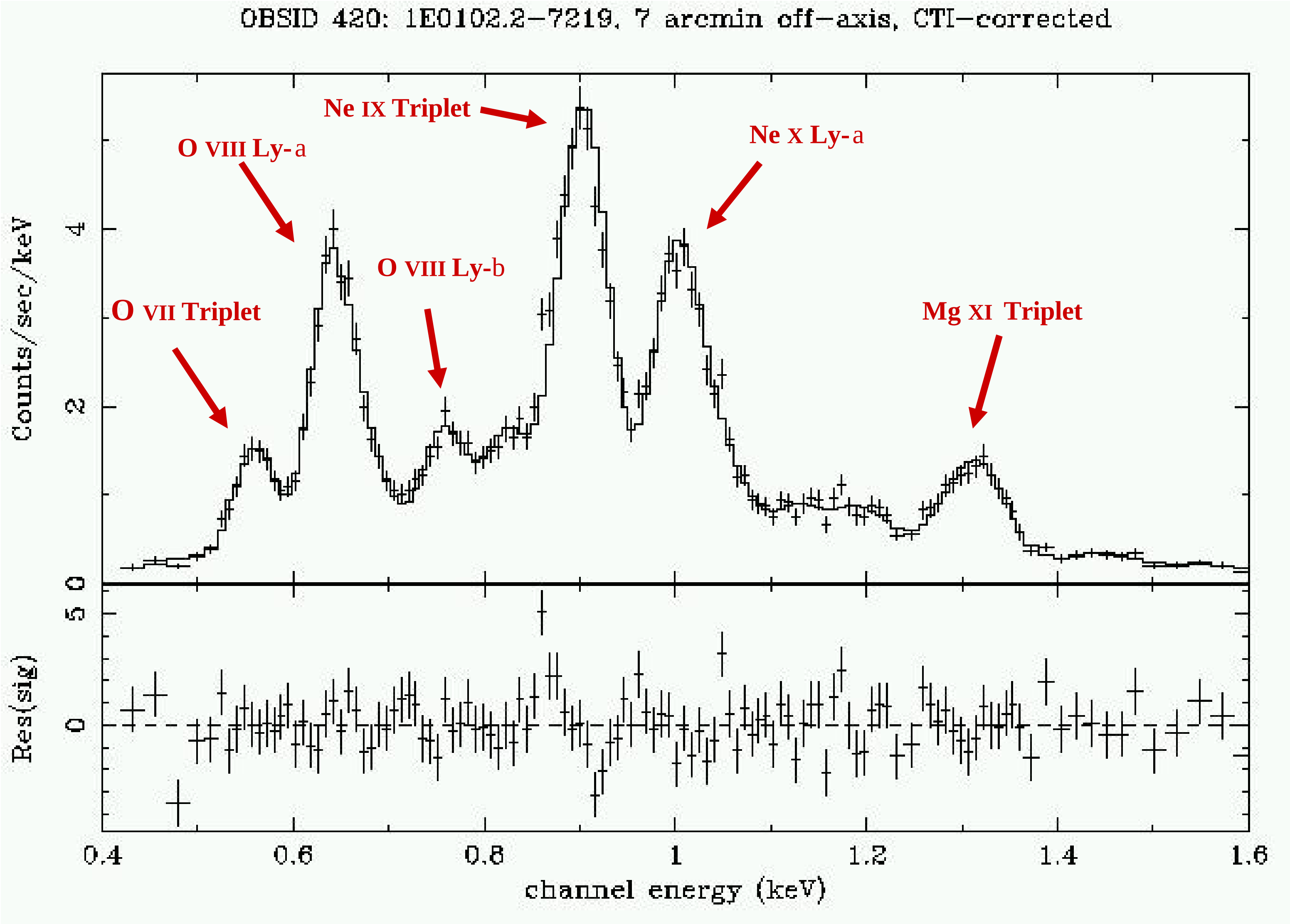
- **The S3 detector is the primary detector of the ACIS instrument and a 0-2% increase in FWHM is not a significant impact on any science program.**

- **An increase in the FWHM of the FI CCDs by 3-20% will be significant, but tolerable.**

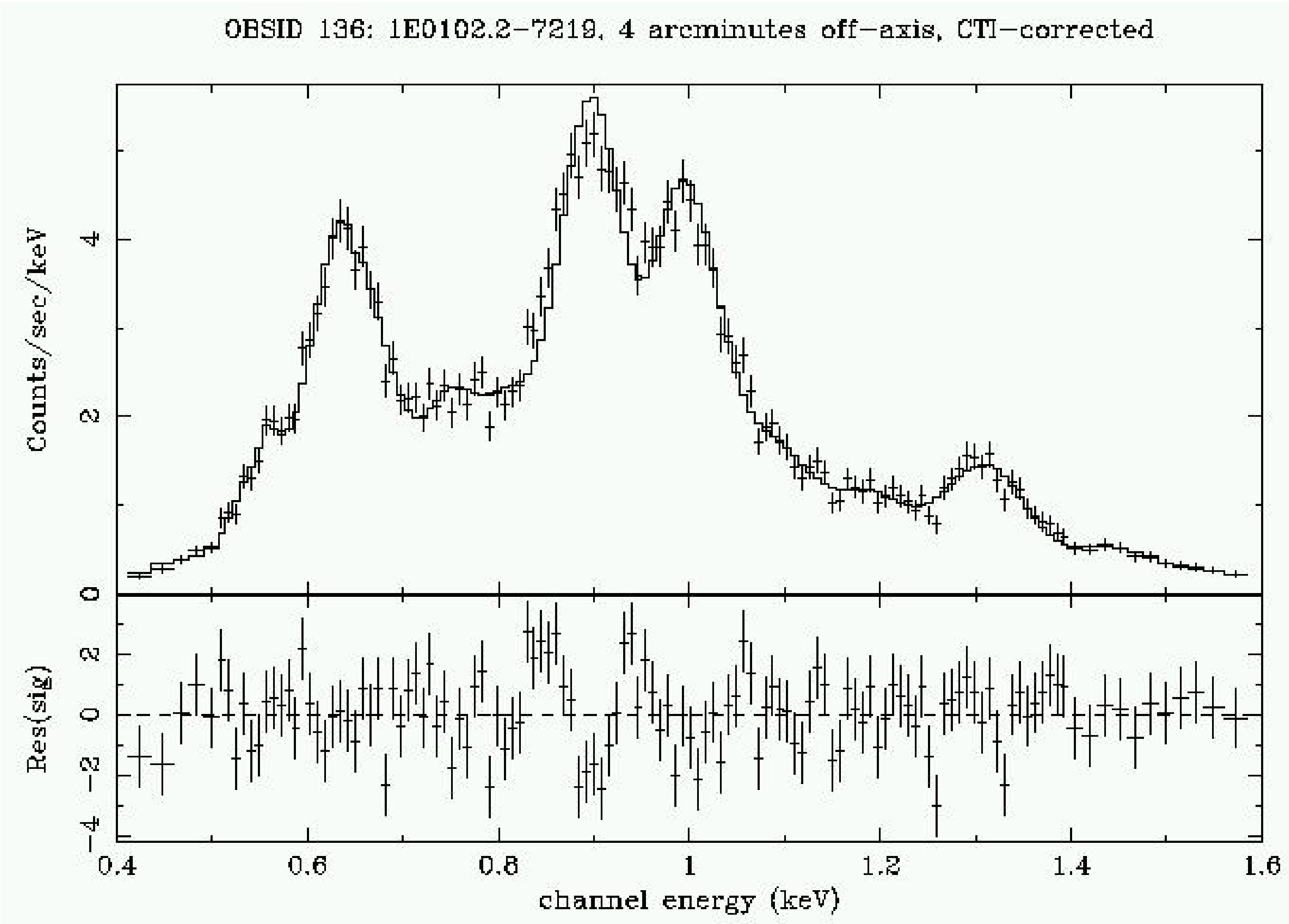
- **We have experimental and theoretical reasons to believe that CTI increases larger than 30% are unlikely.**


Effect of CTI on Spectral Resolution at Mn-Kα
I3 Quad 3, rows 1-92
Black – no CTI correction
FWHM ~139 eV
Histogram – fit with rmf
Red – CTI correction
FWHM ~ 135 eV
I3 Quad 3, rows 929-1024
Black – no CTI correction
FWHM ~ 400 eV
Histogram – fit with rmf
Red – CTI correction
FWHM ~ 275 eV
Counts
Counts
Energy (eV)
0
100
200
300
400
500
0
100
200
300
5.4
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3

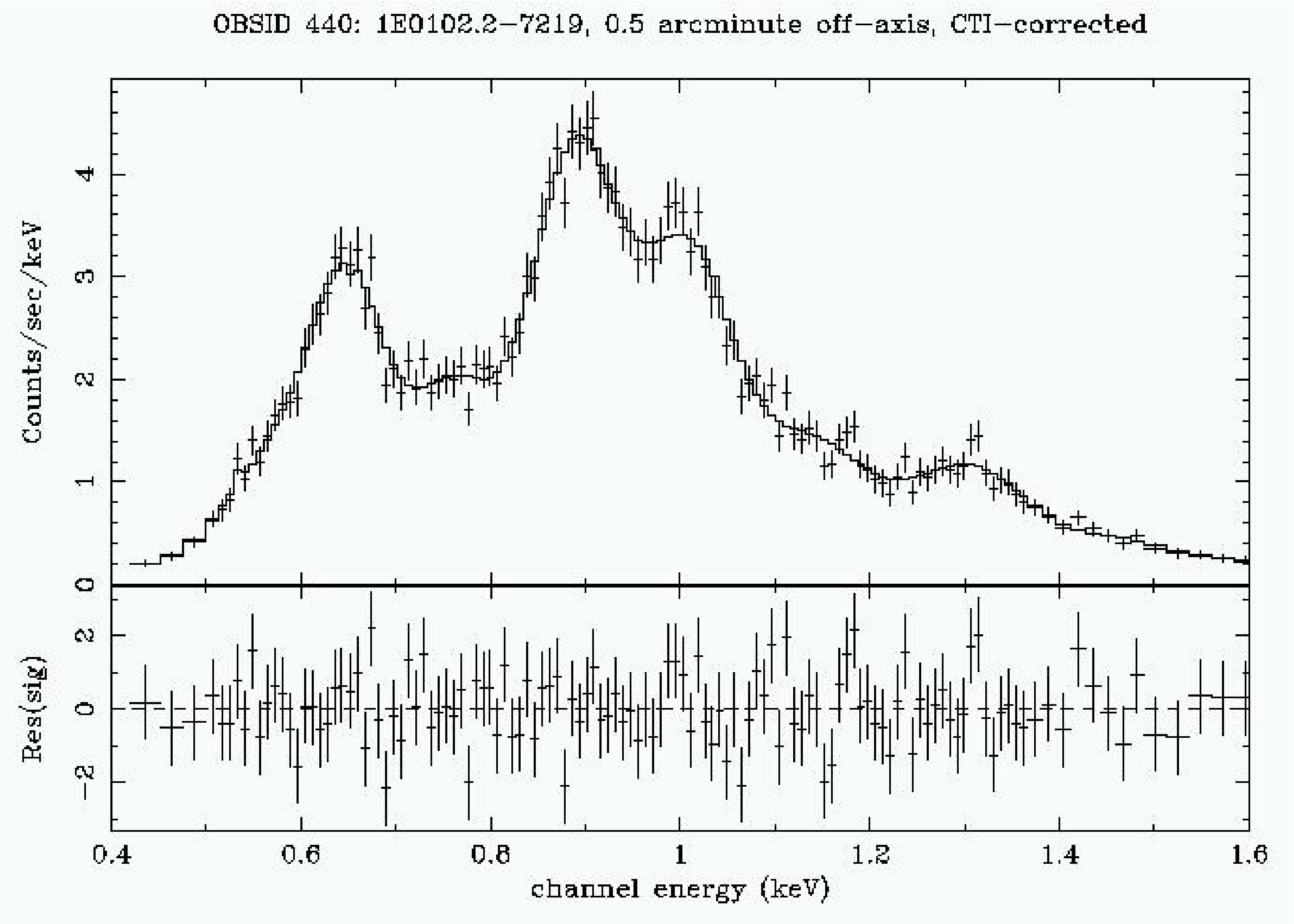
I3 Spectrum of 1E0102.2-7219: CTI Correction and Effective Area Correction



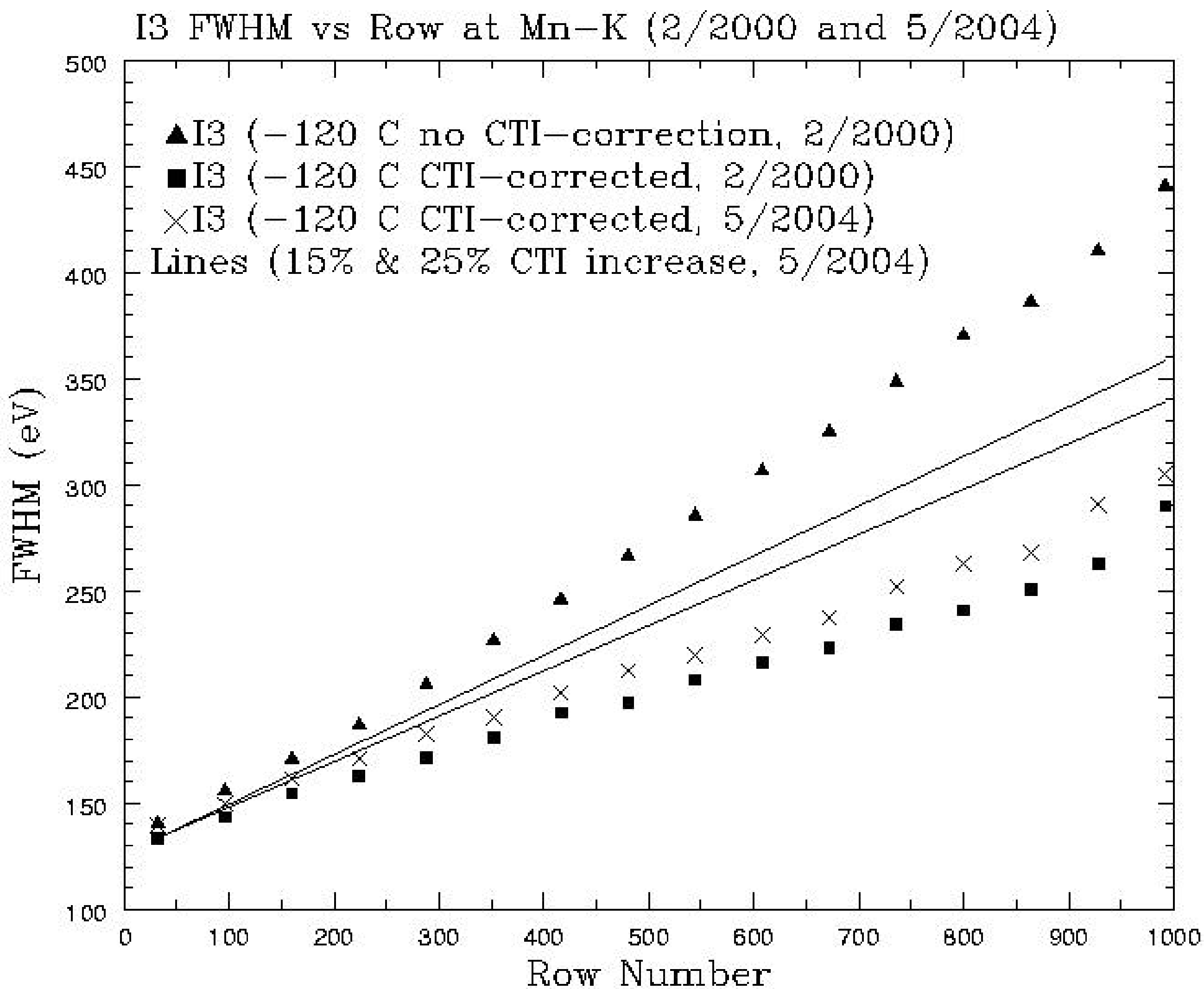
I3 Spectrum of 1E0102.2-7219:CTI-correction and Effective Area Correction



I3 Spectrum of 1E0102.2-7219: CTI-correction and Effective Area Correction

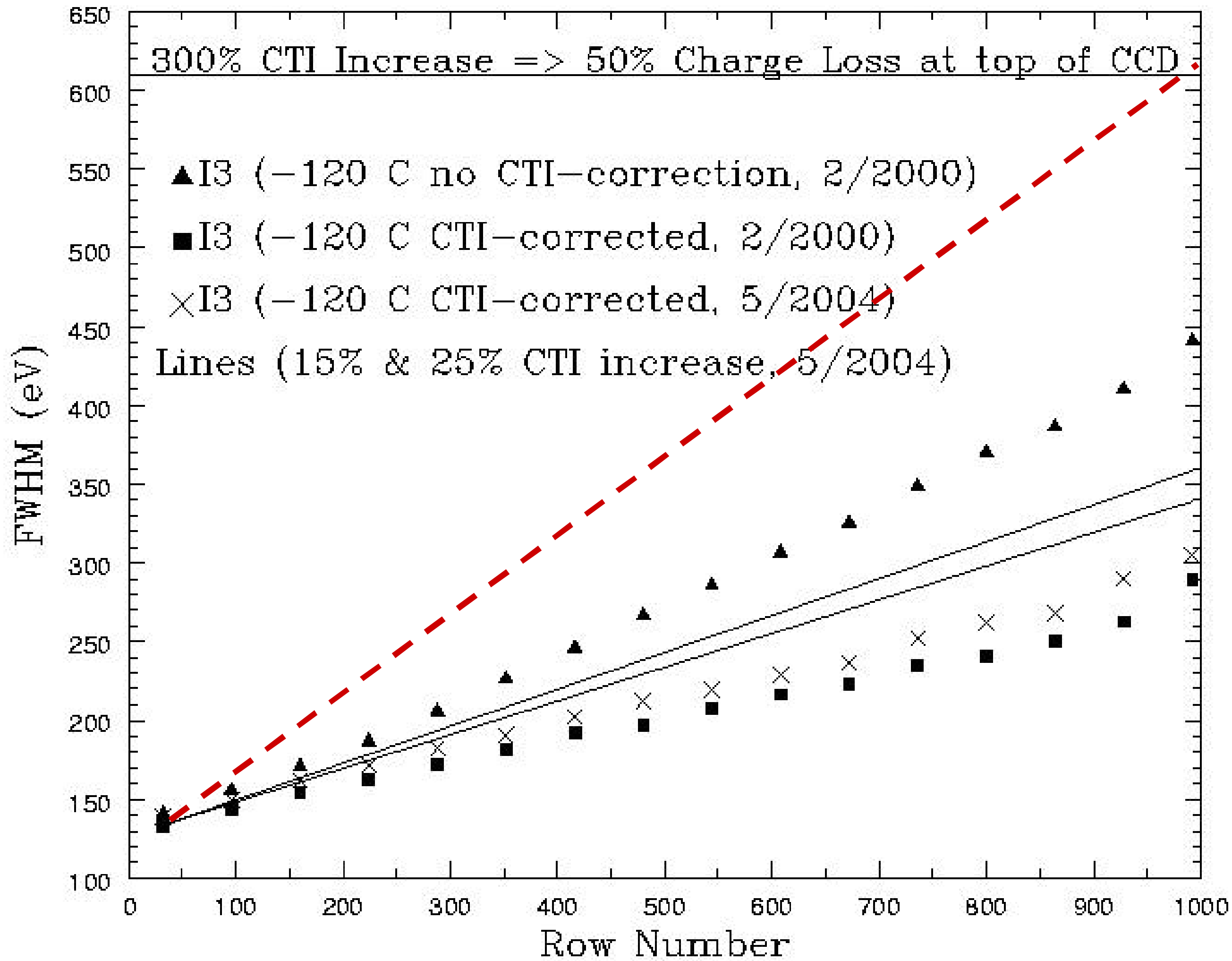


FWHM vs. row number for -120 C and -120 C (CTI corrected) and for 15.0 & 25.0 % CTI Increases



Predictions for FWHM include the 10% increase in CTI from 2000 to 2004 and the estimated 15.0% and 25.0% increase due to the bakeout.

CTI Increase for which Imaging is Severely Impacted



CCDs are no longer useful for imaging at the top of the CCD when, on average, half the charge packet is lost during the transfer.

Impact of Higher CTI on End-of-Life Properties of the CCDs

- CTI increase of the FI CCDs is managed to be less than 3% per year, thus a 15% increase represents 5 years of CTI increase at the current rate

Impact on FI CCDs

- Spectral resolution might degrade by up to 20% at the top of the CCD
- Low energy detection threshold might increase from 340 eV to 400 eV for a 30% increase in CTI
- Gain would need to be re-calibrated, redistribution function might need to be recalibrated for CTI increases approaching 30%

Impact on BI CCDs

- Spectral resolution could degrade by up to 2%
- No change to low energy detection threshold
- Gain would need to be re-calibrated

ACIS CTI Increase During Bakeout

Summary:

- Ground and Flight Experience with Bakeout
- (One) Model for Reverse Annealing
- Model Predictions
- Assessment of Predictions

Flight Experience

- On day 1999:256, after significant, radiation-induced CTI degradation, ACIS focal plane was "baked out" to +30C
- Observed CTI change[a] due to bakeout:
  * Front-illuminated (FI) device:

$$CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.32 \pm 0.01$$

  * Back-illuminated (BI) device:

$$CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.30 \pm 0.36$$

[a] *Expressed as a fraction of pre-bakeout, radiation-induced CTI change.*

Laboratory Experience

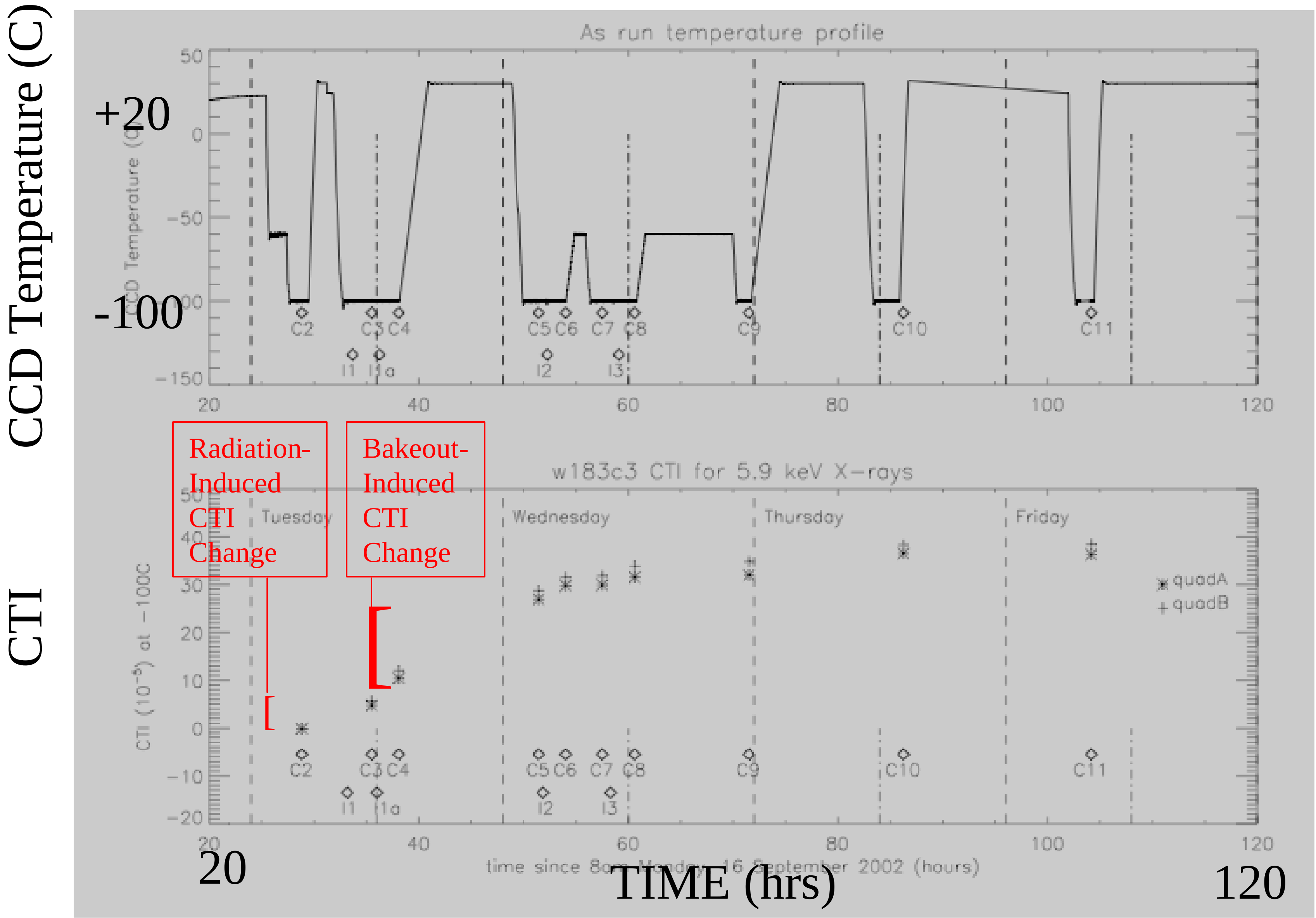
- ACIS sibling (FI) CCD irradiated cold in lab. test
- Test radiation & bakeout profile simulated 1999 flight events
- Post-irradiation bakeout did increase CTI
- Observed CTI change[a] due to bakeout:
  - *Lab:* Front-illuminated (FI) device:

    $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 2.48 \pm 0.01$
  - *cf Flight:* Front-illuminated (FI) device:

    $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.32 \pm 0.03$
- Lab & flight results agree qualitatively, but not quantitatively.

[a] *Expressed as a fraction of pre-bakeout, radiation-induced CTI change.*

Laboratory Bakeout Experience



"Modeling" CTI Increase

- A model is required to predict CTI change in future ACIS bakeout.
- Model must account for differences between laboratory & flight bakeout results.
- One possible model:
  * Reverse annealing of carbon impurities causes CTI increase during bakeout.
  * Model accounts for lab & flight results by supposing plausible chip-to-chip variations in carbon concentration.
  * Model is NOT unique & is probably much simpler than reality.

Model Predictions

CCD	Inferred Carbon Content[a]	Current CTI[b]	Predicted CTI Change from Proposed Bakeout[c] $CTI_{postbake}/CTI_{prebake}$
ACIS S2 (FI)	0.3 - 0.4	1.6	1.14 - 1.26
ACIS S3 (BI)	0.3 - 0.4	0.16	1.06 - 1.12
Lab Test CCD (FI) Hypothetically On-orbit	1	2.7	1.14 - 1.33
Hypothetical Carbon Poor (FI)	0.1	1.3	1.02 - 1.08

[a] *Relative to lab test device.* [b]*Arbitrary units.* [c] *150 ks duration @ focal plane temperature = 20C*

Assessment of Model Predictions

- Simple reverse annealing model predicts

$$CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.02 - 1.33$$

- Model appears to be consistent with all available data, but is not firmly established
- ACIS team consensus: For proposed bakeout,

FI devices:

* $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.15 - 1.3$ is plausible
* $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} < 2$ with very high confidence

BI devices:

* Expect smaller (relative) CTI change than for FI devices
* $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} = 1.0 - 1.1$ is plausible
* $CTI_{post\text{-}bake}/CTI_{pre\text{-}bake} < 2$ with very high confidence

RISK 4A: Contaminant Increase in Thickness

- **Contaminant will migrate to the coldest surface and will remain on that surface for a characteristic time depending on the temperature of that surface**
- **By making the system (ACIS OBF, DH, collimator, etc) as isothermal as possible during the bakeout, the risk that any surface will act as a ``cold trap'' is minimized**

RISK 4B: Contaminant Returns Quickly

- **Venting analysis included in the MSFC PS model was verified by an analysis from Lockheed-Martin and MIT instrument teams**
- **Raising the temperature of the top of the ACIS collimator and the SIM surfaces ensures that the contaminant will migrate quickly to the OBA volume. Once in the OBA volume, the vast majority of the contaminant will vent overboard and very little will remain inside the cavity.**
- **The Bakeout duration was chosen to allow adequate time for the contaminant to migrate into the OBA volume.**

Spacecraft Impact Analysis

- **The proposed ACIS bakeout scenario has been analyzed by NGST to properly assess any impact to the satellite**
  - **2 Issues identified**

1. **Contaminant migration to other sensitive surfaces**
2. **Structural changes due to thermal distortion**

- **There are no known risks associated with the ACIS bakeout that would compromise the safety or health of the vehicle**

RISK #4C: Contamination Migration to Other Sensitive Surfaces

- **Issue**
  - Outgassing products from bakeout could condense on other contamination sensitive spacecraft surfaces

- **Potential surfaces**
  - Telescope mirrors
    - No condensation since they will be warmer (21 deg C) than the much larger and colder OBA (10 deg C)
  - Thermal control surfaces and ACS sensors
    - Minor temperature gradient for most thermal control surfaces
    - Minimal view factors to potential vents
    - Small amount of condensable contaminants (0.3 grams)
  - Solar arrays
    - Cells will be much warmer than outgassing source
    - Small viewfactors to potential vents

RISK 5: Structural Changes due to Thermal Distortion

- **High Output Paraffin Actuators**
  - **Used in ACIS Door (2), HRC Door (1), HRC Cal Source (1)**
  - **Thermally actuated device**
  - **Verified to be "non operational" at 158 deg F**
    - **No ISIM temperature is expected to reach this temperature during the bakeout**

- **Reviewed SIM Translation Table and Focus Structure minimum structural margins of safety in the SIM Structure CDA Package, dated 6 December 1995**
  - **Worst case load condition (either launch, abort landing or on-orbit thermal)**
  - **Include a factor of safety of 2.0**

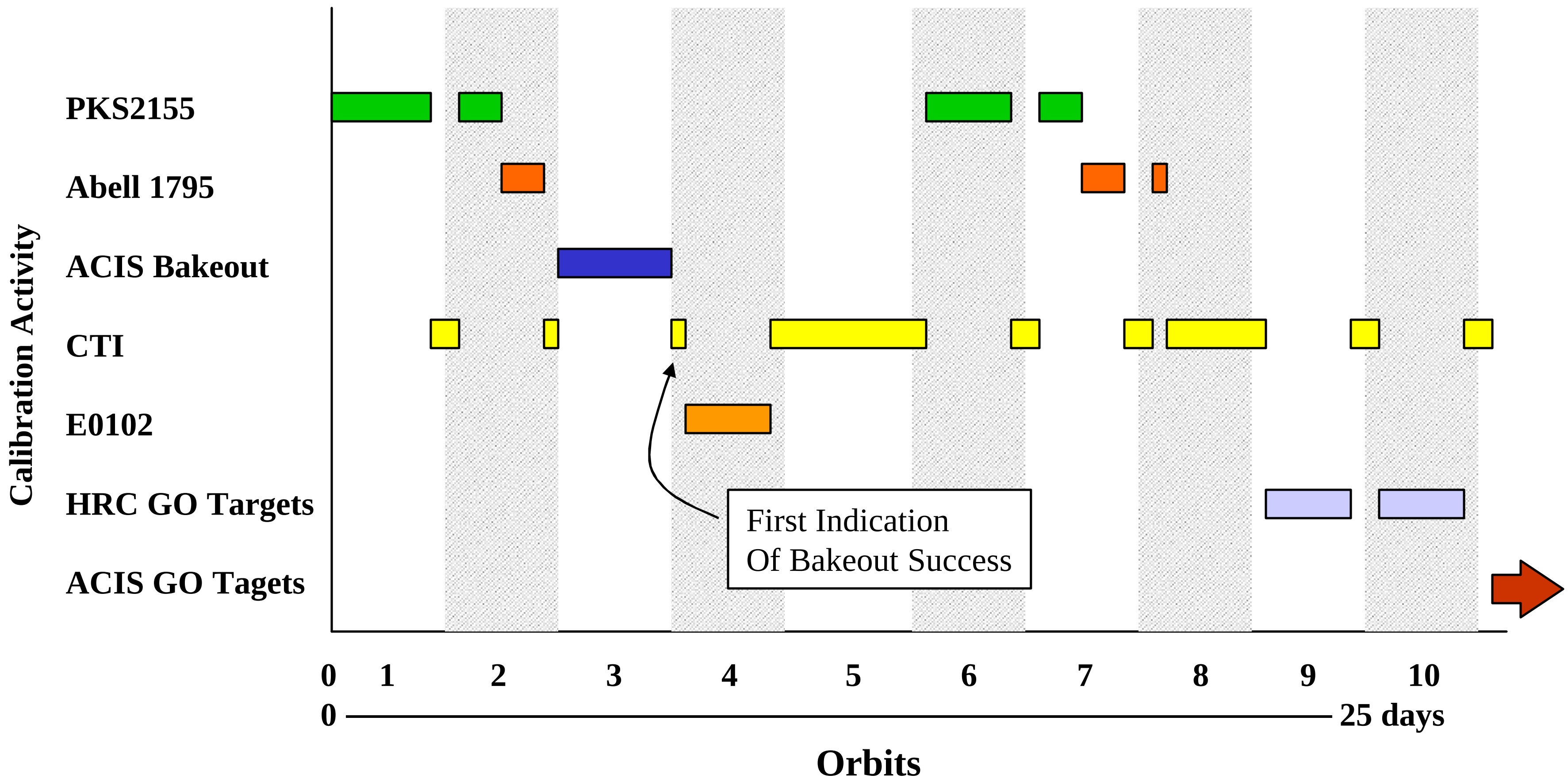
RISK 5: Structural Changes due to Thermal Distortion (cont)

- **Bond joints between the metallic fittings and the graphite structure are the items of most interest**
  - **Fittings & bond joints were designed to sustain Shuttle abort landing loads at a temperature of 10 deg C (50 deg F)**
- **Thermal-only structure load conditions**
  - **Stress generated by CTE mismatch between graphite structure and metallic fittings**
  - **Max delta-T on-orbit cold cases cause the most severe thermal-only bond joint stresses**
  - **The approx 12 deg C (54 deg F) Translation Table temperatures predicted for the ACIS bakeout are less severe than cold operational and survival temperatures**
- **Conclusion: Predicted ACIS bakeout temperatures are not a threat to the SIM structure**

9. Calibration Plans for Bakeout

- **The CXC calibration group has developed a plan of calibration observations before and after the bakeout for roughly a million seconds.**
- **There will be no calibration data collected during the bakeout, however the first calibration observation after the bakeout will be a 30 ks observation of the external calibration source which will tell us immediately the success level of the bakeout.**
- **There are 5 orbits of calibration data to be acquired after the bakeout. We expect that there will be two orbits of HRC observations. ACIS science observations should resume on the eight orbit after bakeout.**
- **The limiting factor on when the data will be useful to GOs is when the CXC calibration team can produce new calibration products for the post-bakeout performance. We believe we will have all of the necessary SW in place by the bakeout. The calibration team believes that the time required to generate new products depends on both the level of removal of the contaminant and the magnitude of the change in the CCD performance. The estimates range from one to five months.**

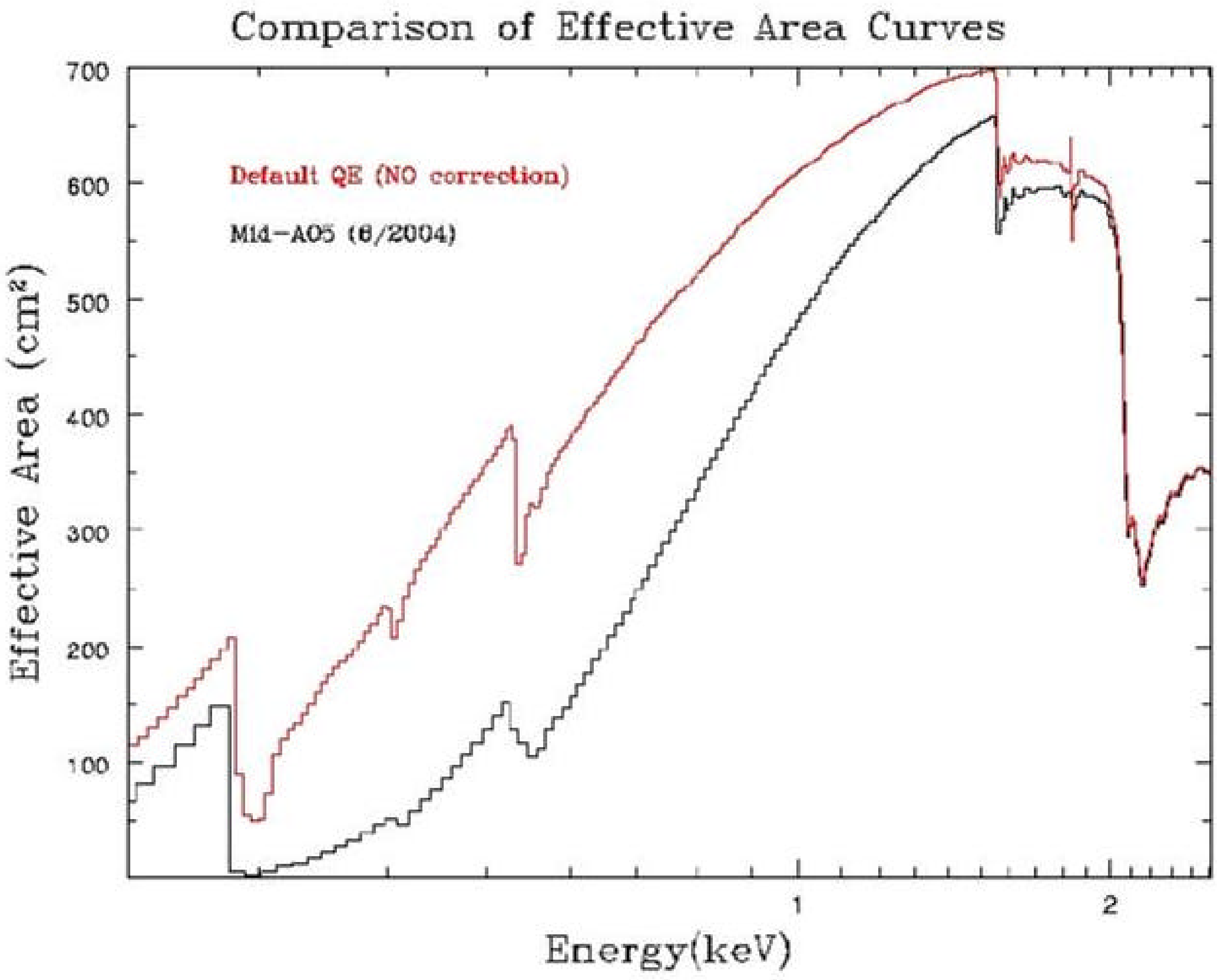
ACIS Bakeout Timeline with Calibration Observations



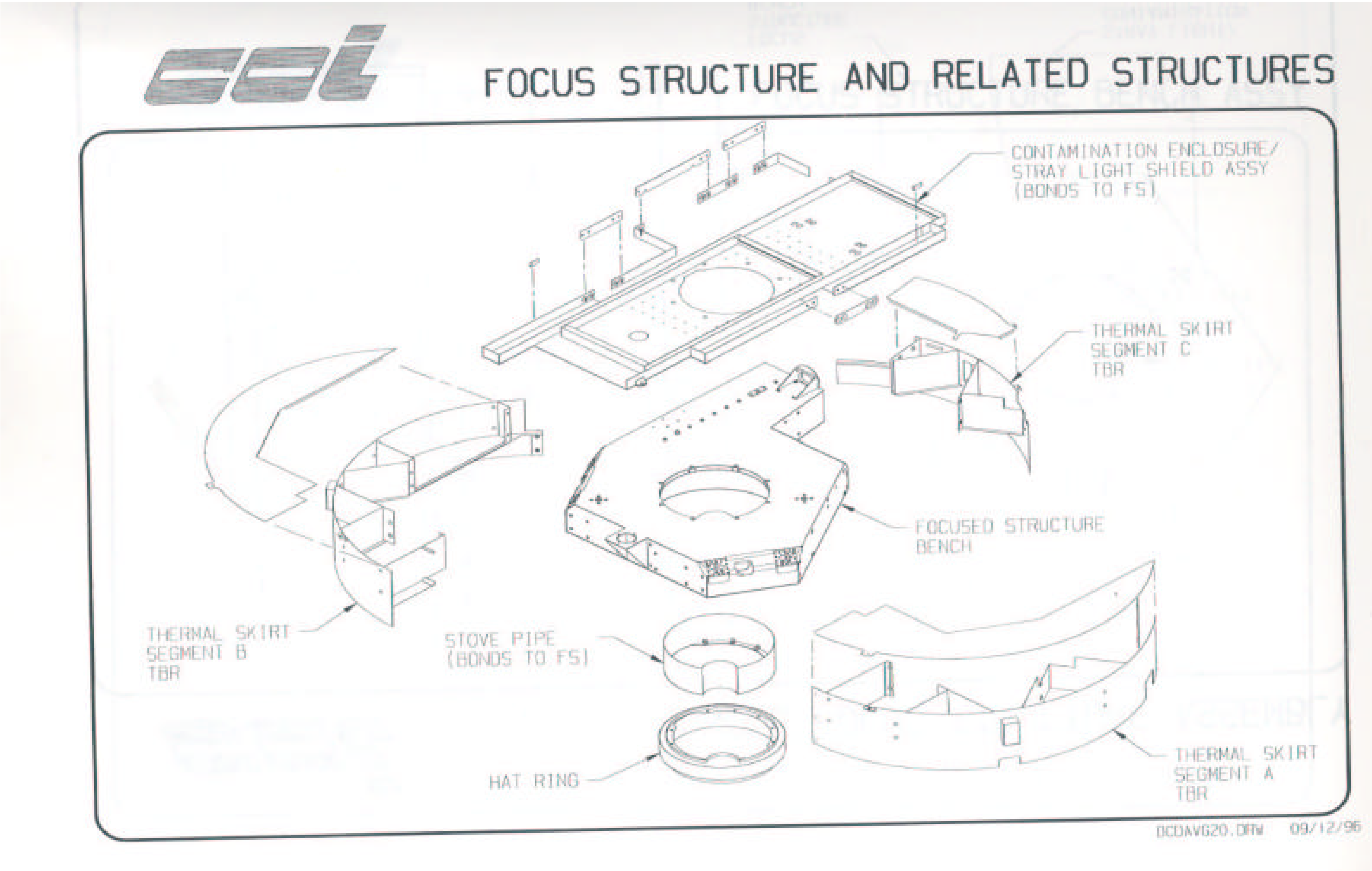
10. Conclusions

- **The ACIS contamination working group has evaluated the risks and the costs versus benefits of a bakeout and has determined that the bakeout is worth perfoming.**
- **The group recommends that a FP=+20 C/DH=+20 C bakeout be executed for one orbit (150 ks of hot phase).**
- **The expected return is recovery of most of the HRMA+ACIS effective area.**
- **This will lead to an additional 1.8 million seconds of observing time in the first year and additional recovery in the following years. The exact amount depends on how quickly the contaminant re-accumulates.**
- **This will also lead to the recovery of science projects which are no longer feasible with *Chandra*.**

Decrease in Effective Area vs. Time



Focus Structure

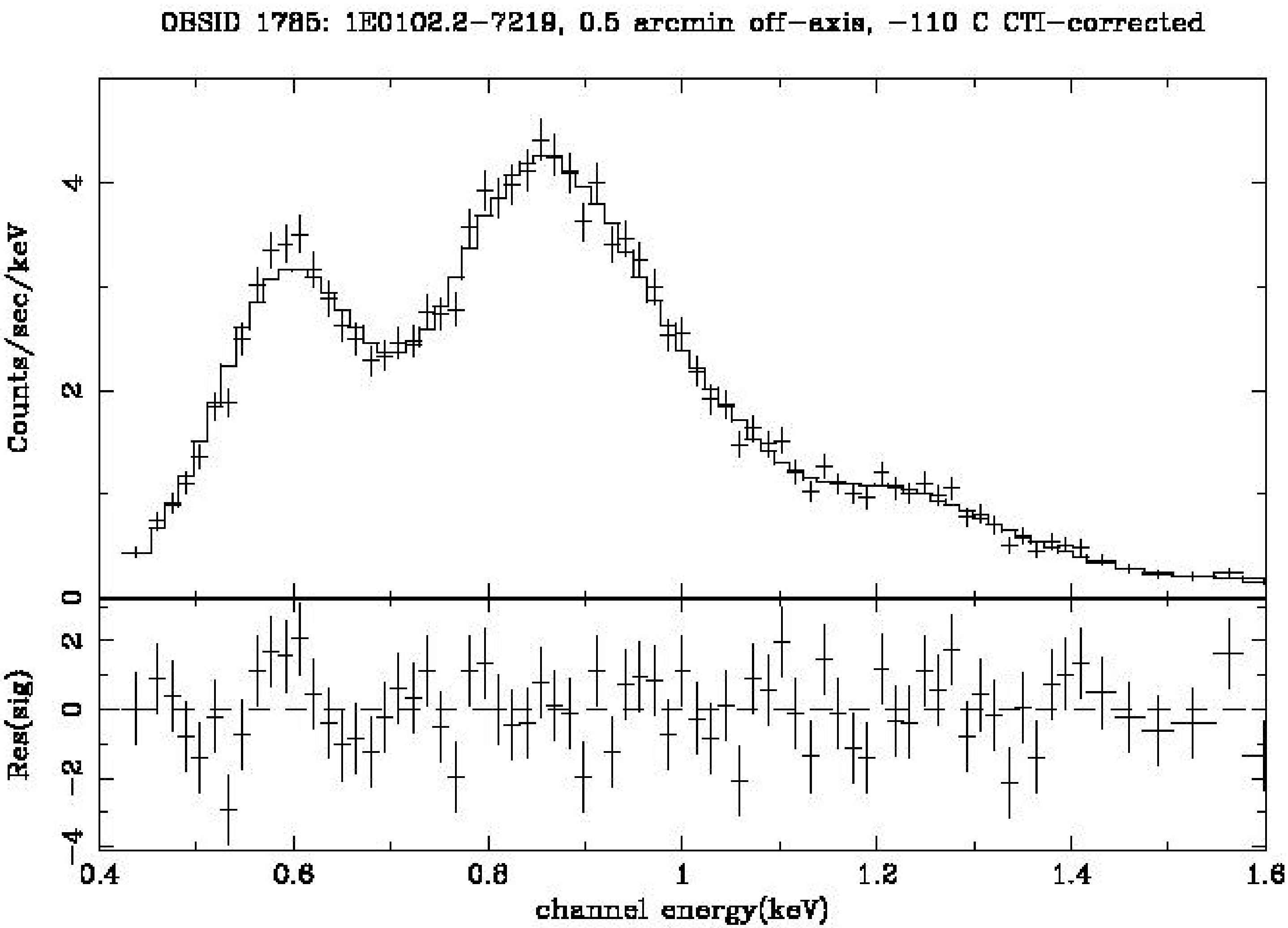


RISK #2: Thermal cycling results in Damage to the ACIS OBF (Part II)

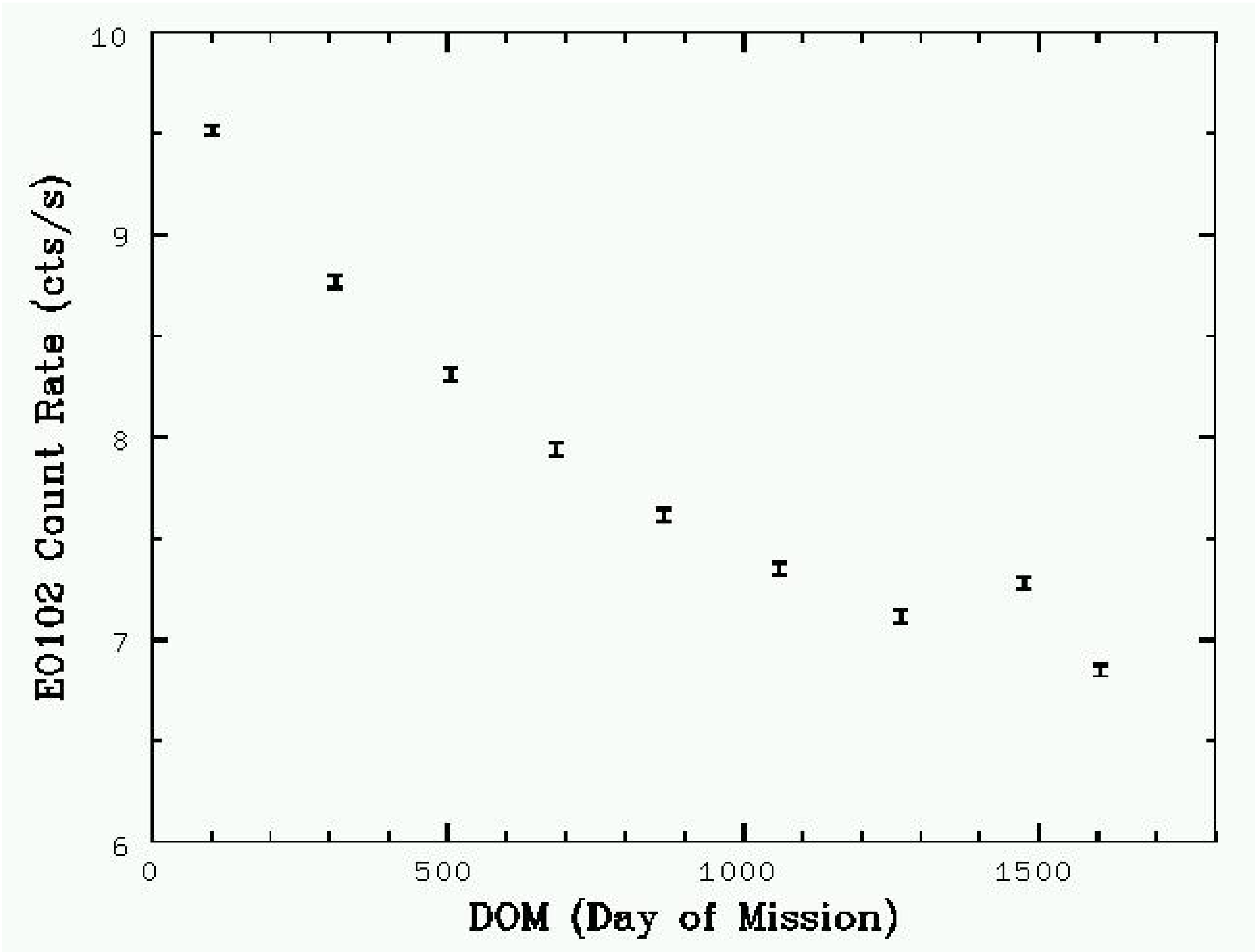
Summary of NGST Tests: Executed in March and April 2004

Description	# of Cycles	Contaminant Thickness at start	% of max thickness remaining at end
Simulate FP=+20 C, DH=+20 C bakeout	40	**118 mg/cm^2**	80%
Removal at +50 C	1	**94mg/cm^2**	20%
Simulate FP=+20 C, DH=+20 C bakeout	5	**24mg/cm^2**	20%
Simulate FP=-60 C, DH=+20 C bakeout	40	**180mg/cm^2**	88%
Removal at +60 C	1	~ **4mg/cm^2**	2%
Simulate FP=-60 C, DH=+20 C bakeout	5	~ **4mg/cm^2**	2%

I3 Spectrum of 1E0102.2-7219: CTI-correction at -110 C, 35% Higher CTI



E0102 Count Rate vs. Time



Benefit Analysis: Current Observing Time Penalty

Data from the GTO survey:

^1 Time proposed if no contamination

^2 Additional time to compensate for contamination

^3 Observing time ==

(base time) +

(delta time)

	ACIS-S/NONE	ACIS-I/NONE	ACIS-S/Grat	HRC
ACIS Team				
Base^1(ks)	275.5	279	0	0
Delta^2(ks)	100	0	0	0
HRC Team				
Base^1(ks)	90	490	0	90
Delta^2(ks)	0	0	0	0
HETG Team				
Base^1(ks)	0	0	567	0
Delta^2(ks)	0	0	140	0
GTO program				
Base^1(ks)	365.5	769	567	90
Delta^2(ks)	100	0	140	0
% Delta	27.4	0	24.7	0
Cycle 5 Program				
Observing^3	11497	5398	4020	1387
Delta time	2473	0	796	0

BENEFIT ==

3.27 Ms per year

Cost Analysis: Extra Time Requirements

EXPECTED:

Delta Calibration	**1 Ms**
Impact of 25% CTI increase (to recover some spectroscopy of extended sources)	**380 ks per year**

UNEXPECTED, CTI Doubles:

Switching observations to S3, taking multiple fields.	**1.4 Ms per year**
Effect of high energy detection efficiency to grade migration	**380 ks per year**