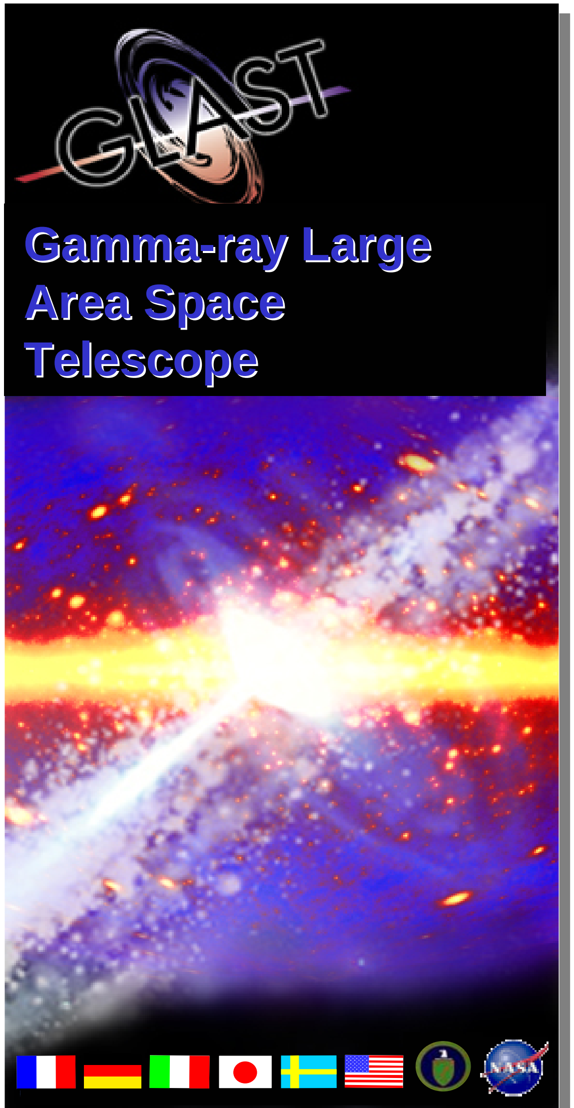


GLAST Large Area Telescope:

AntiCoincidence Detector (ACD)

PhotoMultiplier Tube Glass Failure

Michael Amato

Charles He, Steve Schmidt, Kevin Dahya, Tony DiVenti, Walt Thomas, Henning Leidecker, et al.

NASA Goddard Space Flight Center

March, 2004

OUTLINE

- INTRODUCTION AND BACKGROUND
- INVESTIGATION - APPROACH
- INVESTIGATION – FAILED UNIT REMOVAL AND CRACK ANALYSIS-First failure
- SOLUTION PATH RESULTS – PATH 1
- SOLUTION PATH RESULTS – PATH 2
  - DETAILED STRESS ANALYSIS
  - RELIABLITY REQUIREMENT ANALYSIS
  - STRENGTH TESTING, WEIBULL ANALYSIS
- INVESTIGATION – FAILED UNIT REMOVAL AND CRACK ANALYSIS-Second failures
- THE SOLUTION
  - ANALYSIS OF SOLUTIONS
  - SOME BUMPS WE RAN INTO
  - CURRENT SOLUTION
  - MARGIN AND STRENGTH PREDICTION SPECULATION

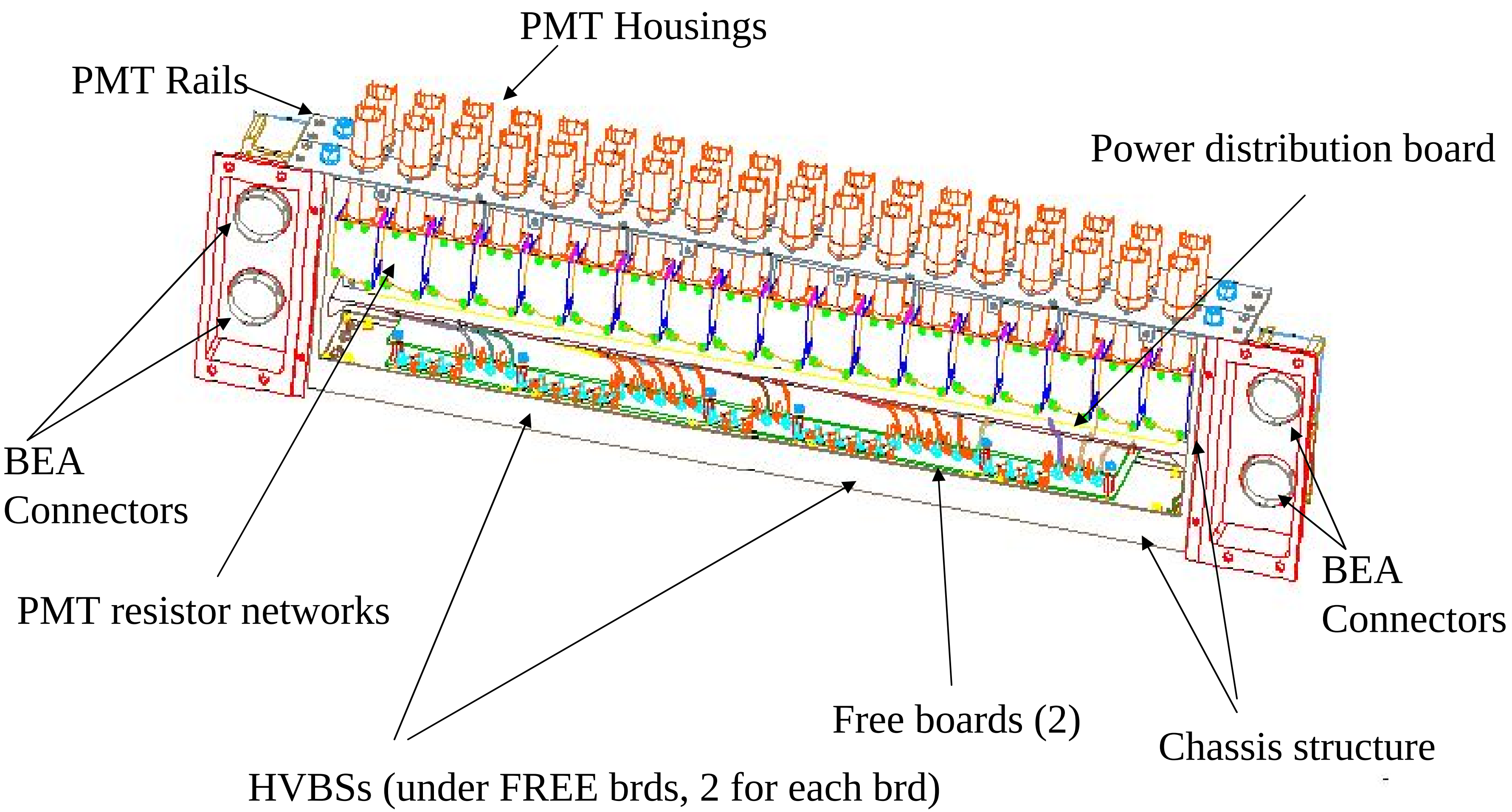
INTRODUCTION AND BACKGROUND

Background

- Background – ACD flies 2 Hamamatsu Photo Multiplier Tubes (PMTs) per detector for a total of 194. They convert the tiny light pulses produced in the detectors by high energy particles and transferred down clear fibers to signals. PMTs out perform any other device for the needed response and gain for these small signals.
  - Specifications - Minimum current gain at maximum high voltage - 2,000,000 (2E+6), High voltage required at a gain of 2E+6 shall not exceed 1250 V, Projected gain degradation shall be less than 30% (84% probability) after 50,000 hours of operation at a mean anode current of 30 nanoamps.
- In the flight assembly process we remove bases provided and after potting the PMTs into flight housings we add custom flight resistor networks. That design works but the crack issue has given us an opportunity to redesign the boards to reduce workmanship issues we had seen on the first batches and add reliability. It also reduces production time.
- They are partially redundant. They are not fully redundant because detectors running with only one PMT do not operate with as much efficiency. Simulation shows that if no other components fail we can lose up to 18 PMTs and still meet the overall ACD efficiency requirement, as long as both don't fail on one detector. If you run the numbers the odds of this happening are quite low. However we can still barely meet minimum science requirements with one detector completely gone.
- Each ACD Electronic Chassis has one or two rows of PMTs (up to 17 per chassis). Recent reliability updates focused on the PMT give us a 1.5% to 3% PMT reliability failure rate allocation.

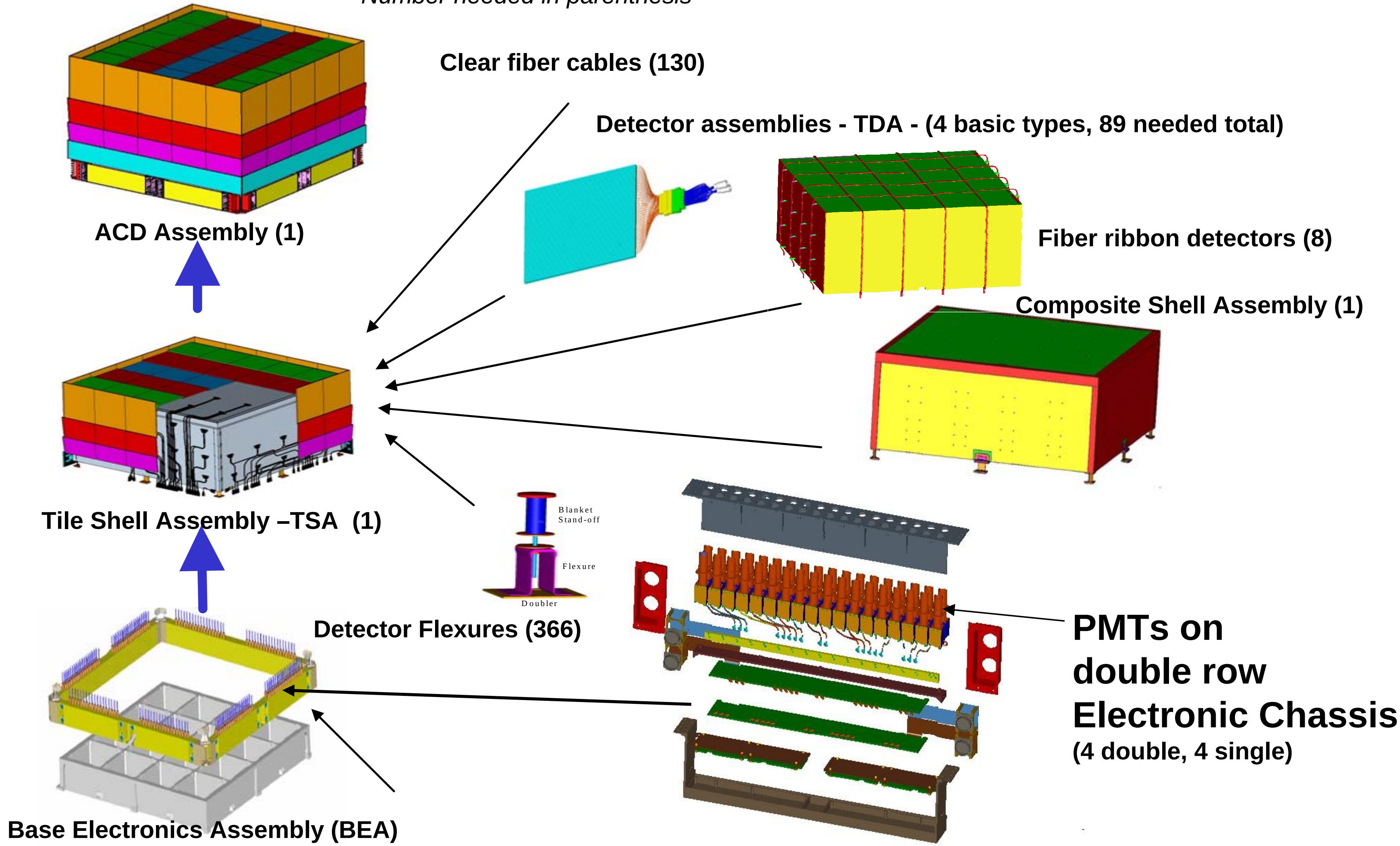
Background – PMTs in the Electronic Chassis

- **Electronics Chassis**

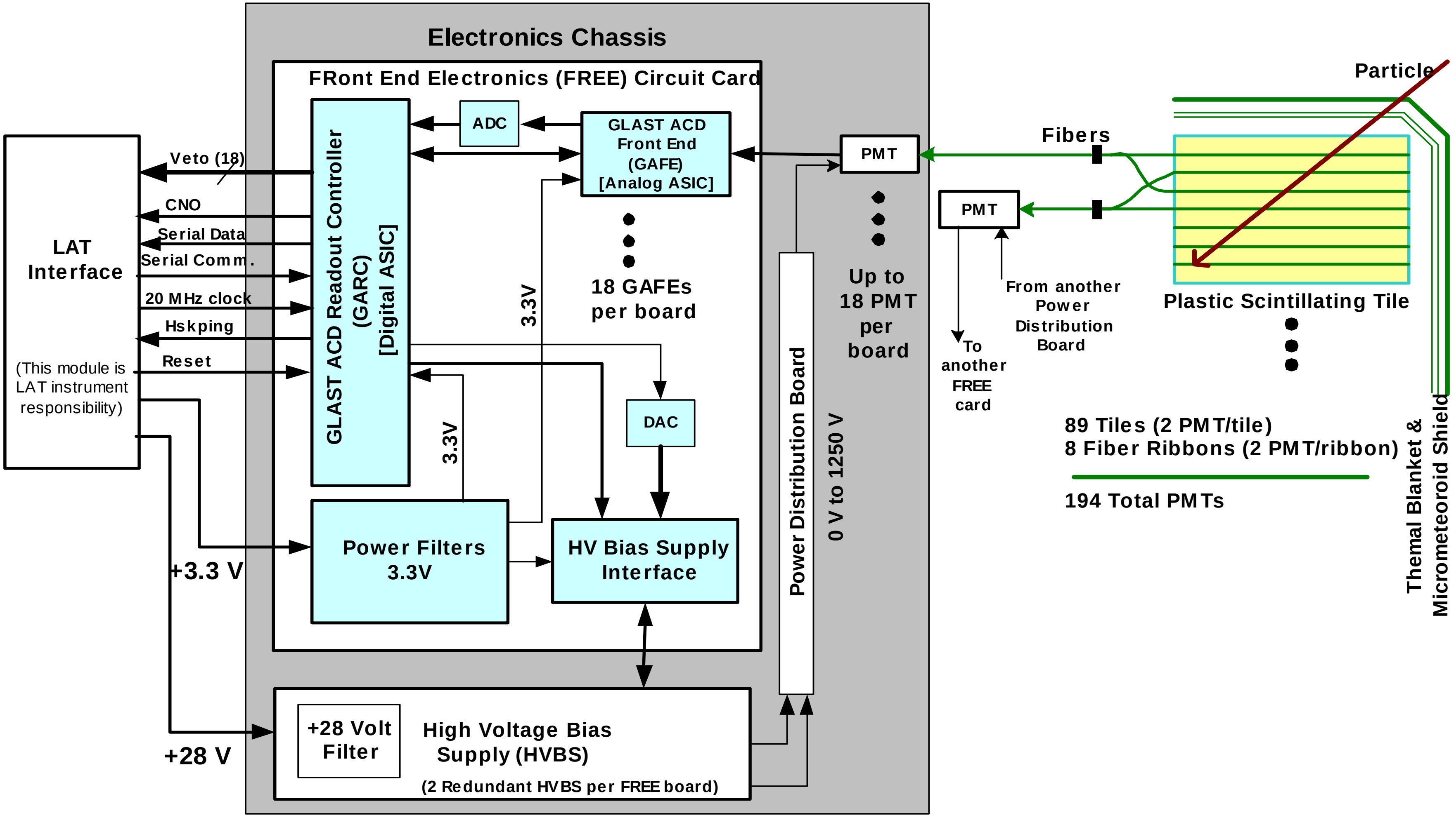


Background – PMTs in the assembly flow

Number needed in parenthesis



Background – PMTs in the electronic System Overview



The Issue

- Over a year ago 4 engineering model PMTs were qualified in thermal vaccum (3 cycles to -30C, 1 cycle to -38C) and vibration with all passing – successful qualification test

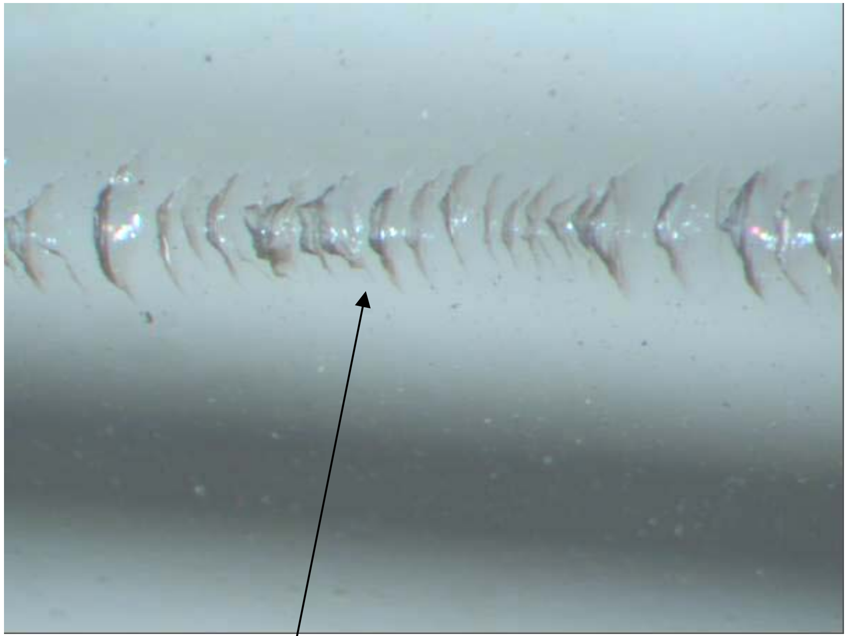
- Before we assembled an electronic chassis engineering model we decided to retest some new PMT assemblies. Some minor changes had been made to the resistor networks and their housings. These changes did not effect the PMT housing and did not change the stresses on the PMTs

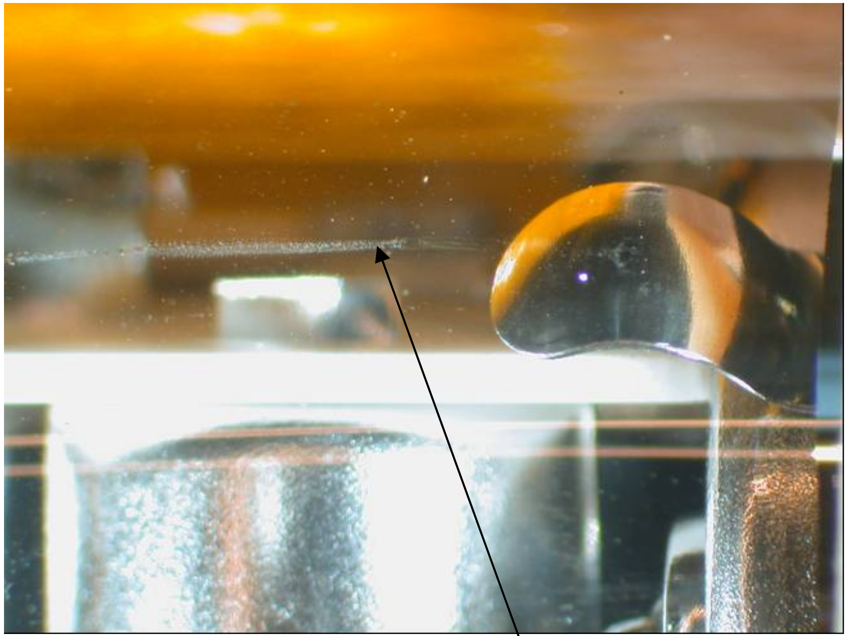
- PMT engineering model failure – During this second qualification test one of 5 PMTs cracked during first -30C cold cycle of thermal vac test. Again this was a repeat of successful test one year ago. Remaining four from latest test survived two more cycles to -30C and one cycle to -40C. They are six to nine month lead time items, all have been received and performance tested. None have begun flight processing.
  - Inspection of PMTs not yet in housings revealed 4 sets of score marks along inside of all tubes consisting of 2 to 3 thousand microcracks caused by insertion of dynode assembly. Also discovered microscopic air bubbles in tube to window transition area. Inspection of earlier PMT failed by excessive vice force shows it failed at score marks.

- Very recently, towards the end of our investigation, the Electronic Chassis engineering model thermal vacuum test failed 3 more PMTs out of 23.

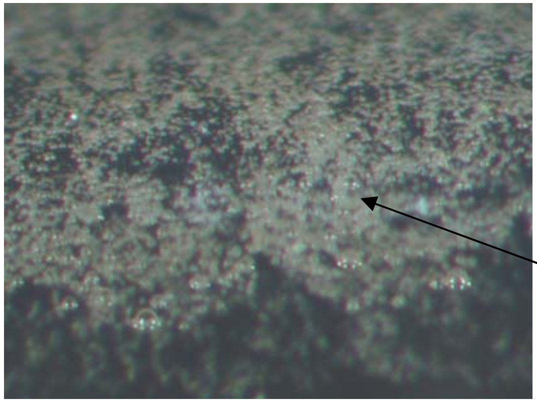
INVESTIGATION - APPROACH

Investigation





Close up of
one score line,
PMT vulnerable at scores



Score line ending
at dynode mount

Bubbles at window
to tube transition

Investigation

- Evidence inspection path - Investigation towards determining cause on failed PMT (and later failures). It proved to be difficult and slow.

Two additional major paths were pursued

Path 1.) Were the scores part of the manufacturing process. Was it possible to get tubes without the score weaknesses?

Hamamatsu confirms these are results of normal manufacturing processes and they have not run into significant problems. A process change could be pursued to apply sleeve insert techniques used on thinner tubes but they were not initially very interested in doing that , would cost money, as would ordering 250 more, and delay delivery. Hamamatsu has now agreed to try a modified process. Latest results show some success in greatly reducing scores. We have ordered 30 of these units to supplement our spares (~5 month delivery, very serious delay and cost for 250 more)

Investigation

- PMT engineering model failure continued –

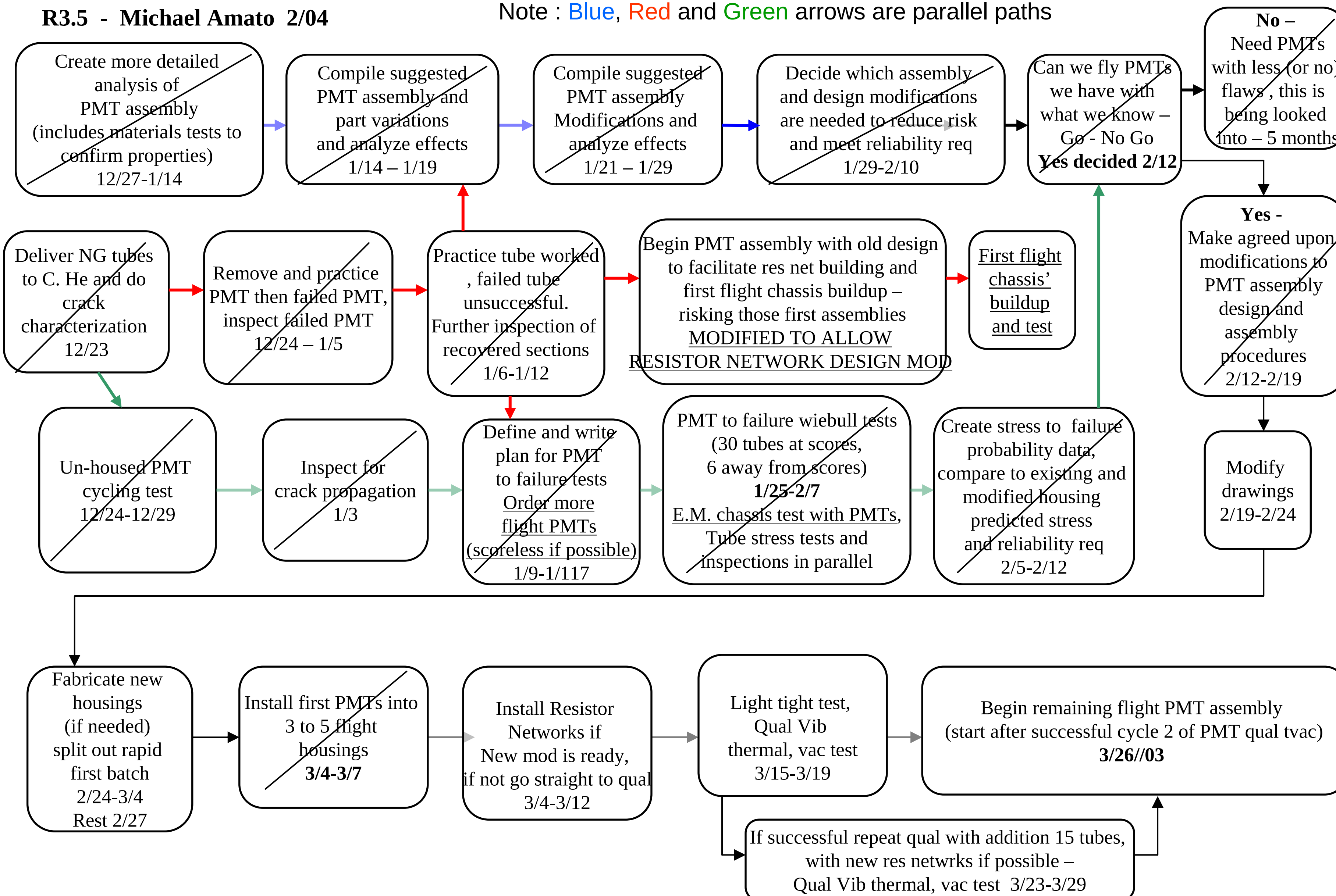
  Path 2.) Try to understand if there is a way to fly the tubes we have.

  – This required us to investigate and understand the failure mode more. Inspection of failed unit completed, inconclusive, did not fail at score.
  – Some tubes not in housings were inspected and cycled to 20 cycles to see if microcrack propagation could be measured just due to internal stresses. None of the cracks propagated in a measurable way which gives us some hope that reducing stresses gives us a chance.
  – We need to be able to calculate and show we can meet a minimum reliably requirement if we are to fly these tubes. Since glass failure is probabilistic we will fail statistically significant number of tubes (~30) to get a Weibull failure probability curve vs stress for our tubes. Weibull tests have just begun. It is hard to set up such a test which emulates our flight stresses. Multiple tests were investigated by materials group.
  – Questions forwarded to Hamamatsu to determine as delivered internal stress, they were of some limited help. Low internal stresses measured in tests here. Our PMTs do not appear to be tempered, probably due to unavoidable heating during assembly.
  – Stress analysis has been redone in much more detail to determine stresses added by housing. Stresses are higher than expected and previously predicted, particularly at the Mu metal overlap.
  – Analysis to investigate changes in the housing design which could greatly reduce stress. Examples of ideas to investigated- change in housing material, reduce nonsymmetrical stress causing features like Mu metal overlap or un-centered tubes, change potting material and thickness, increase venting to allow PMTs to function with a crack in flight, do no redesign and do extensive lifetime tests on 30 or more flight tubes in current housings.

PMT Anomaly Resolution Flow - Investigation plus two solution paths

R3.5 - Michael Amato 2/04

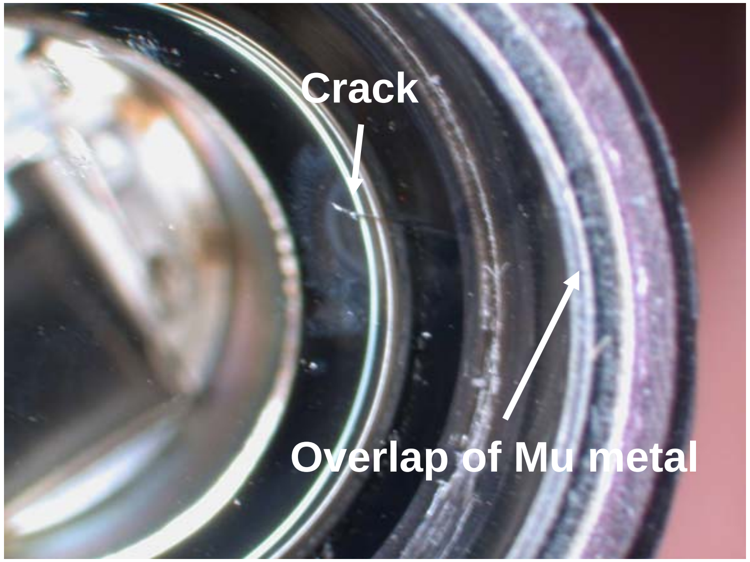
Note : Blue, Red and Green arrows are parallel paths



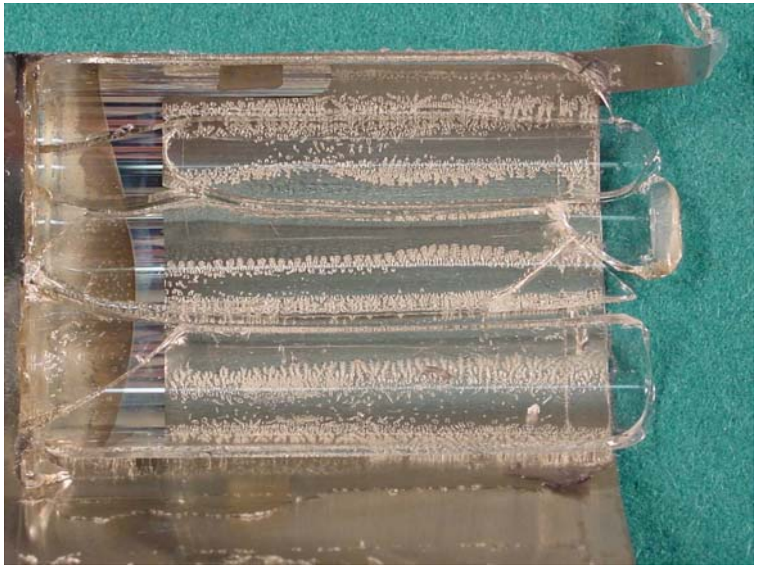
INVESTIGATION – FAILED UNIT REMOVAL AND CRACK ANALYSIS – First Failure

Investigation

– **Crack in failed PMT is aligned with Mu metal overlap. Removal of flight unit to confirm crack origination was not successful despite success of practice unit. Could not identify initiation point of failed PMT. But surprisingly did not appear to fail at one of the scores.**

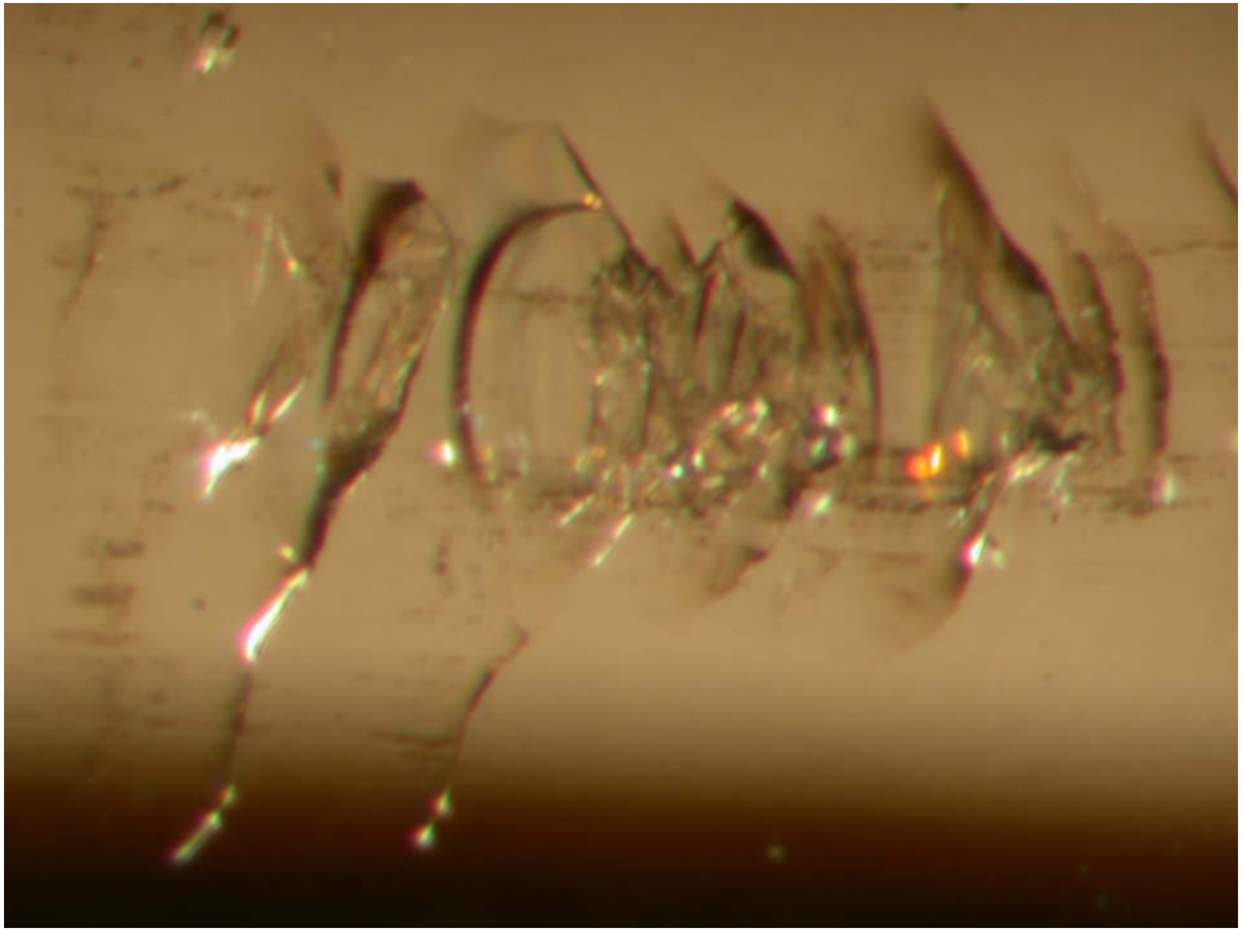


Crack position relative to Mu metal



Soaking in toluene destroyed the tube

Investigation



Another score example

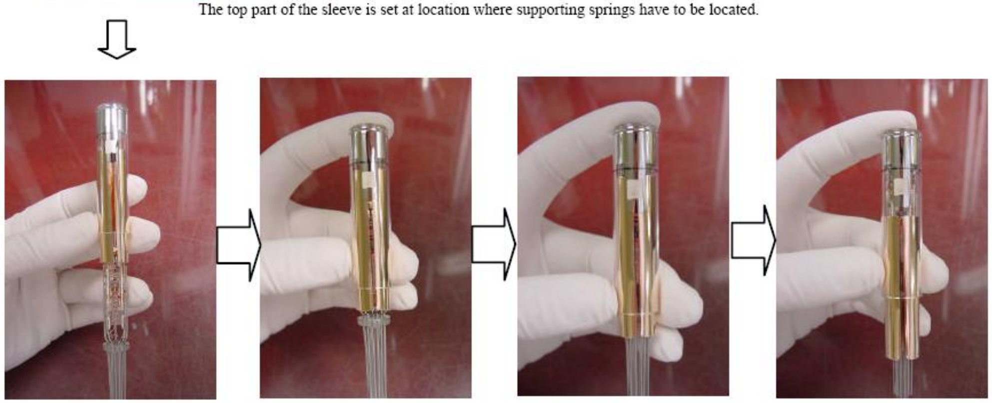
SOLUTION PATH RESULTS – PATH 1

Solution Path 1 Pursuit

- **Path 1 results**
  - **Hamamatsu did eventually did agree to try some different production steps. We agreed to buy more spares if they agreed to try a new process to reduce scores. See below. They were ordered. Still wont be here for many months.**

Sample PMTs = R4177-04 (High temperature type of R4443)

The top part of the sleeve is set at location where supporting springs have to be located.



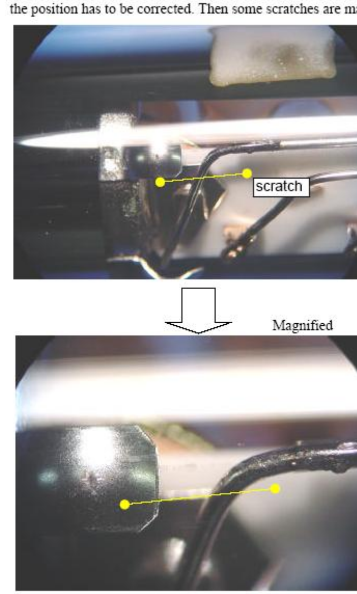
The electrode is inserted inside the sleeve. It's moved to the top part of the sleeve while the sleeve is kept at the same position.

The supporting springs are set at correct location while leaving from the sleeve and then springs attach to the bulb.

The sleeve is taken off from the bulb.

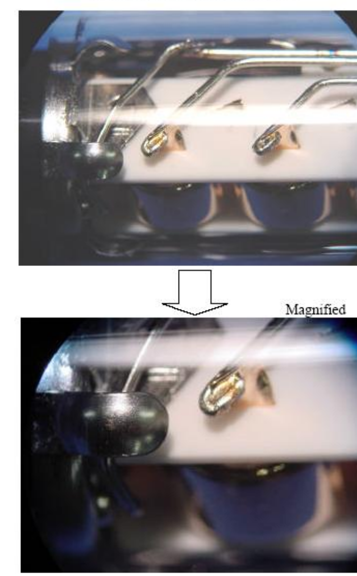
Small-Scratches

If the springs leave from the sleeve unsuccessfully, the position has to be corrected. Then some scratches are made.



No Scratch

If the springs leave from the sleeve successfully, there is no movement and no scratch.



SOLUTION PATH RESULTS – PATH 2

DETAILED STRESS ANALYSIS

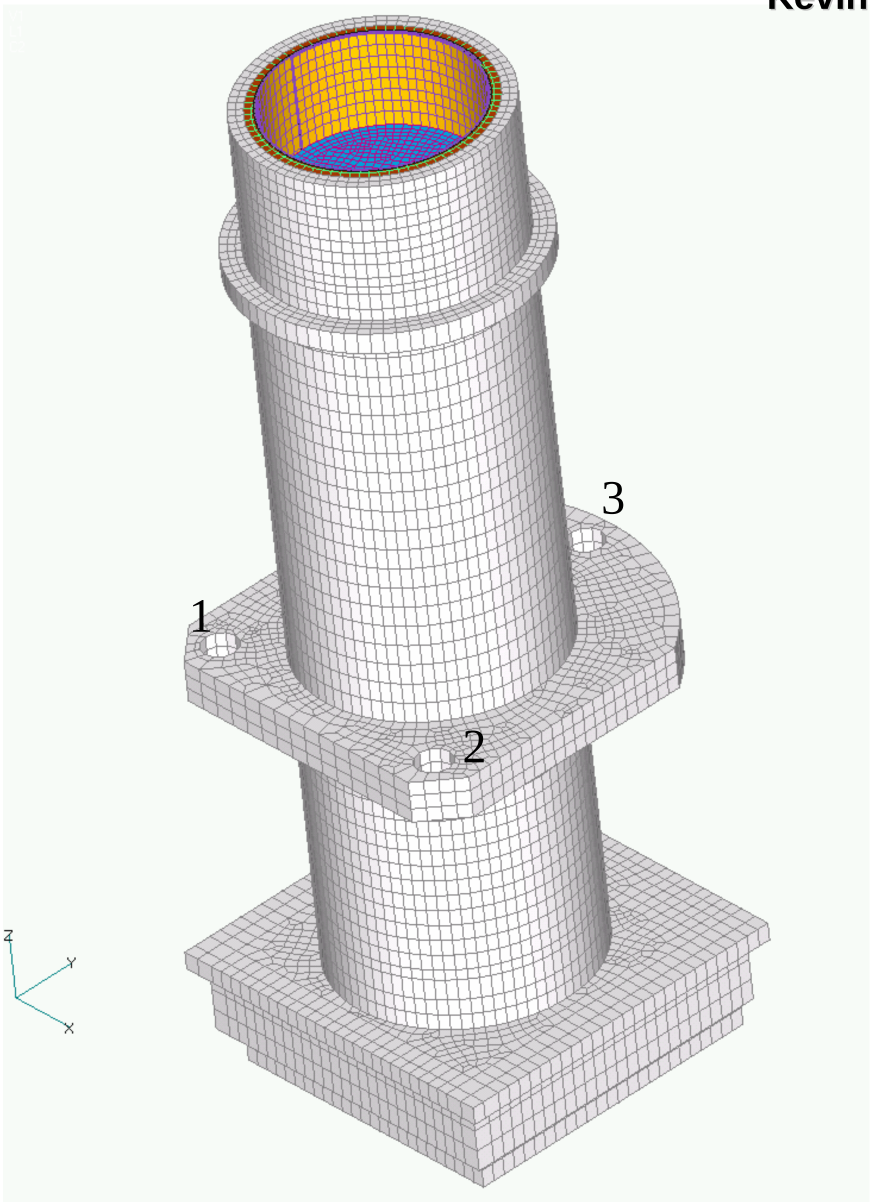
Path 2
What are our current stresses in the existing design

- Review of initial analysis shows 2-d simplified analysis did show low stresses but was overly simplified and had some at temperature material properties off that made a large difference in stress upon our review of that analysis.

- Stresses on surfaces of PMT tube for existing design initially showed tensile hoop stresses peaking at ~4.3 ksi on inner surface and ~3.2 ksi on outer surface.

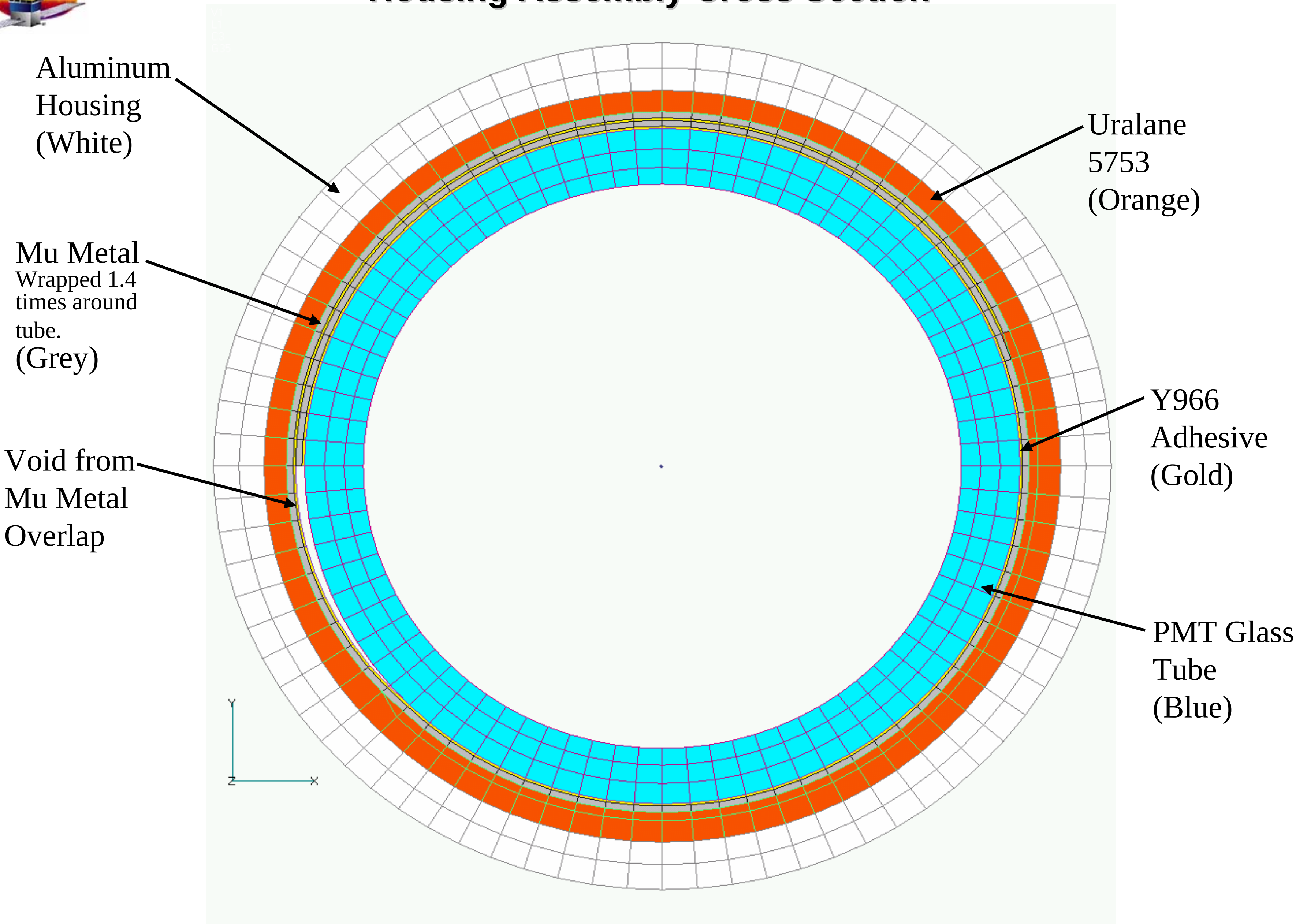
PMT Detailed Stress Analysis

Kevin Dahya - SAI



- Composed completely of solid elements.
- Constrained with pure kinematic conditions. (1-XYZ, 2-YZ, 3-Z).
- Threads for PMT Cap not modeled. Assumed nominal OD.
- Model does not include R/N (Resistor Network) & R/N housing.
- Assumed worse case is cold temperature of –40 deg C.

Housing Assembly Cross Section

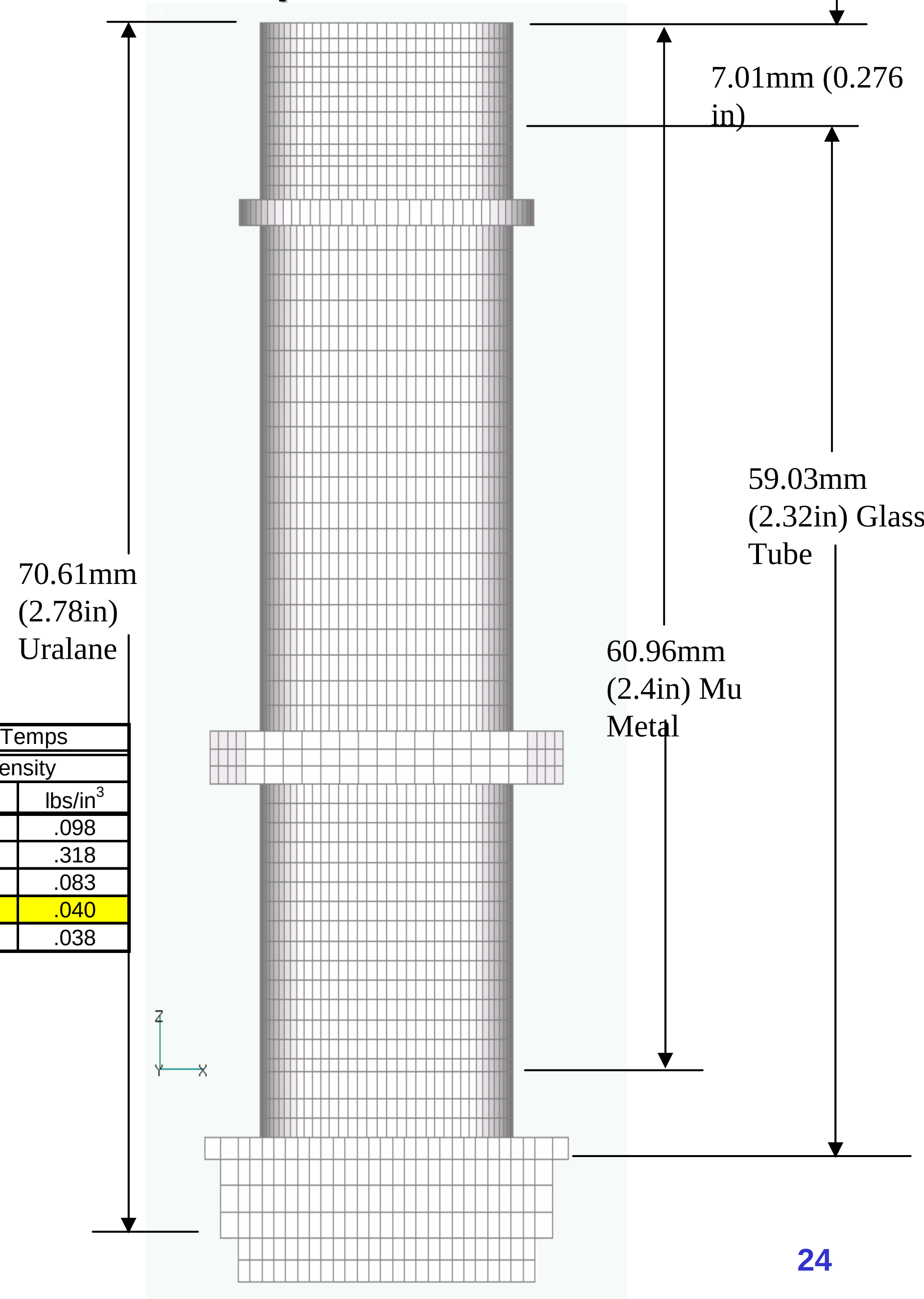


Initial Dimensions & Material Properties

	mm	*inches*
OD PMT Tube	14.5	0.571
PMT Tube Wall Thickness	1.19	0.047
Y966 Adhesive Tape Thickness	0.0508	0.002
Mu Metal Thickness	0.132	0.005
ID Aluminum Housing	16.15	0.636
OD Aluminum Housing**	18.19	0.716

**OD dimension does not include any flanges or threads.

Material	Manufacturer	-40°C				All Temps	
		Young's Modulus		CTE	Poisson's Ratio	Density	
		MPa	psi	ppm / °C		g/cm^3	lbs/in^3
Al Aly 6061-T6		68948	10.0E+06	23.6	.33	2.7	.098
Mu Metal		206843	30.0E+06	12.6	.36	8.8	.318
7056	Corning	63432	9.2E+06	5.15	.21	2.29	.083
966	3M	596	86442	584	.49	1.102	.040
5753 Black	Huntsman	35.7	5181	222	.45	1.05	.038



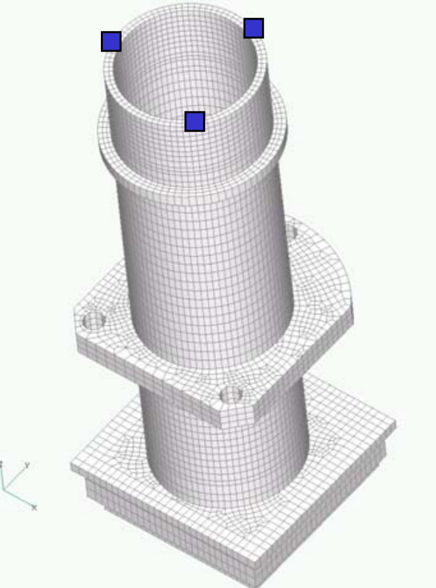
Model Checks

- **Passed all grounding checks and element geometry checks as well as free-free check.**
  - **Higher order modes (7-10) unrealistic. Mass properties not incorporated in all material cards.**

R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	3.12E-03	5.59E-02	8.89E-03	1.00E+00	3.12E-03
2	2	3.50E-03	5.92E-02	9.42E-03	1.00E+00	3.50E-03
3	3	3.96E-03	6.30E-02	1.00E-02	1.00E+00	3.96E-03
4	4	5.05E-03	7.10E-02	1.13E-02	1.00E+00	5.05E-03
5	5	7.60E-03	8.72E-02	1.39E-02	1.00E+00	7.60E-03
6	6	8.93E-03	9.45E-02	1.50E-02	1.00E+00	8.93E-03
7	7	3.82E+09	6.18E+04	9.84E+03	1.00E+00	3.82E+09
8	8	3.83E+09	6.19E+04	9.85E+03	1.00E+00	3.83E+09
9	9	5.83E+09	7.64E+04	1.22E+04	1.00E+00	5.83E+09
10	10	5.84E+09	7.64E+04	1.22E+04	1.00E+00	5.84E+09

- Thermal displacement of Aluminum housing checked with hand analysis.
  - T3 displacement, at 3 locations shown, compared using $\delta = \alpha \Delta T L$



Output Set 2 - MSC/NASTRAN Case 1

D I S P L A C E M E N T V E C T O R

POINT ID.		T1	T2	T3	R1	R2	R3
102268	G	-1.709379E-2	-2.470292E-2	-6.037343E-2	0.	0.	0.
102339	G	-2.299179E-2	-4.072376E-3	-6.046476E-2	0.	0.	0.
102453	G	-2.975052E-4	-1.131378E-2	-6.052147E-2	0.	0.	0.

Using minimum shear requirements :

$\alpha = 2.365e^{-5} /^{o} C$

$\Delta T = -60^{o} C$ (+20 to –40 degrees Celsius)

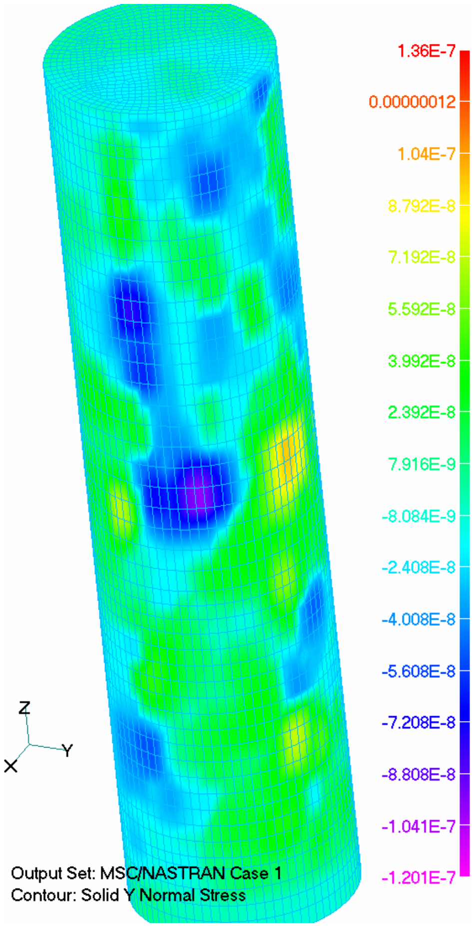
$L = 41.15mm$ (Distance from top surface of mounting flange to top of cylinder)

$\delta = -0.058mm$ vs. –0.06mm shown above in T3 direction of Displacement Vector box.

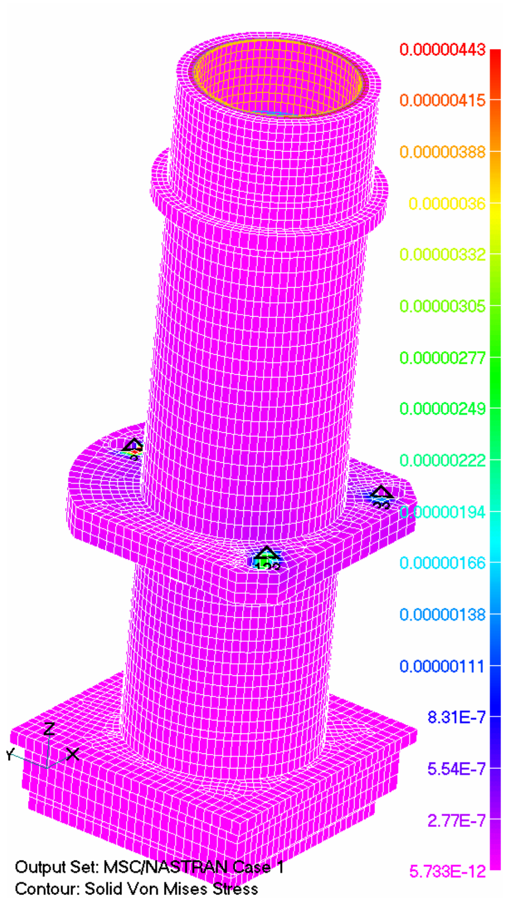
Model Checks (Contd.)

- Relative stress free conditions shown assuming uniform CTE for all materials, bulk temperature change, and kinematic constraints.

Glass Tube Stresses in kPa.



Full assembly shows approximate stress free conditions.

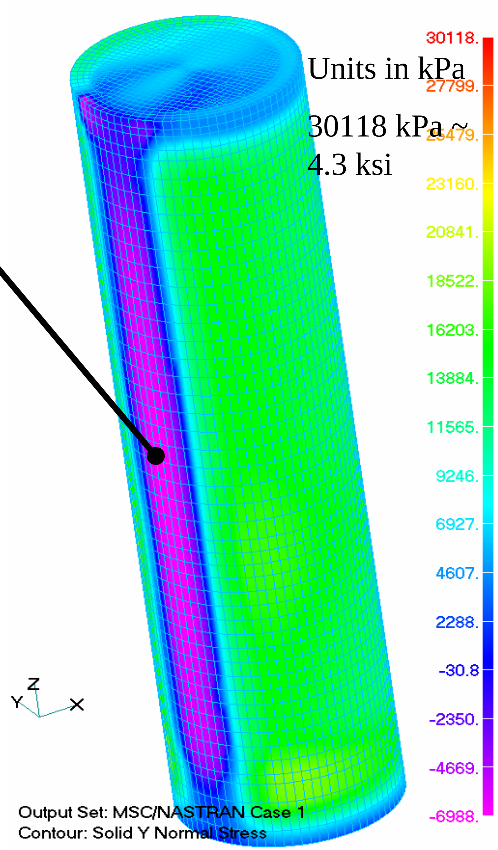


Nominal Conditions – Initial Design

- Area of compression (purple) is located at Mu metal transition area (from one layer into overlap).

Units in kPa

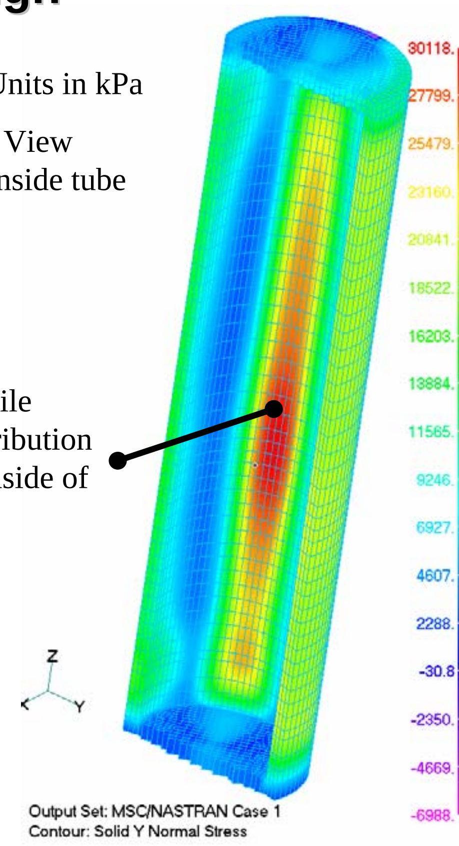
30118 kPa ~ 4.3 ksi



Units in kPa

- View Inside tube

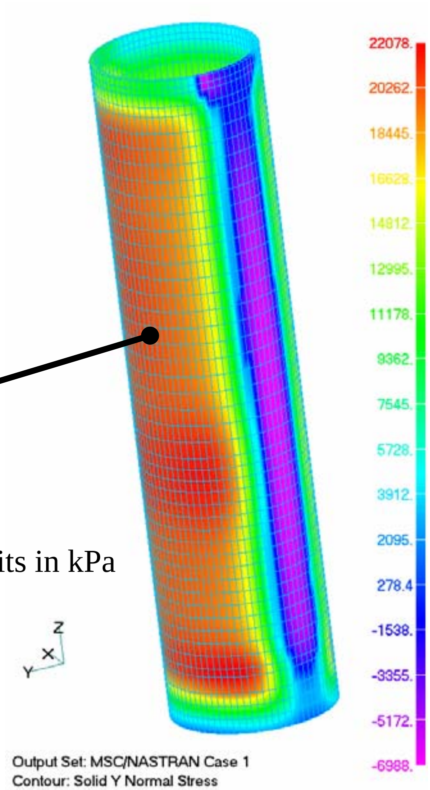
Tensile Distribution on inside of wall.



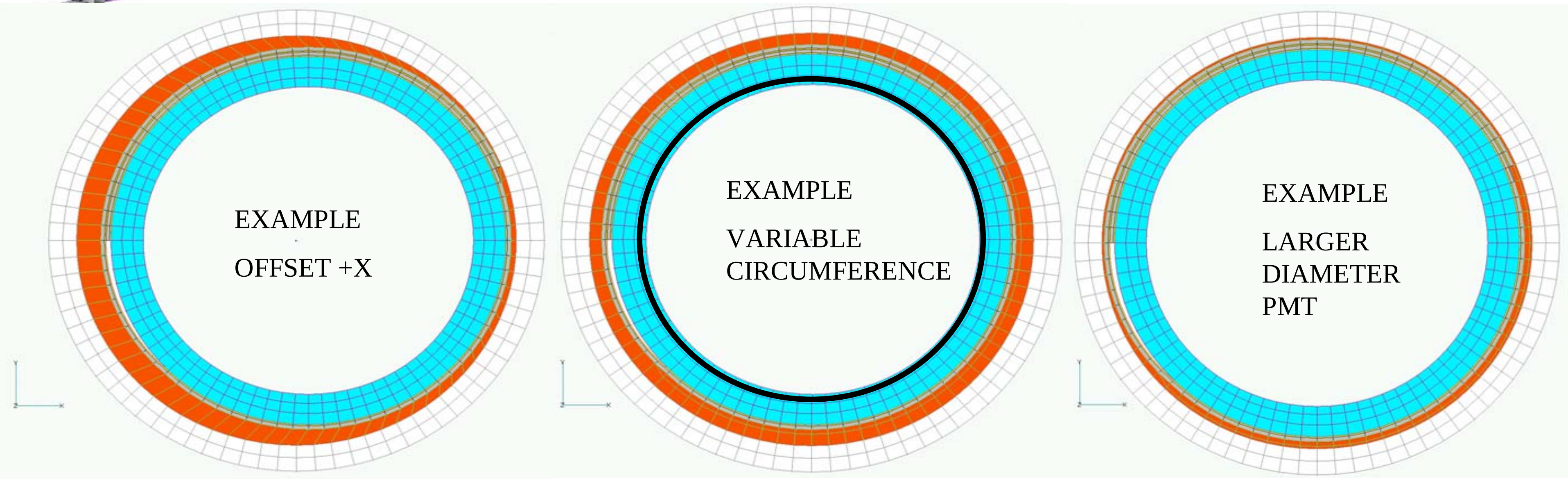
Max Hoop Stresses

Outer wall tube stresses. ~3.2 ksi

Units in kPa

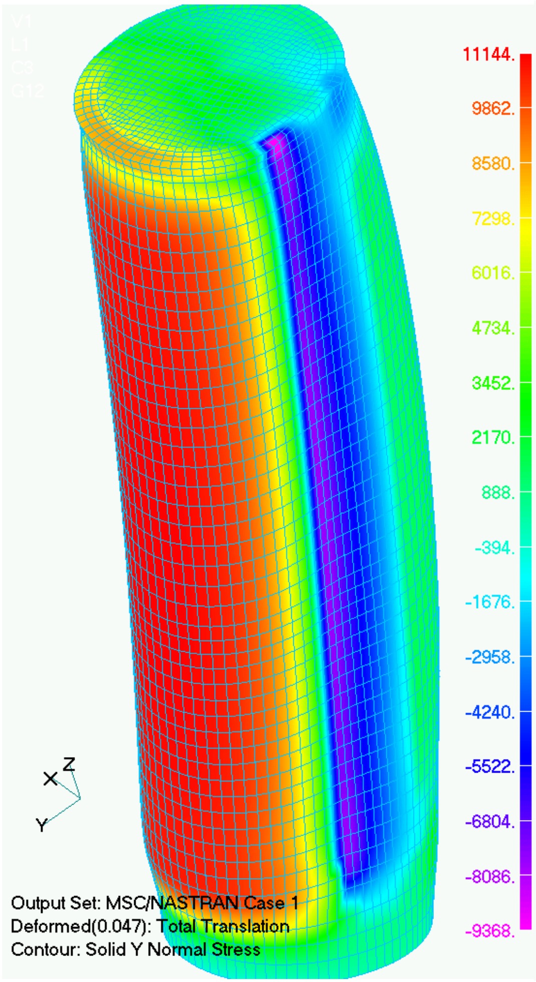


Other Initial Concerns

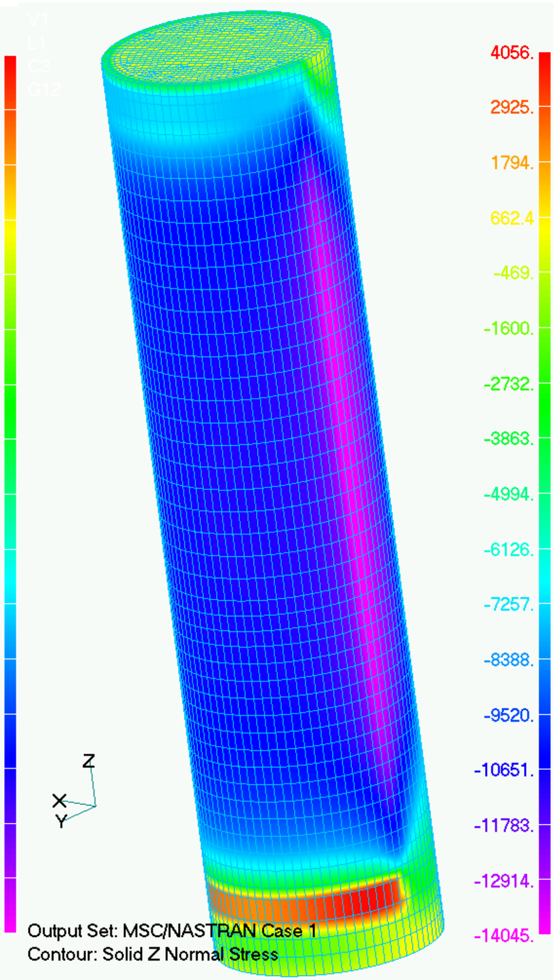


Case	Description	% From Nom.	% From Nom.	Loading Description
		Inner Wall	*Outer Wall*	
1	ORIGINAL NOMINAL CONDITIONS - BASELINE	***0***	***0***	Asymmetric
2	0.025" OFFSET	***+95.34***	***+89.57***	Asymmetric- Max in -Y direction
3	0.010" OFFSET	***+13.20***	***+3.37***	Asymmetric- Max in -X direction
4	0.002" VARIABLE CIRCUMFERENCE	***+5.03***	***+0.81***	Asymmetric- Max in -X direction
5	0.598" LARGER DIAMETER PMT	***-9.69***	***-17.00***	Asymmetric

Mu Metal effects



Hoop Stress & Deformed Shape in kPA



Long. Stress in kPa

- Effects of Mu Metal on Tube.
- Model consists of Mu Metal, y966 adhesive tape, and PMT tube only. No aluminum housing or potting.
- Deformed shape shows asymmetric deformation due to Mu Metal overlap.
- Tensile stress primarily in hoop direction.
- Compressive stress primarily in longitudinal direction.
- Max tensile 11.1 Mpa ~ 1.6 ksi.
- Accounts for approximately 37% of inner wall stress and 50% of outer wall stress in tube for initial conditions.

RELIABLITY REQUIREMENT ANALYSIS

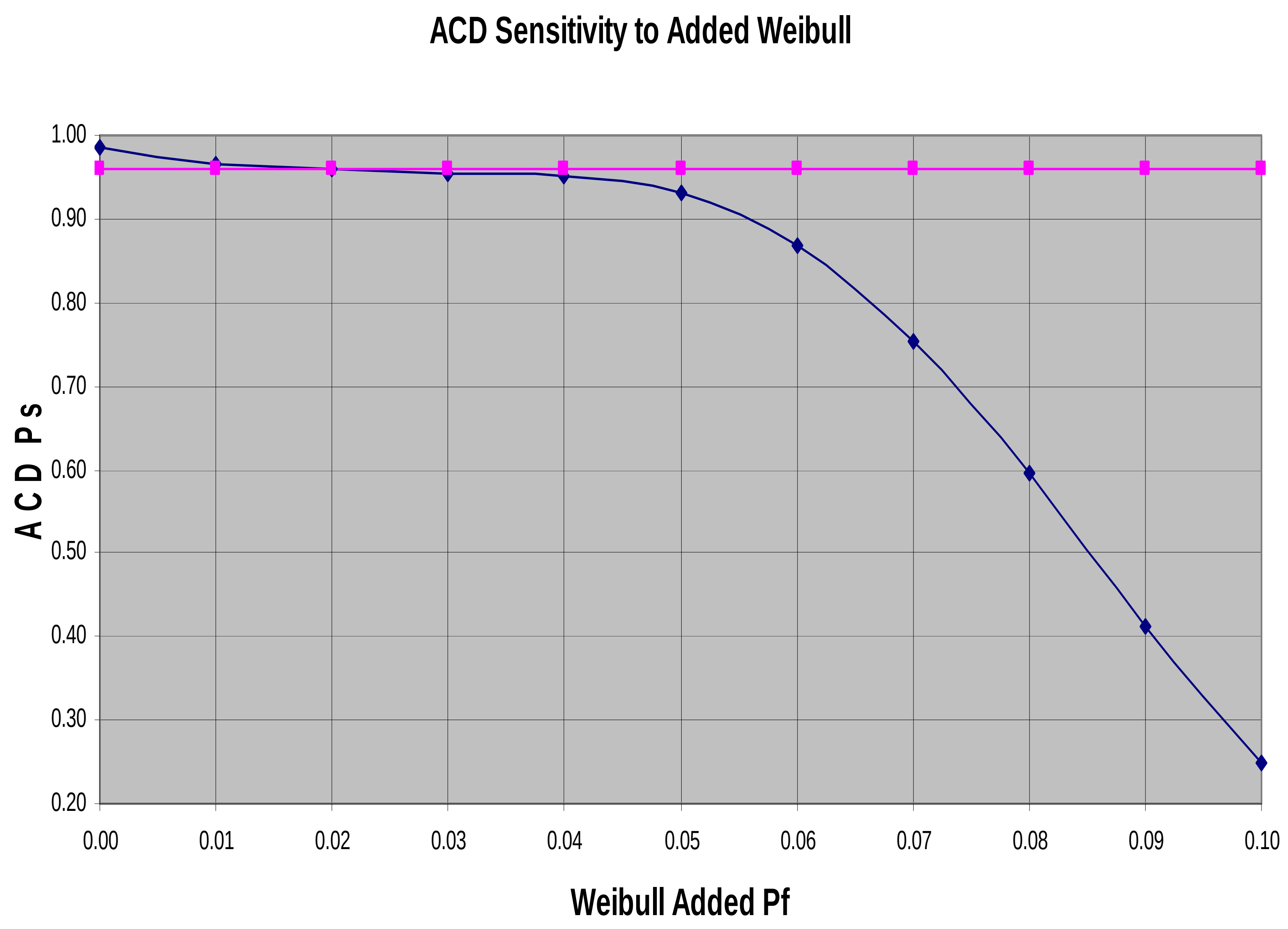
Path 2 – Needed PMT reliability

• ACD can fail up to 18 PMTs (with some caveats). This is ~9.3%. However you must add the reliability numbers in each chain in a real reliability model.

• Project reliability people updated reliability models and predictions and created an updated PMT specific allocation.

• The current allocation based on current assumptions is 3%.

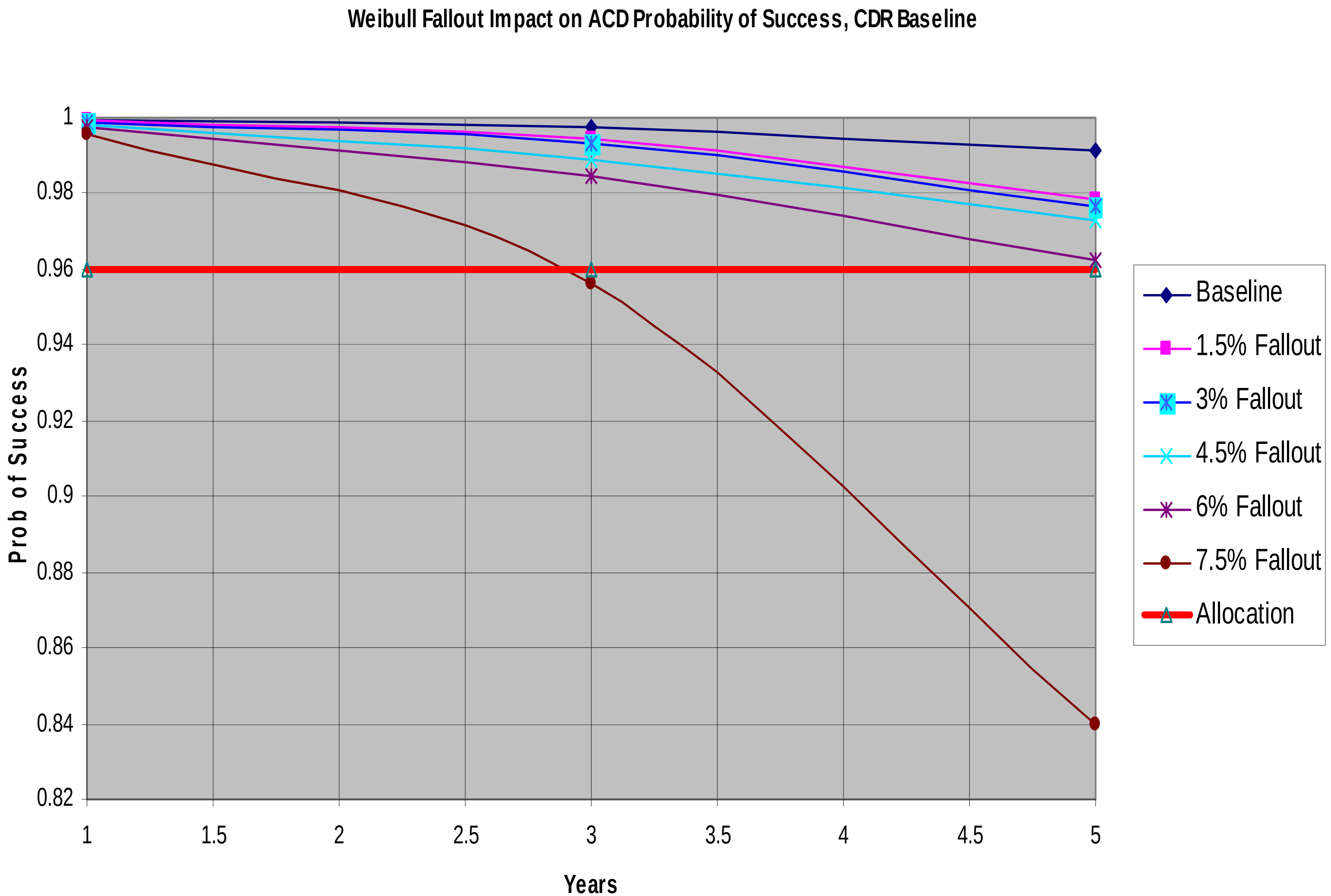
Initial ACD Sensitivity Analysis



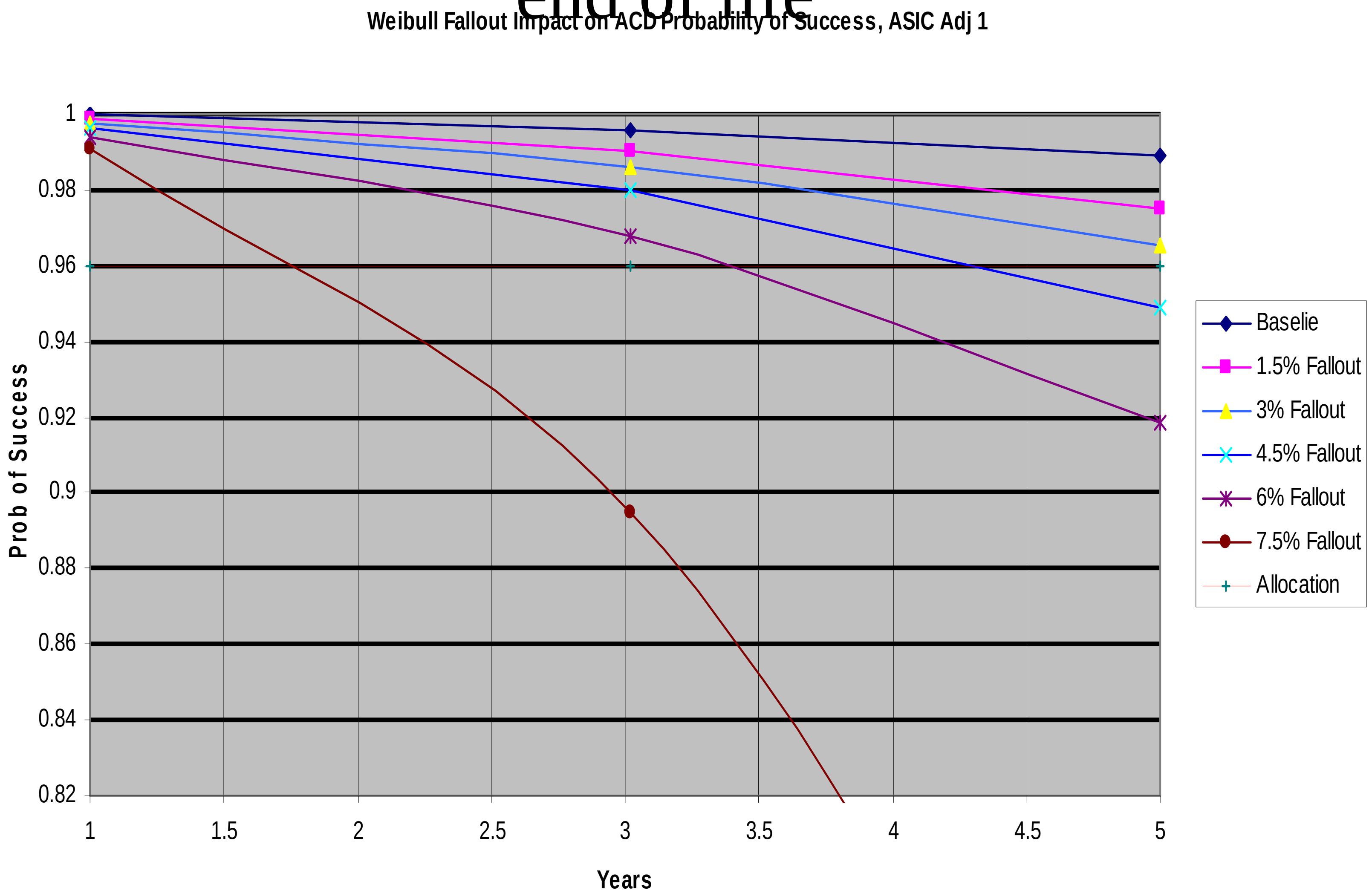
Genesis of 1.5 % Goal

- **The process of generating a reliability model for the ACD was a continuing process of refinement as modeling the actual redundancies was beyond most software.**
- **At the time of the initial study a Relex model was the most accurate tool available and was exercised for prediction and sensitivity analysis. Sensitivity being determined by varying an element and determining it's impact on the whole.**
- **A glass-fracture failure element was added to the PMT string and varied in 1 % increments resulting in the presented ACD Probability of success which crossed the 96% Ps threshold at about 1.5 % fallout.**
- **Since then, two significant developments have occurred. First, a Monte Carlo simulation model has been developed to more accurately reflect the PMT, Tile, and ribbon relationship. Second, a Uncertainty Adjustment has been added to the prediction in order to account for uncertainty resulting from potential optimism previously used for the ASIC failure rates. New predictions were performed using the Monte Carlo simulation model based on the CDR baseline and Uncertainty Adjustment.**

Weibull Fallout- Baseline, 5 yr end of life



Weibull Fallout- Uncertainty Adjustment, 5 yr end of life



Guidance on Present Margin

- Prediction baseline is still missing small items such as resistors and capacitors – may expect some growth in failure rate
- CDR Model shows improved reliability with up to 6% fallout clearing 96% ACD Allocation
- CDR Model may be optimistic without small items and potentially optimistic ASIC expectations. The results from the Uncertainty Adjustment assumptions may be closer to a final number.
- Uncertainty Adjustment assumptions reduce fallout capability to 3% with the 96% allocation.
- Model is based on acceptable loss of up to 18 PMT and no more than 1 tile pair of PMT lost.
- If the science community can withstand additional PMT losses, the reliability gain would be about one step up on the curves for each set of 3 additional PMT failures allowable

Assumptions and Modeling Parameters

- Reliability projections based on a model derived from the TDA to PMT Mapping Document, Rev 2.3, and Monte Carlo simulations
- Forty thousand Monte Carlo trials are used for each reliability point estimate
- Failure rates estimates used for Baseline are consistent with CDR model
- Failure rate estimates used for Uncertainty Adjustment involve the following modifications:
  - GARC ASIC (change failure rate from 1.0E-11 to 1.0E-07 or 100 FITS)
  - GAFE ASIC (change failure rate from 1.0E-8 to 1.0E-07 or 100 FITS)

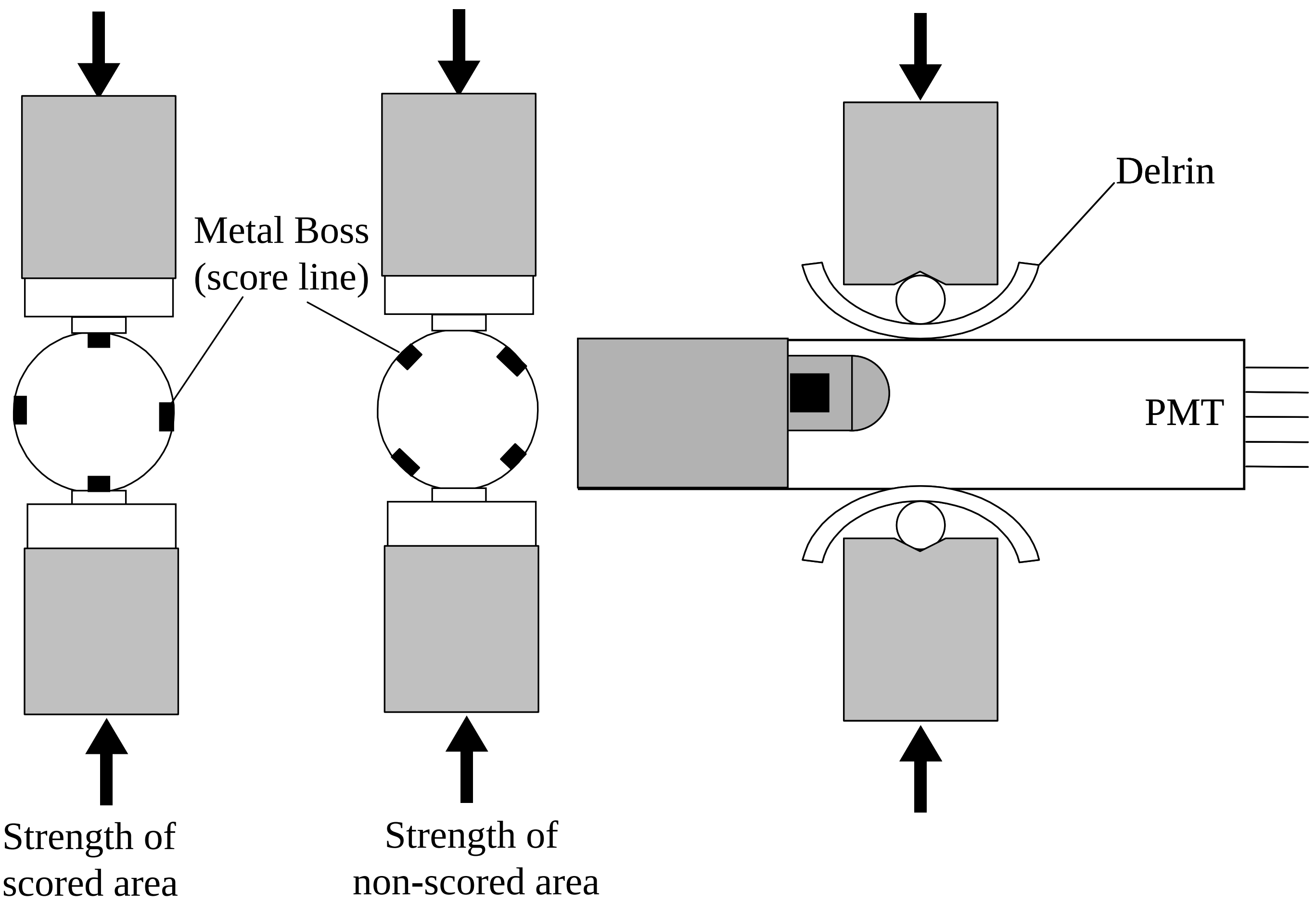
STRENGTH TESTING, WEIBULL ANALYSIS

Solution Path 2 Pursuit – Strength testing/Weibull analysis
Purpose of the Test

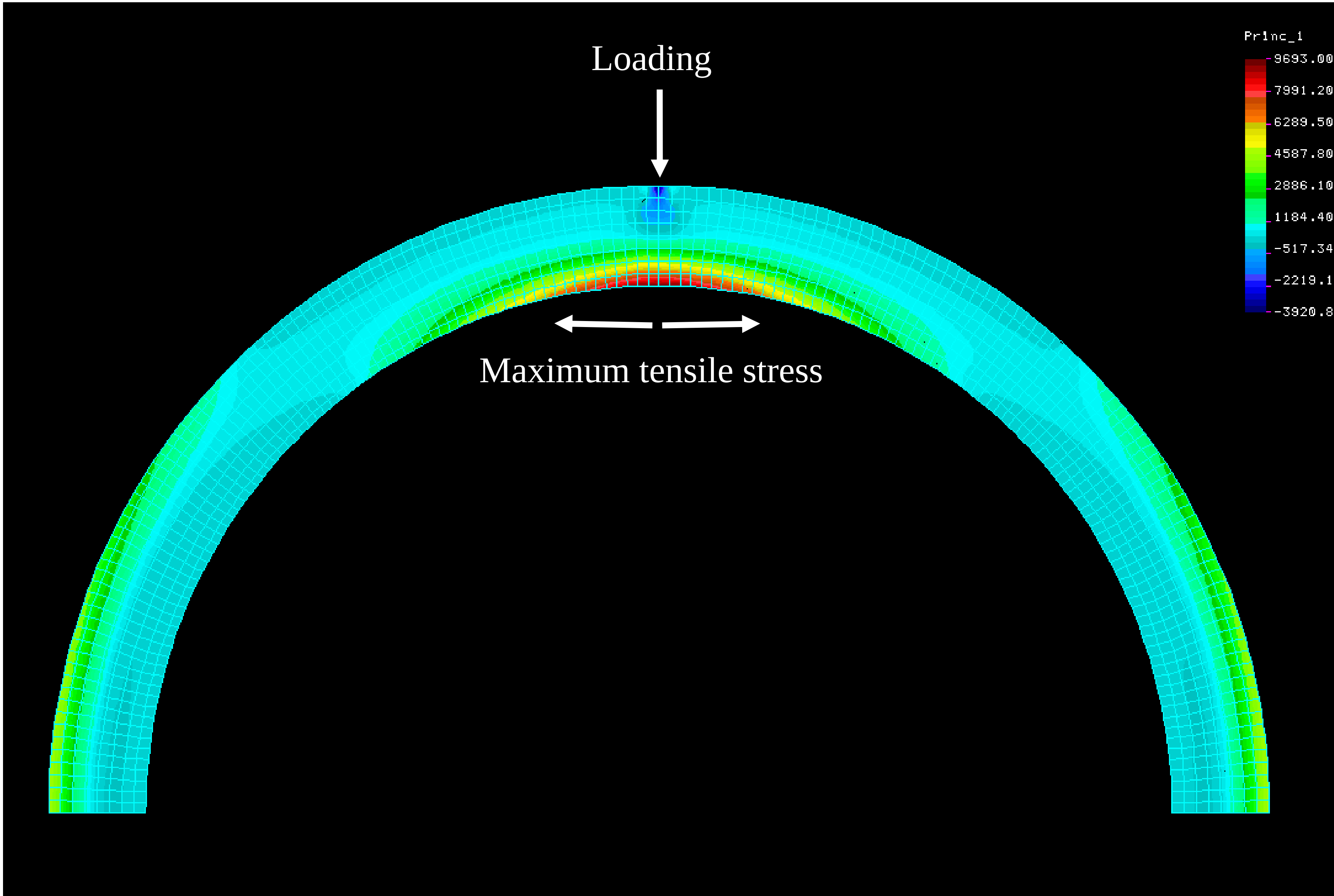
- **Unlike metals glass materials have large scatter in strength data.**
- **Weibull weakest-link theory: flaws randomly distributed; fail when the largest flaw (weakest link) reaches critical stress; for any given stress, there is a probability a flaw will meet the failure requirement.**
- **Measure the strength of scored PMTs and obtain Weibull distribution parameters (*m* and σ_o) for PMTs.**
- **With Weibull parameters, we can estimate probability of failure for PMTs under a given stress level, or calculate the maximum stress level for a given probability of failure.**

Solution Path 2 Pursuit – Strength testing/Weibull analysis

Test Setup



Path 2 Results - Stress analysis and Strength Calculation
3-D linear elastic model



Path 2 Results - Weibull 2-parameter Function

$$P = 1 - \exp[-(\sigma / \sigma_o)^{m}]$$

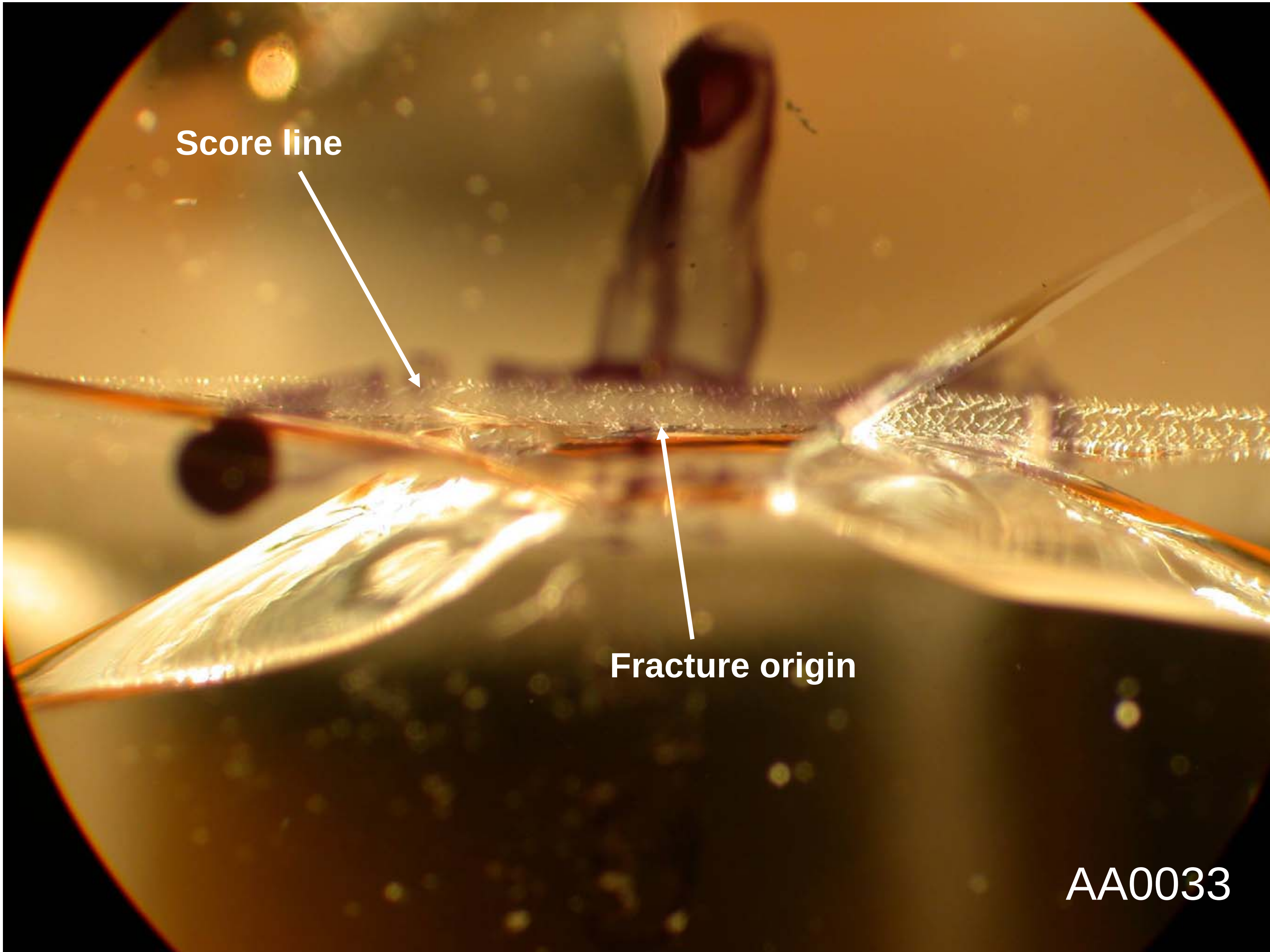
P:	probability of failure
σ:	fracture stress
σ_o:	characteristic strength (stress corresponding to 63.2% probability of failure)
m:	Weibull modulus

Consider different area/volume under max tensile stress between strength test and actual PMT in application

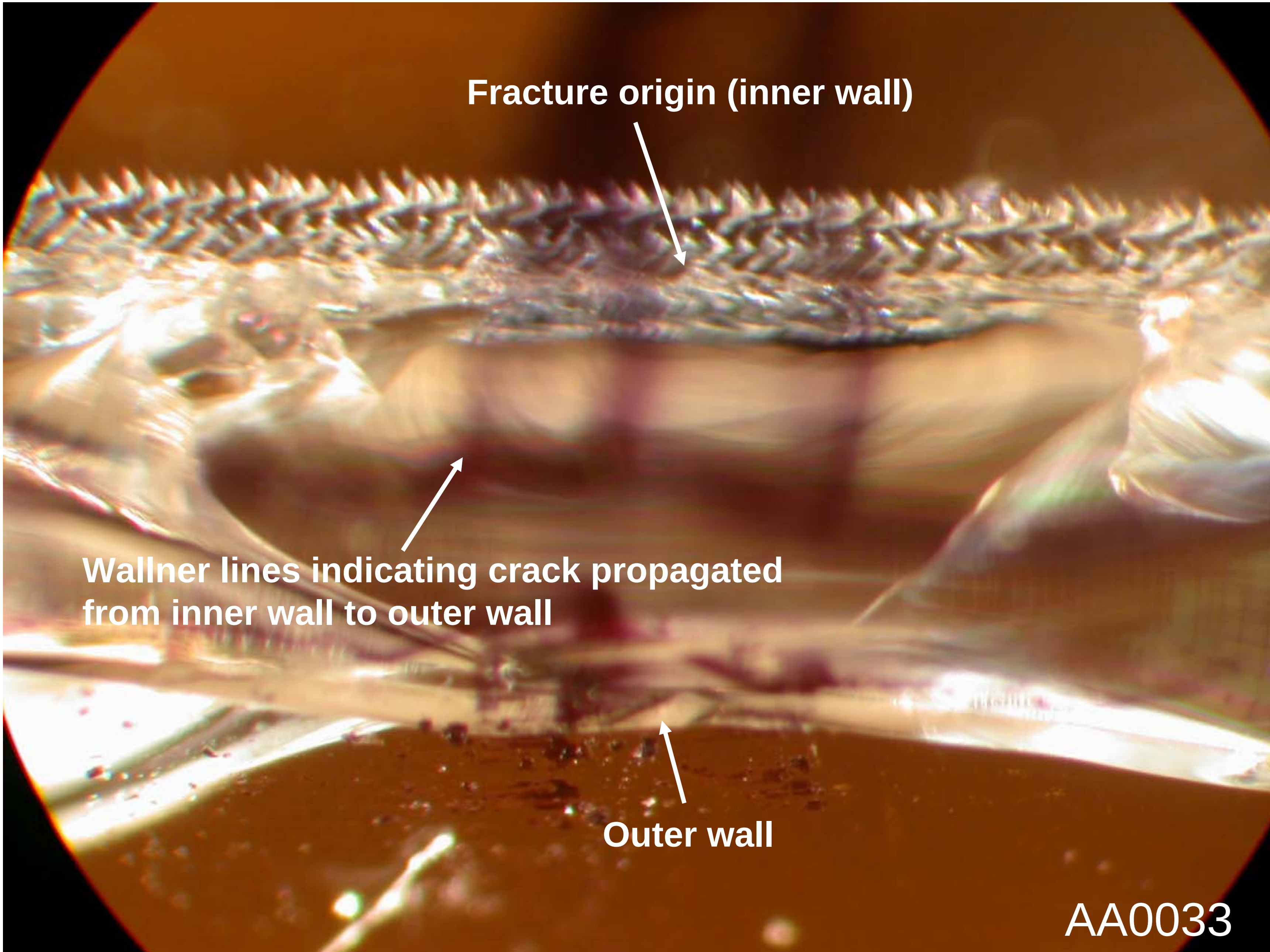
$$(\sigma_1 / \sigma_2) = (S_2 / S_1)^{1/m}$$

S:	Area with maximum tensile stress
m:	Weibull modulus

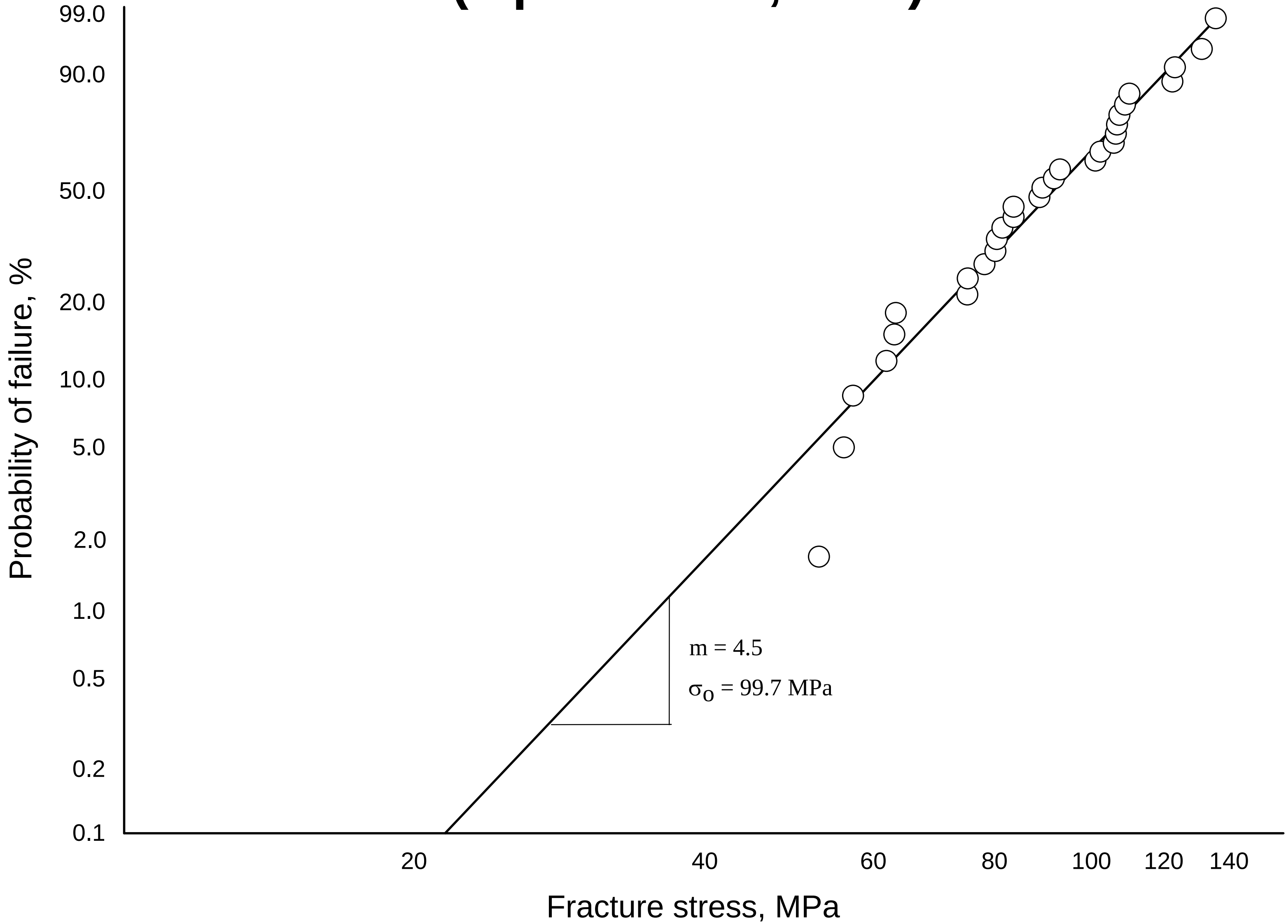
Path 2



Path 2


Fracture origin (inner wall)
Wallner lines indicating crack propagated from inner wall to outer wall
Outer wall
AA0033

Path 2 - Weibull Distribution of PMT Strength (2 parameter, MLE)



Path 2 - Weibull Parameters (Maximum-Likelihood Estimate, MLE)

$$P = 1 - \exp[-(\sigma / \sigma_o)^m]$$

$$(\sigma_1 / \sigma_2) = (S_2 / S_1)^{1/m}$$

S_{PMT} / S_{test} = 6.5 (FEA estimation)

PMT	*m*	σ_o, ksi
Off-score, for test configuration	7.9	33.4
On-score, for test configuration	4.5	14.5
Off-score, for PMT in application	7.9	26.4
On-score, for PMT in application	4.5	9.6

Strength reduction ratio $\sigma_{on\text{-}score} / \sigma_{off\text{-}score} = 0.43$

Path 2 - Use strength reduction as a correction factor

$$\sigma_{score} = \sigma_{borosilicate} * F_{reduction}$$

Assume:

- borosilicate glass strength = 100 MPa (14.5 ksi) (from *Engineering Materials Handbook*, vol 4, Ceramics and Glasses, ASM International, 1987)
- strength reduction ratio due to scoring = 0.43

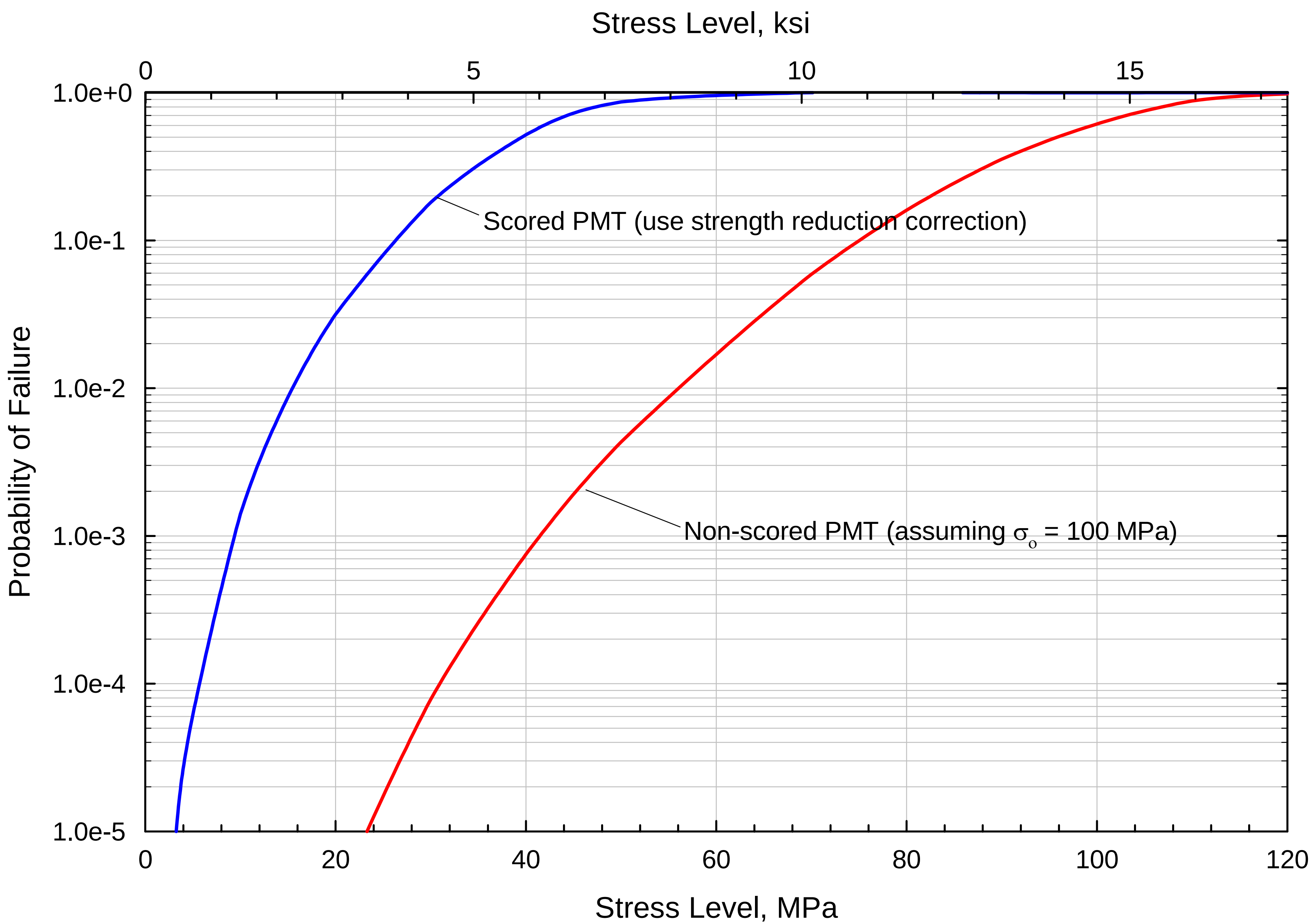
Weibull parameters for scored PMT under thermal stress:

$m = 4.5$

$\sigma_o = 6.2$ ksi

Path 2 - Weibull Distribution

Assuming borosilicate strength 100 MPa



Path 2 – Initial Weibull results Observations

- From assumption that borosilicate glass strength = 100 MPa and strength reduction due to score = 0.43, the score PMT has m = 4.5, σ_o = 6.2 ksi

- To achieve a 1.5% probability of failure (goal, vs. 3% requirement) the stress must be less than 2500 psi. For 600 psi, the probability of failure = 2.6×10^{-5}

- <u>However</u>- what we know very recently, but did not then, was the crack initiations are likely away from score flaws, on the outer surface, initiating at smaller flaws.

INVESTIGATION – FAILED UNIT REMOVAL AND CRACK ANALYSIS – Second set of Failures

Investigation

- Well into our work, a second set of failures in the old design

- The full E.U chassis qual testing in late February failed 3 more PMTs (out of 17) in thermal vac at the second cycle (which was down to -40C).

- All three units removed successfully with extremely careful but time consuming approach.

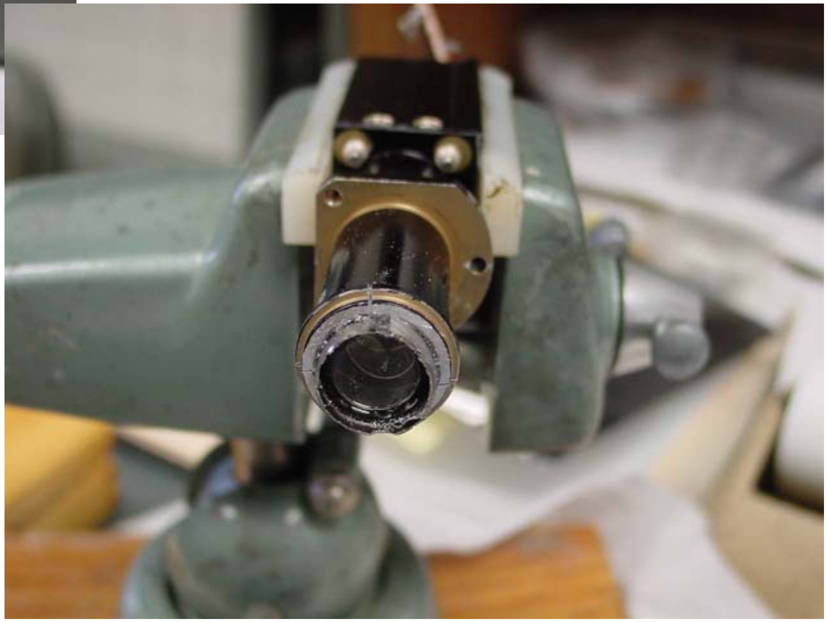
- A week of inspections revealed the score lines were not the cause for the failure. All failed from defects on the outer surfaces. We learned this after we had made our preliminary solution decision.

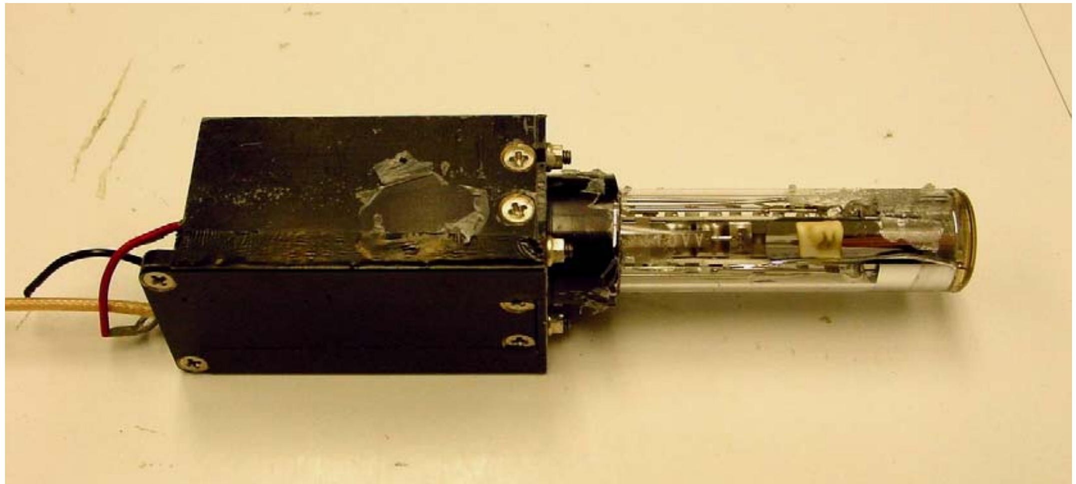
- All three PMTs failed at similar positions: circumferentially near middle of mu-metal overlap and longitudinally near the middle of the tube [AA0005 - 35 mm, AA0021 - 22 mm, & AA0128 - 27 mm (from window end)]. Similar to the first failure

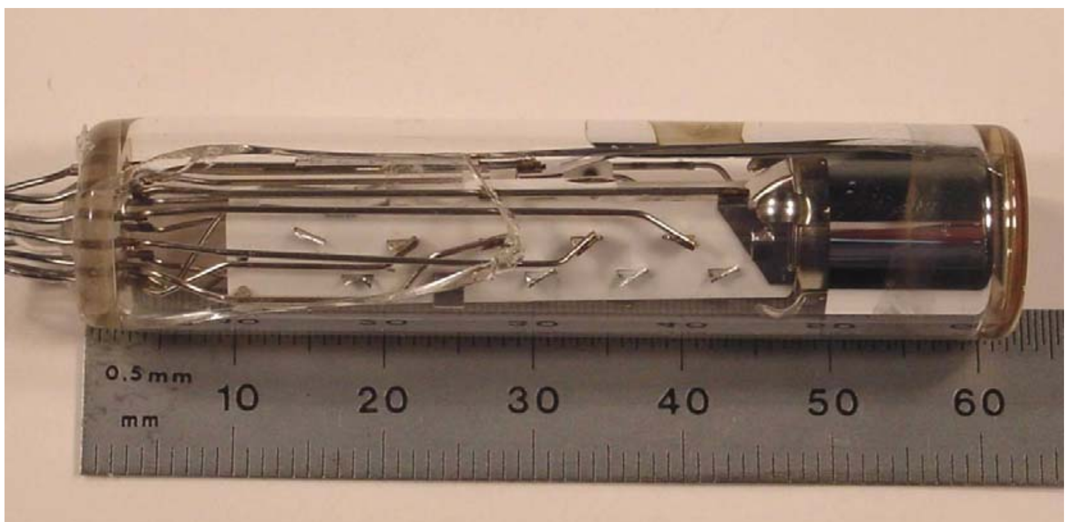
Path 2 – Defects on the outer surface of PMTs

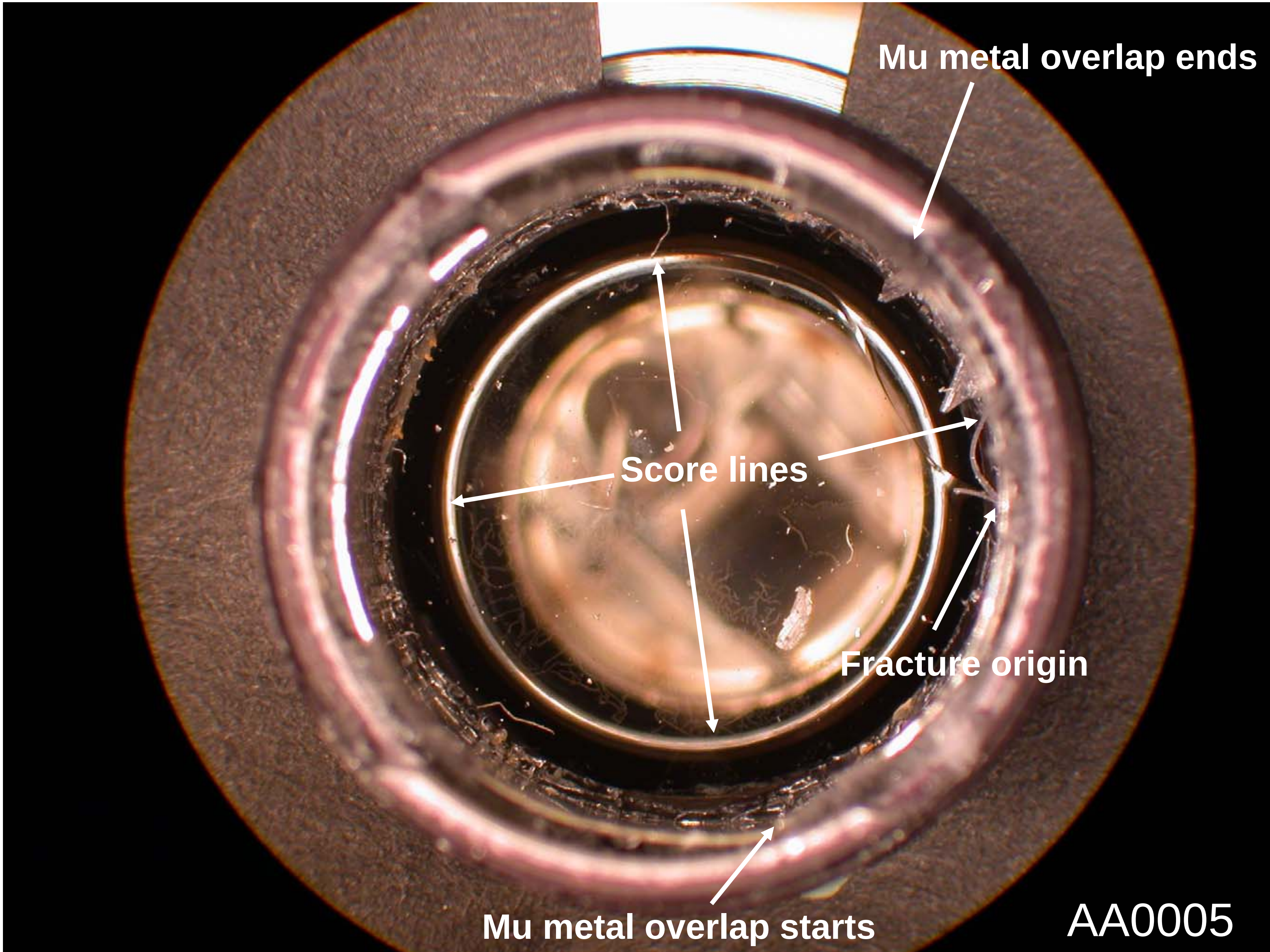
- Predicted stress on outside surface in region of Mu metal overlap is not 4300 psi but around 3200 psi.
- Inspected outer surfaces of 8 NG PMTs. Scores/pits/scratches were found, but are small in size compared to scores on inner surface. NG tubes handled very little at GSFC
- No new strength tests have been performed on the outer surfaces of the PMT.
  - More difficult to test the strength of outer surface.
  - Time constrain
  - PMTs better used for qualification of new designs.
  - The data we have: failed 4 of 23, in an area with calculated stress around 3200 psi

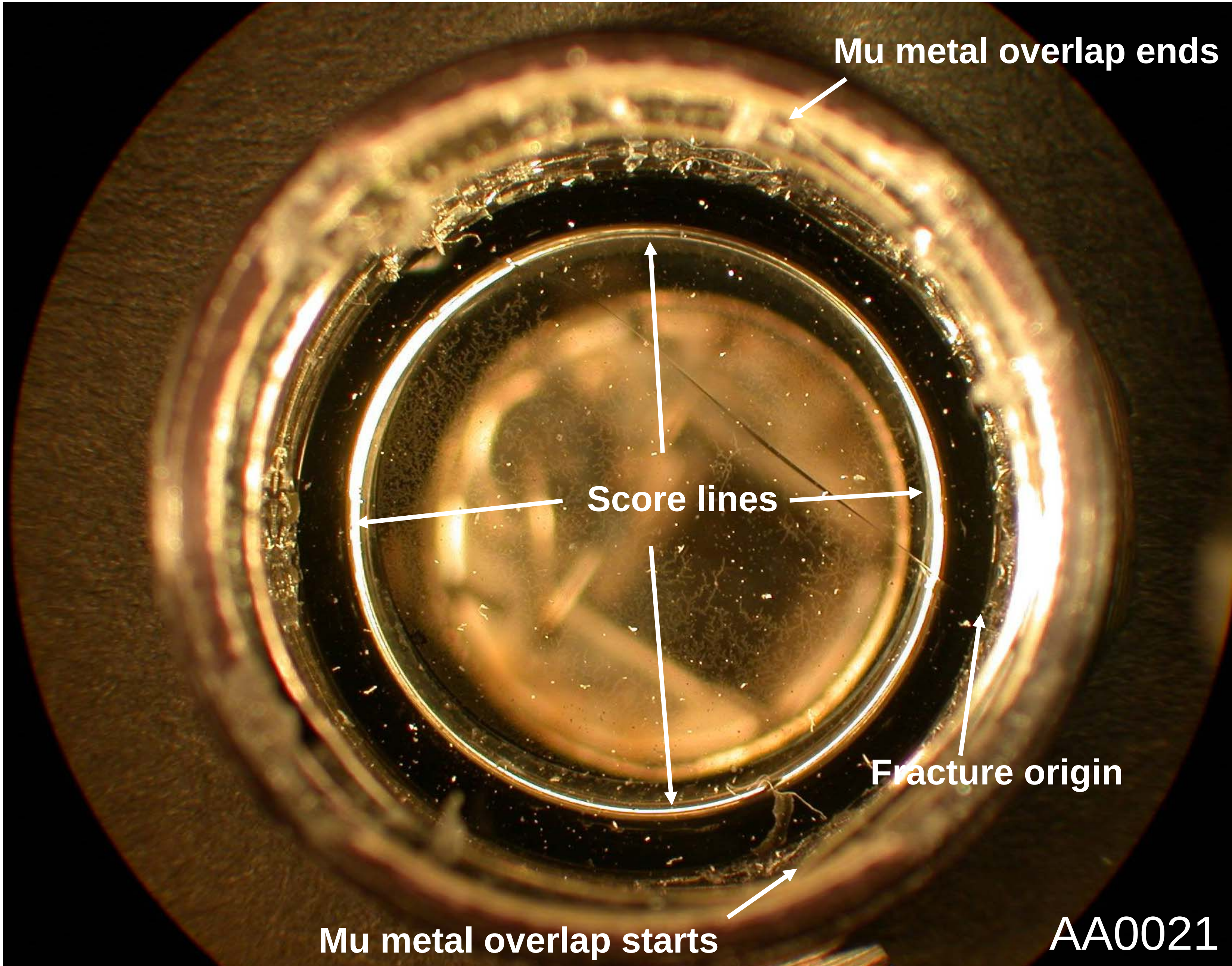
Cut with handsaw and removed the housing piece by piece

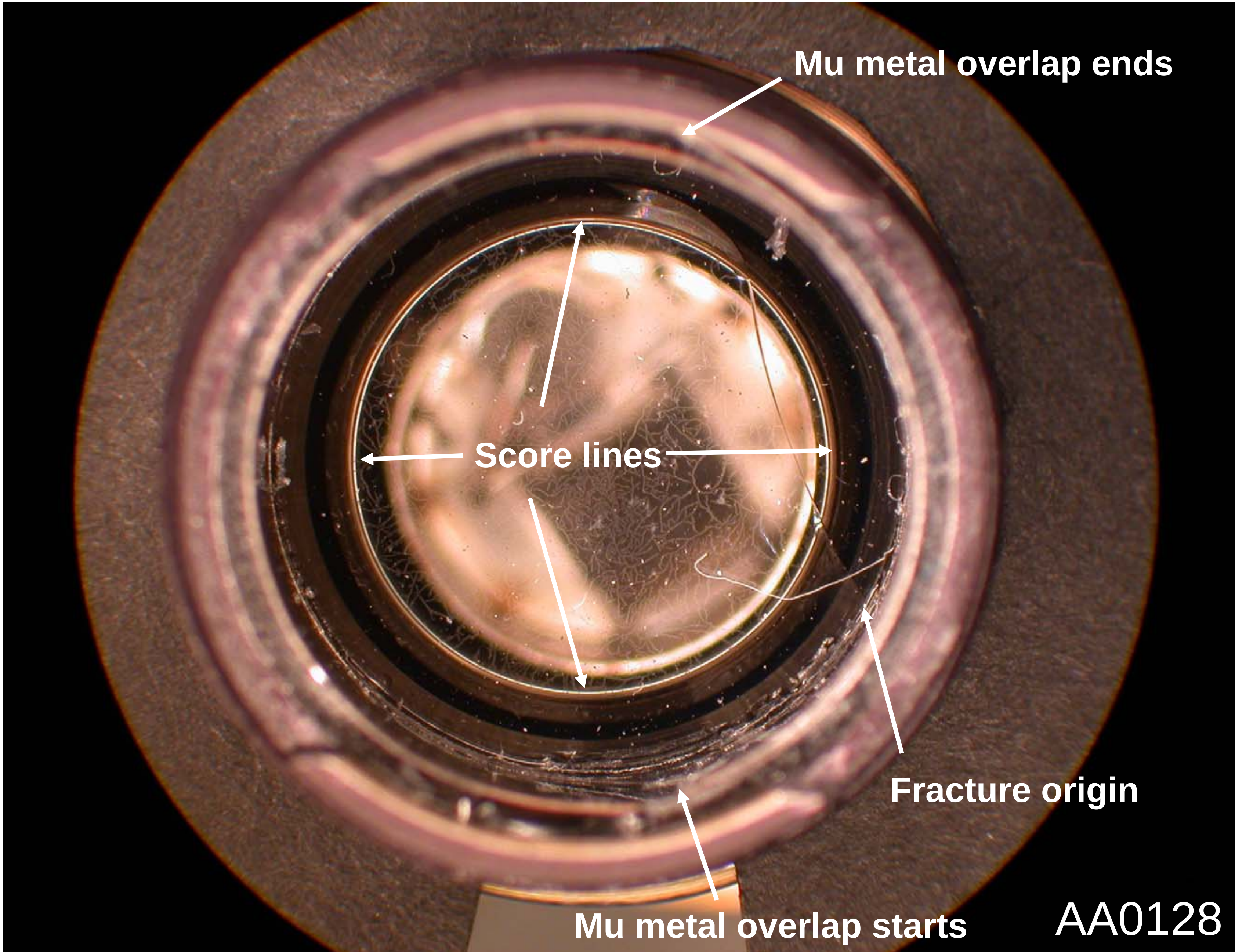


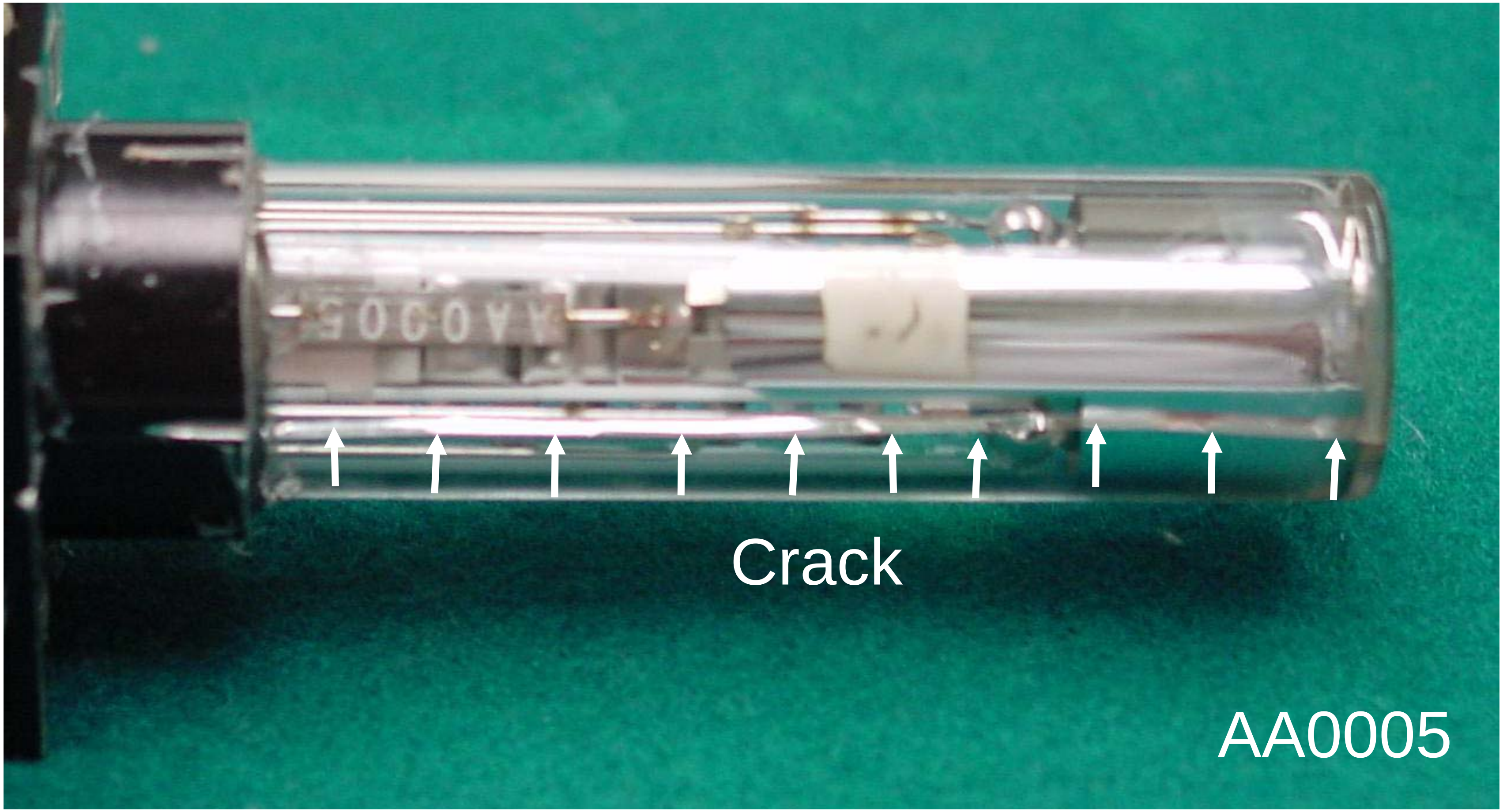


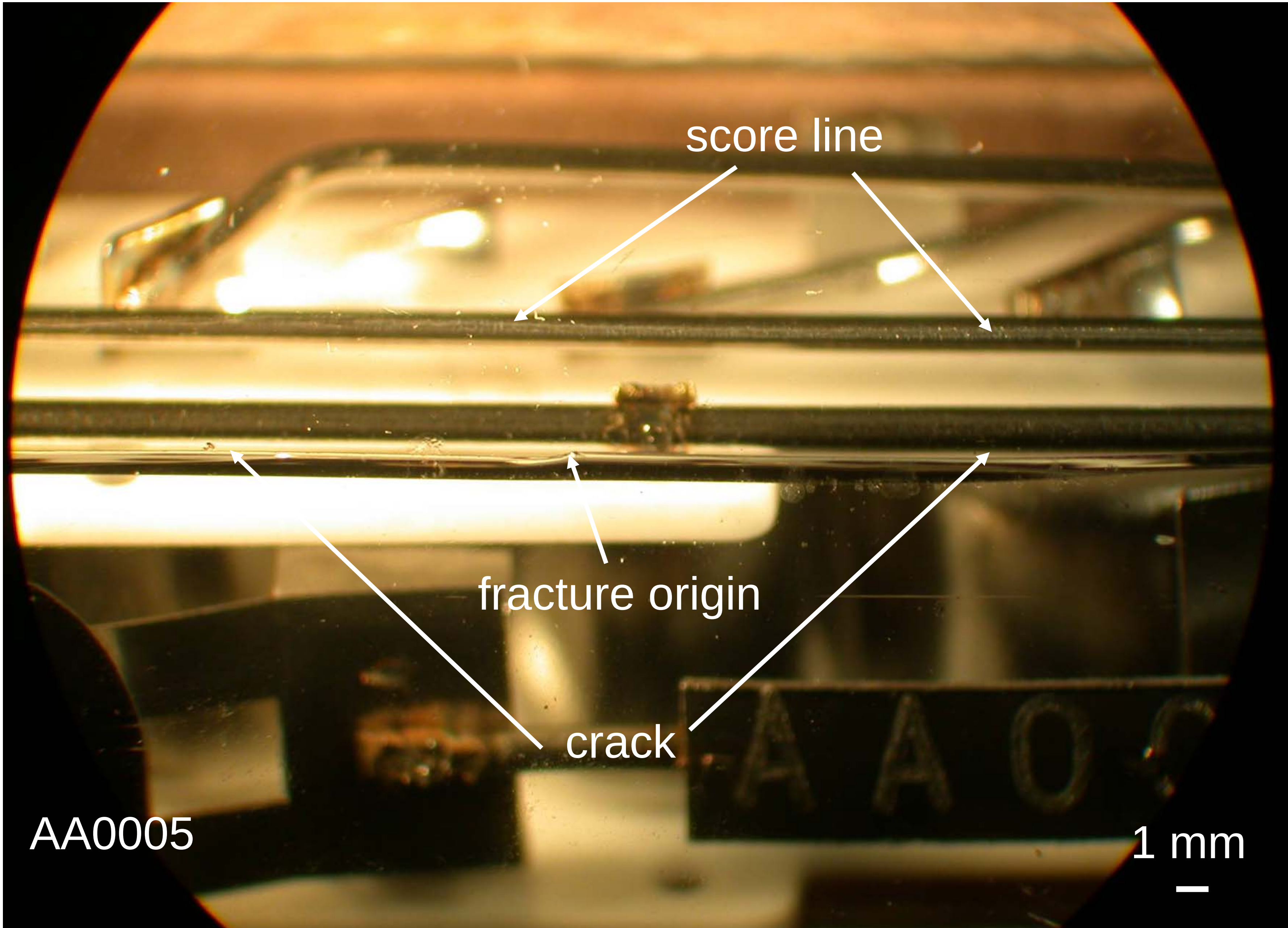

0.5mm
mm
10
20
30
40
50
60

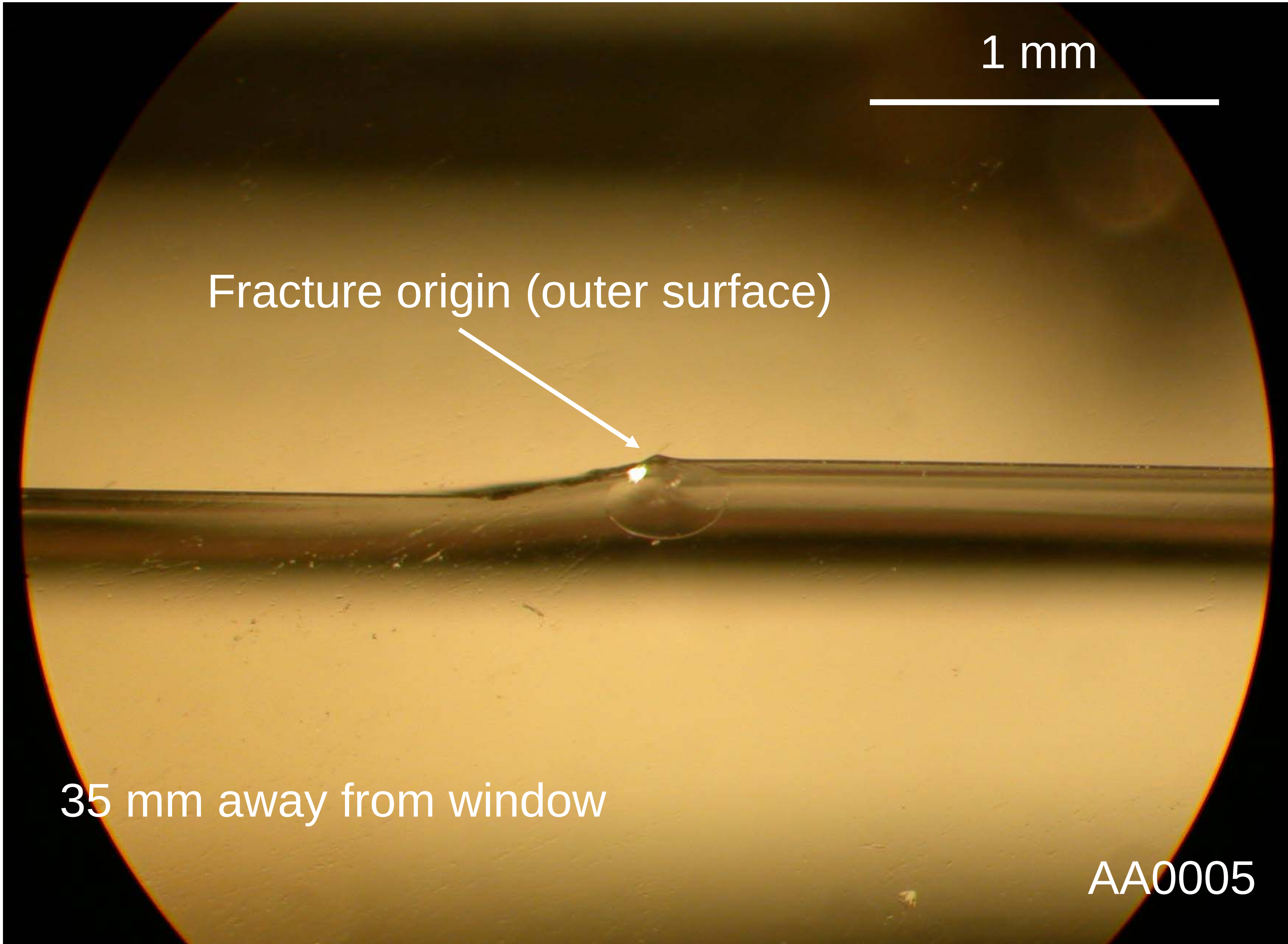

Mu metal overlap ends
Score lines
Fracture origin
Mu metal overlap starts
AA0005

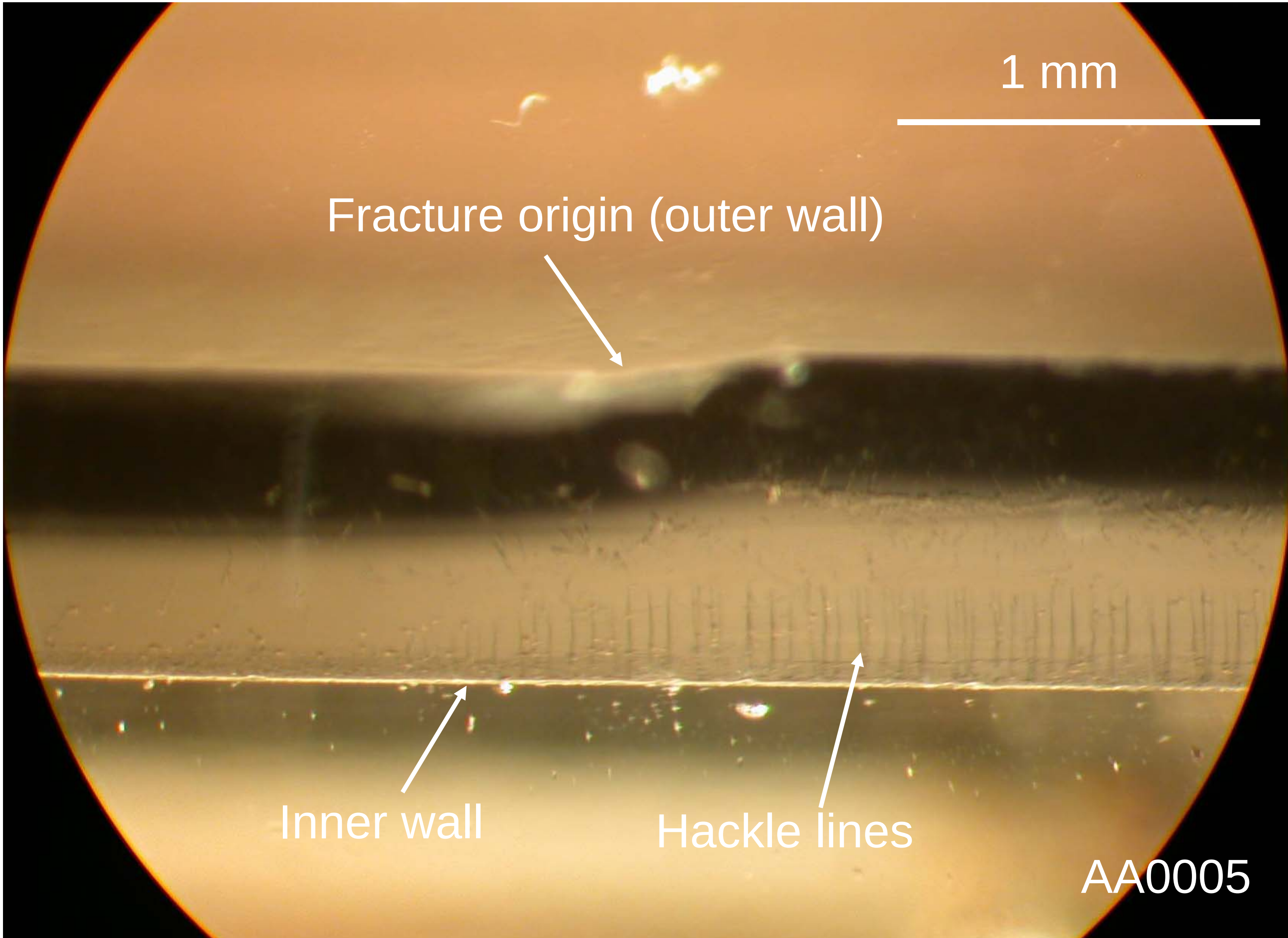

Mu metal overlap ends
Score lines
Fracture origin
Mu metal overlap starts
AA0021

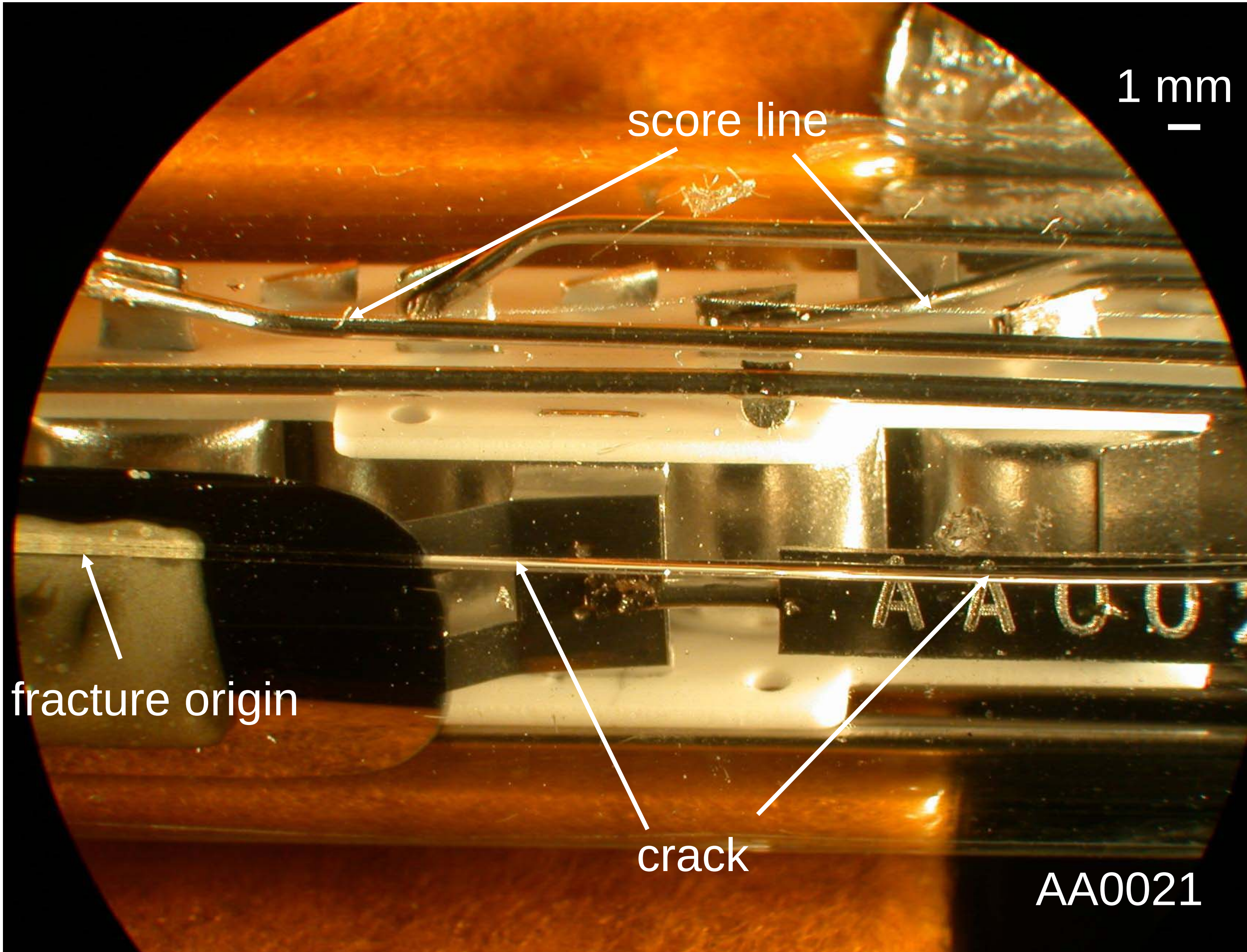

Mu metal overlap ends
Score lines
Fracture origin
Mu metal overlap starts
AA0128

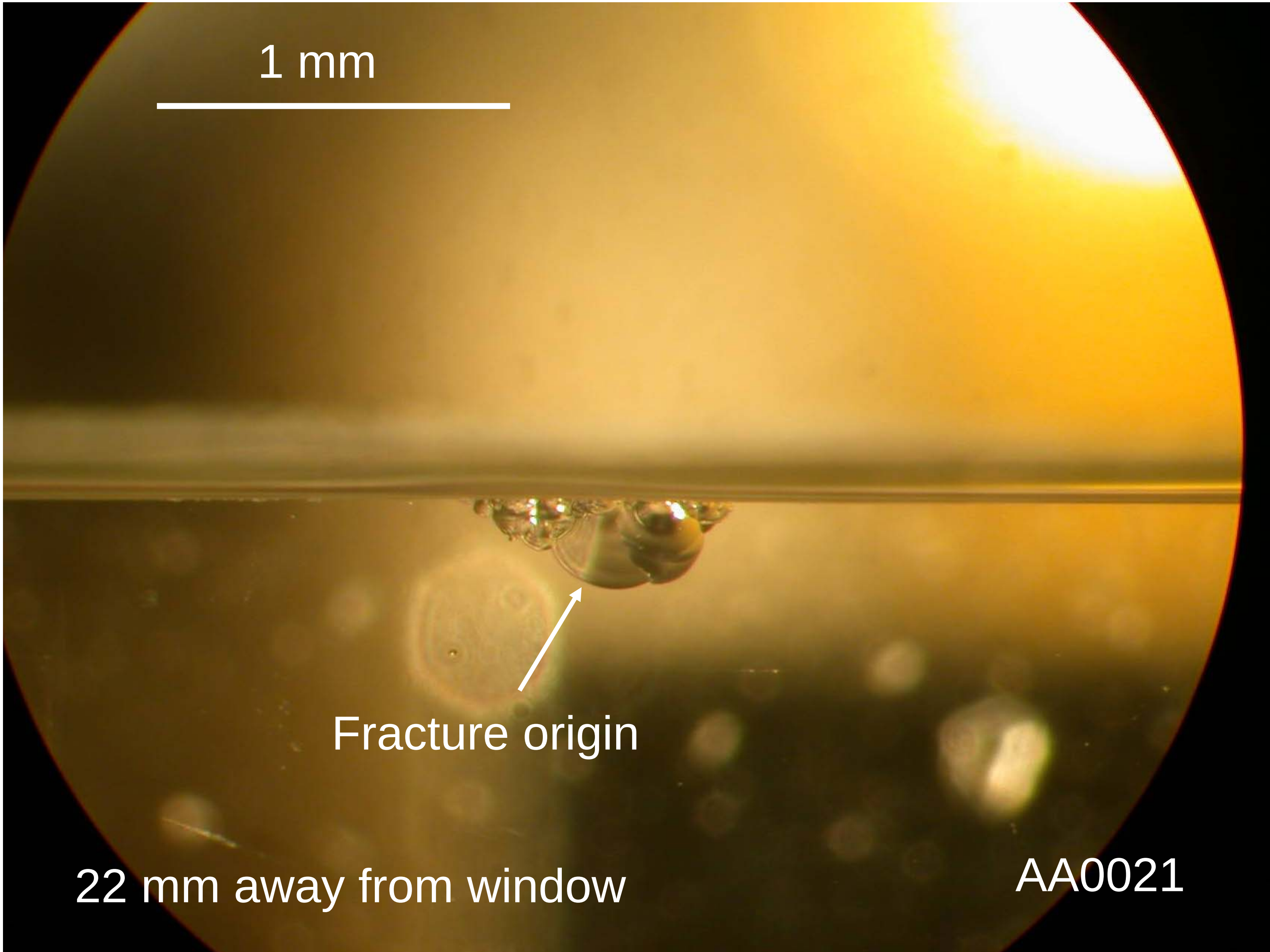

AA0005
Crack
AA0005

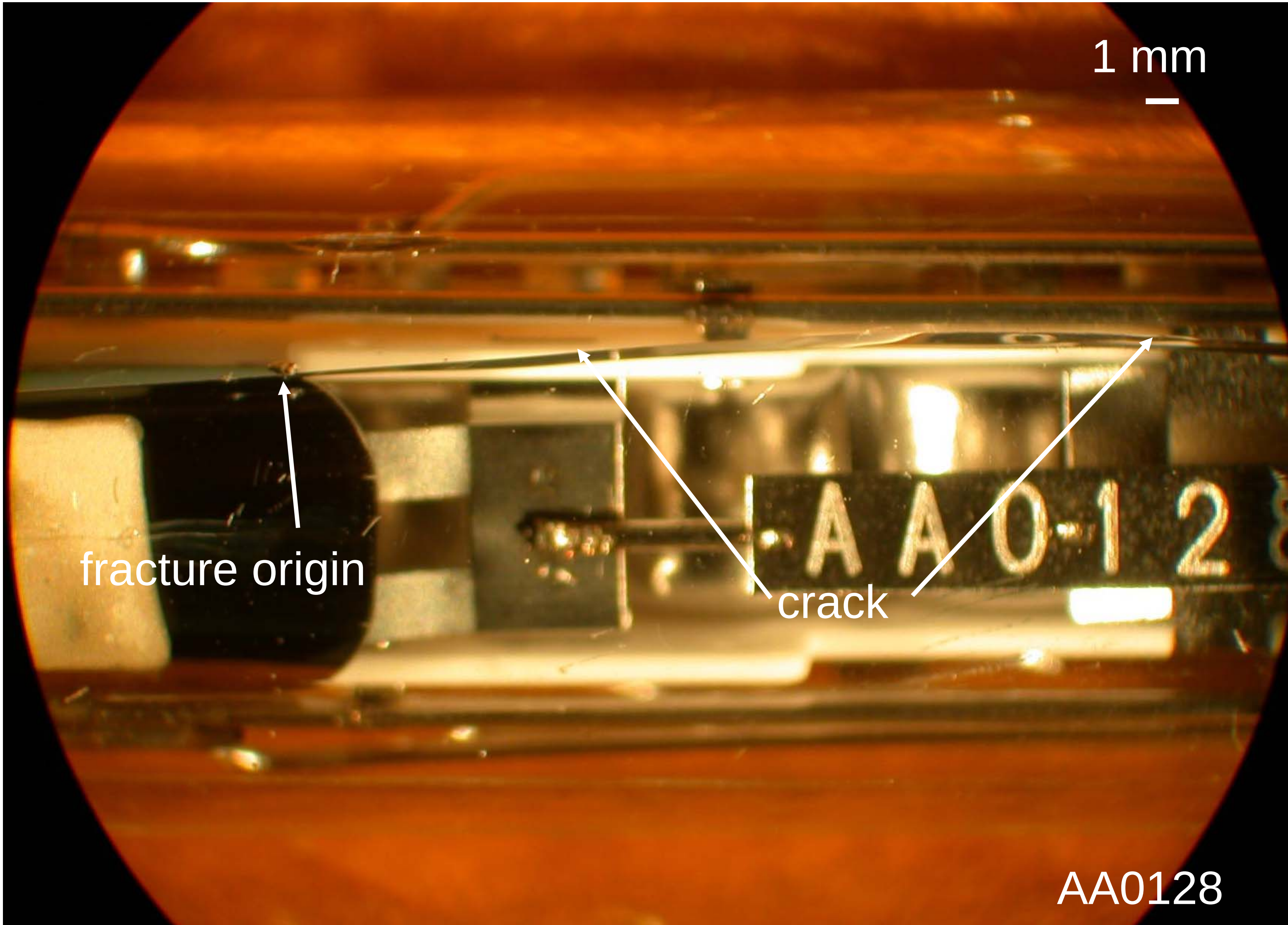

score line
fracture origin
crack
AA0005
1 mm

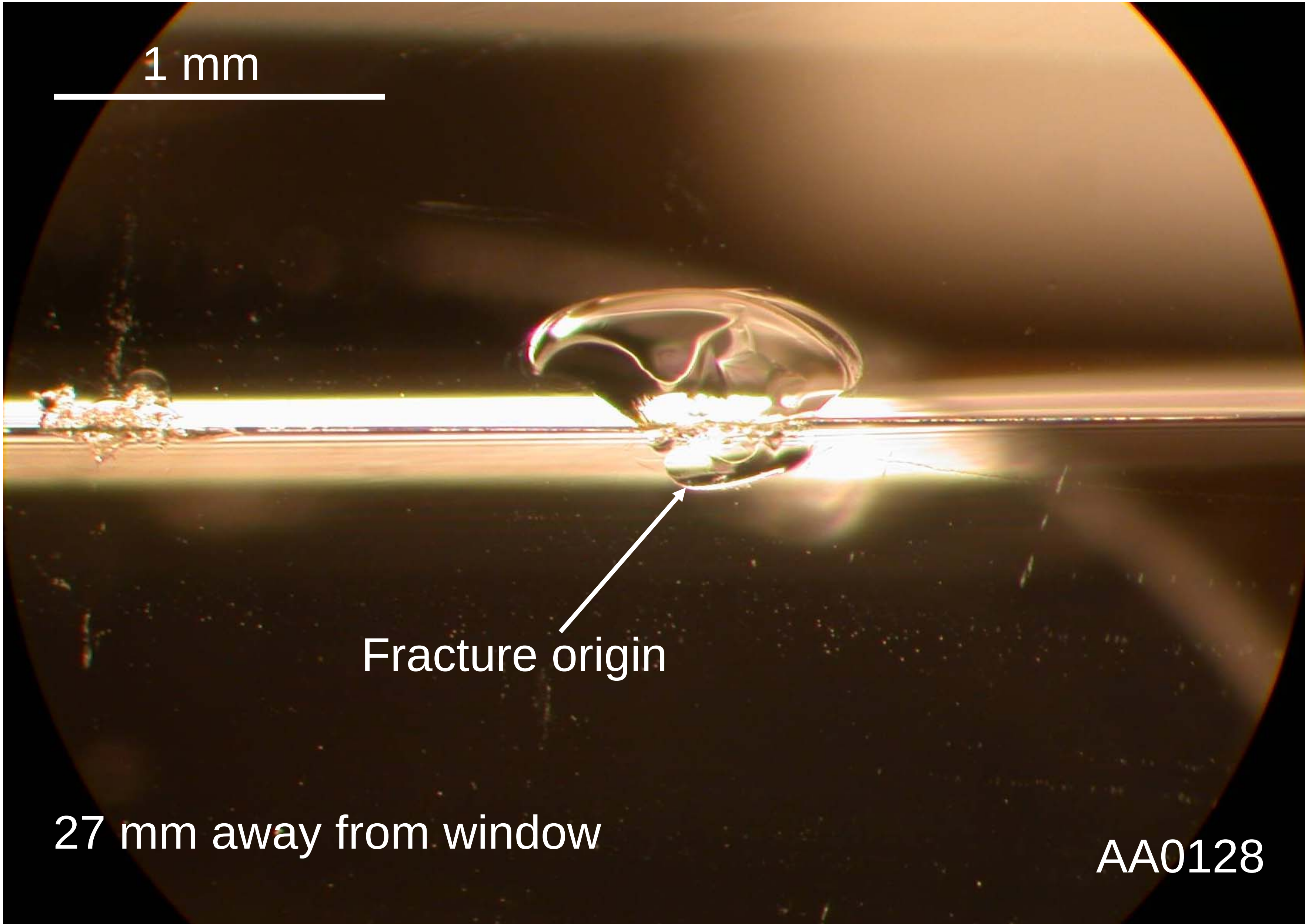

1 mm
Fracture origin (outer surface)
35 mm away from window
AA0005

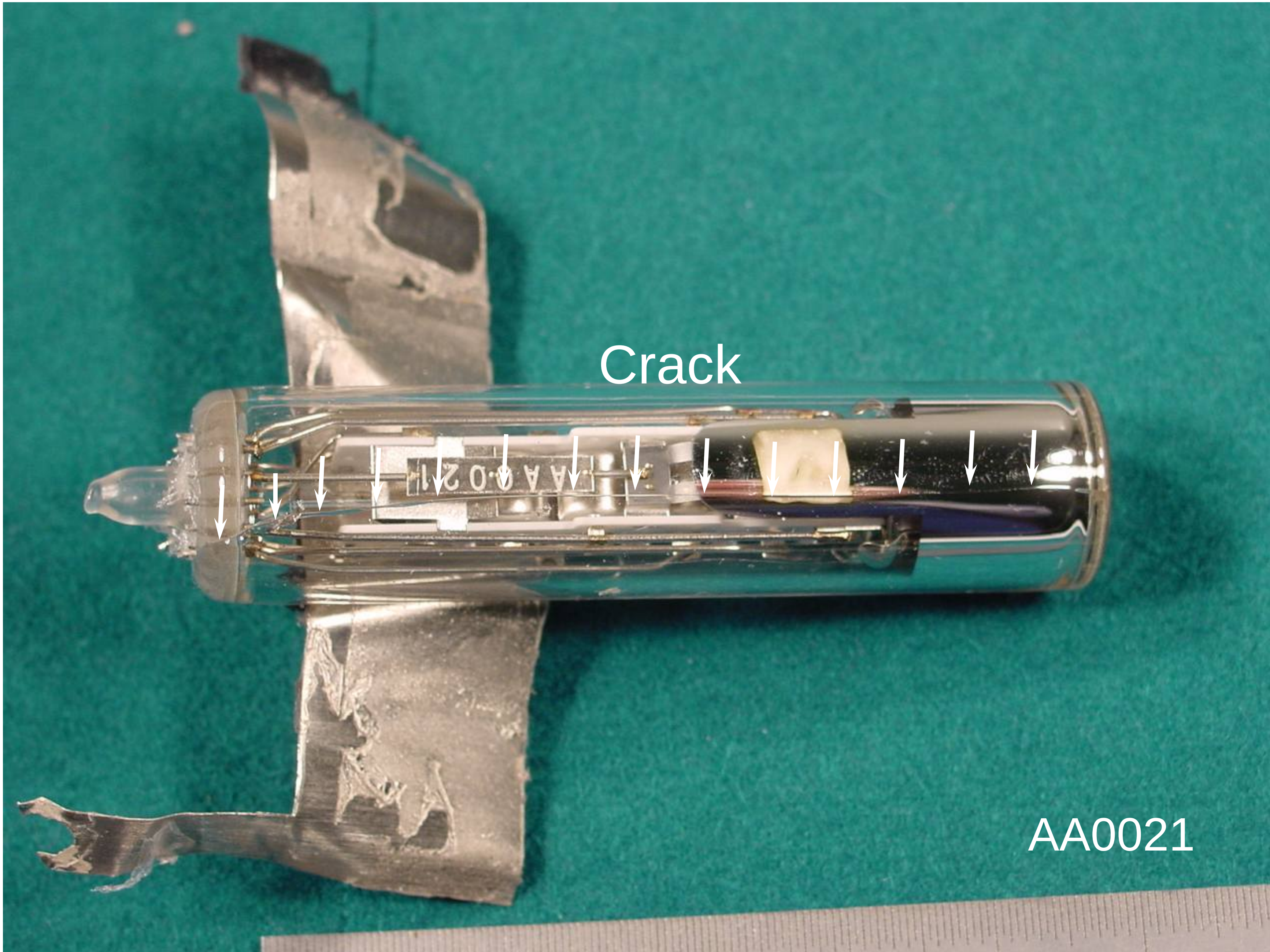

1 mm
Fracture origin (outer wall)
Inner wall
Hackle lines
AA0005


1 mm
score line
fracture origin
crack
AA0021


1 mm
Fracture origin
22 mm away from window
AA0021


1 mm
fracture origin
crack
AA0128


1 mm
Fracture origin
27 mm away from window
AA0128


Crack
AA0021

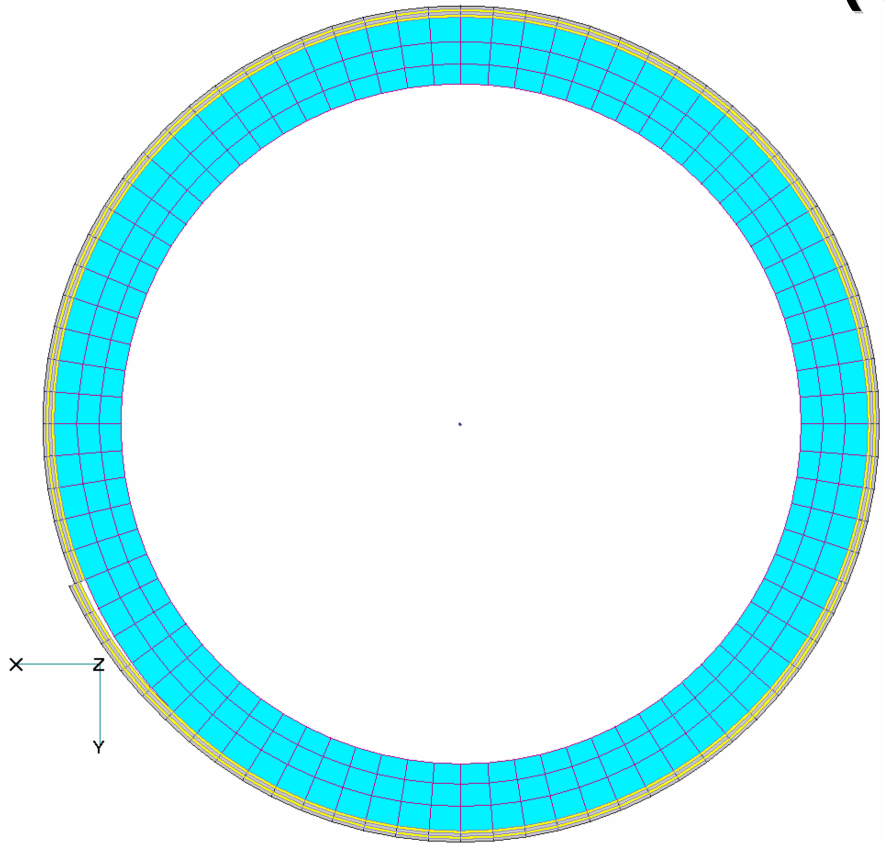
THE SOLUTION

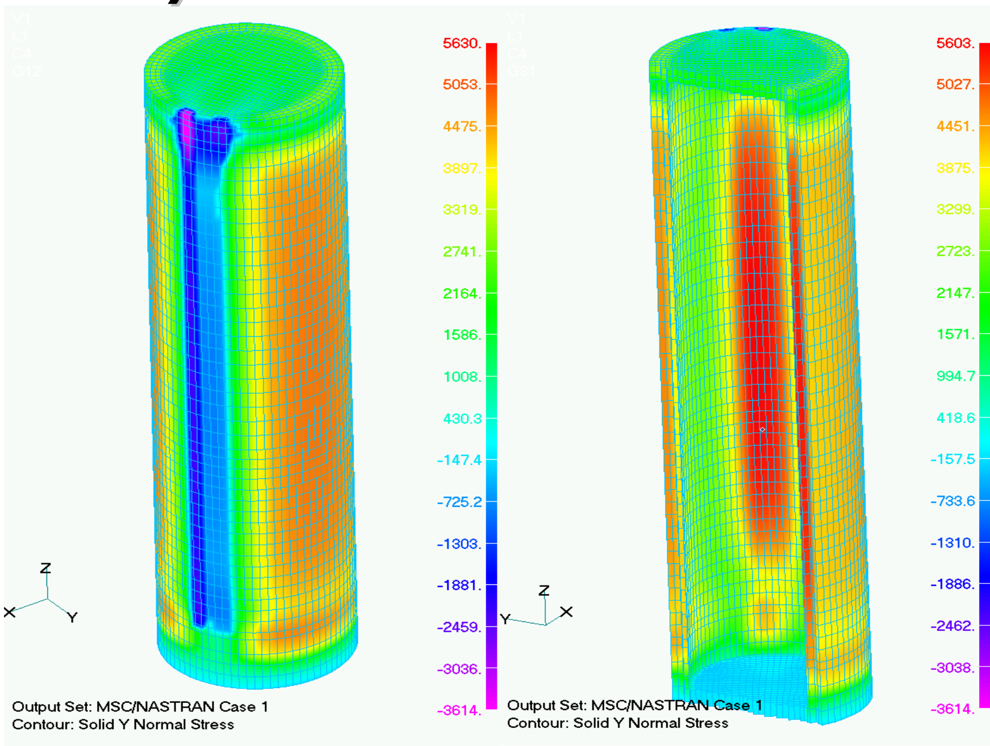
STRESS ANALYSIS OF POTENTIAL SOLUTIONS

Initial Investigation & Solutions

- Initial conditions show high stresses on inner and outer walls of PMT tube.
- Mu Metal causes adverse loading conditions on PMT tube at a relatively high tensile stress (~ 1.6 ksi).
- Uralane stiffness also adds to tube stress
  - High CTE of uralane "pulls out" on PMT tube adding stress in tube.
- Evidence shows cracks propagate from center of Mu Metal overlap region.
  - Area of peak tensile stress on outer wall
- Solution path needs to eliminate adverse effects of Mu Metal on PMT tube and effects of high stiffness and CTE of Uralane.

Eliminating Mu Metal Effects with Double Wrap (Case 2)



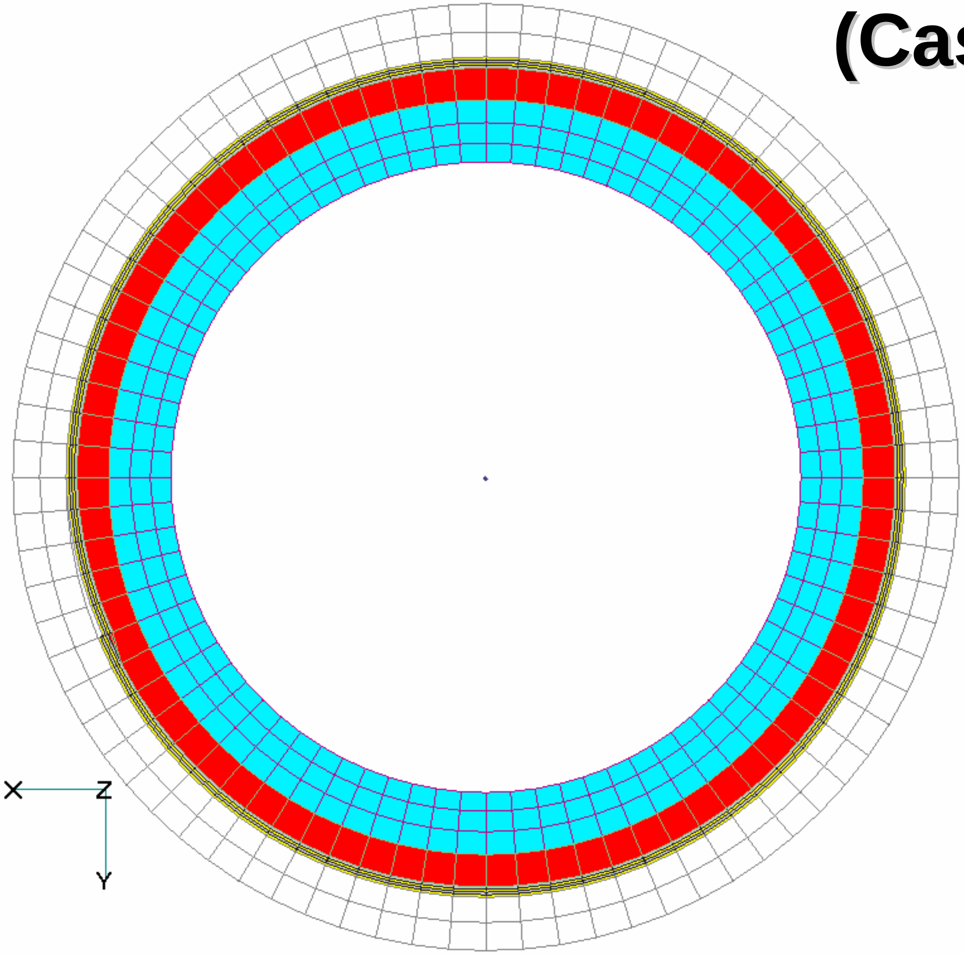


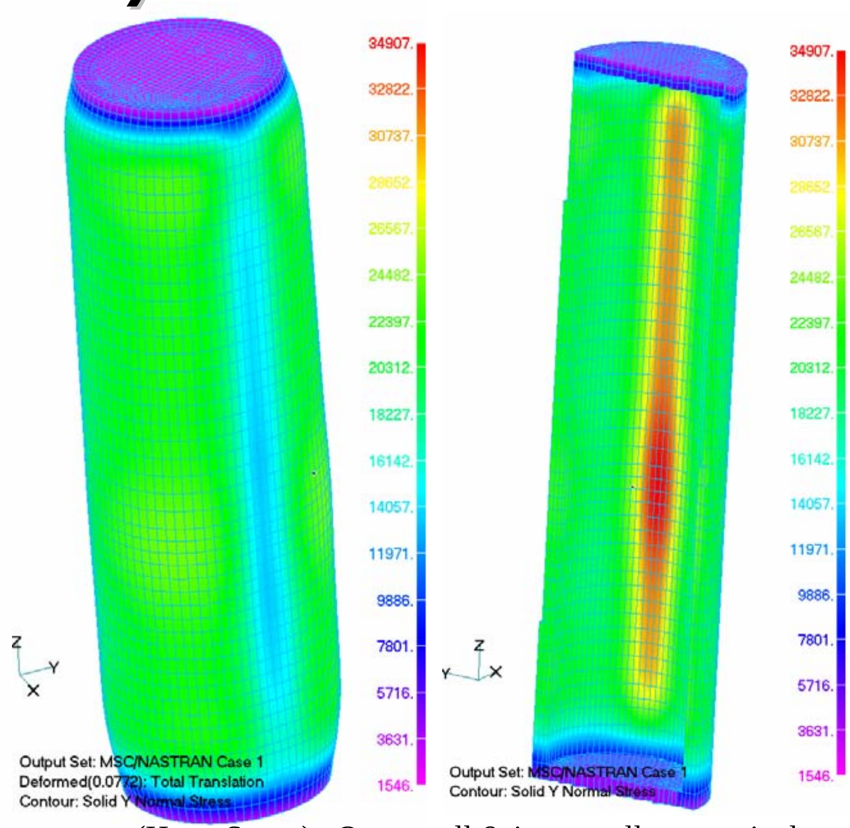
(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

• Mu Metal effects only. No aluminum housing or potting included in model. *Comparable to results from previous slide titled “Mu Metal effects”.

• Peak stress due to Mu Metal reduces 50% on inner wall (~1600 psi to ~800 psi) and 67% on outer wall (~1600 psi to ~691 psi).

Moving Mu Metal to inside wall of housing (Case 3)

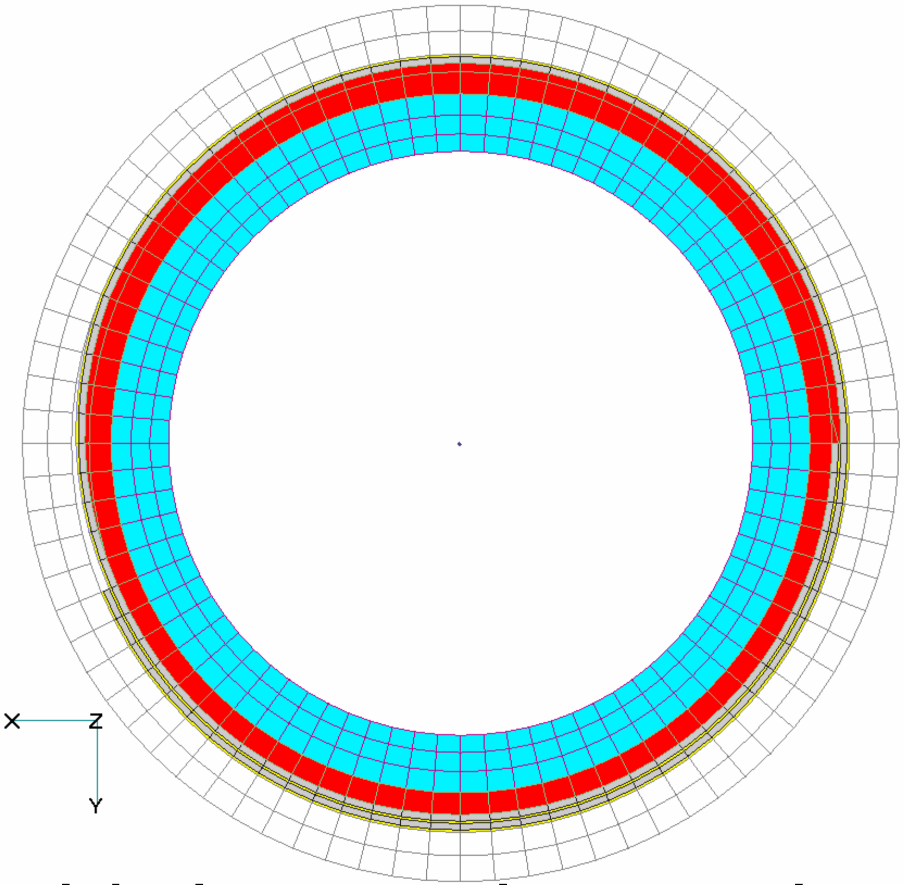


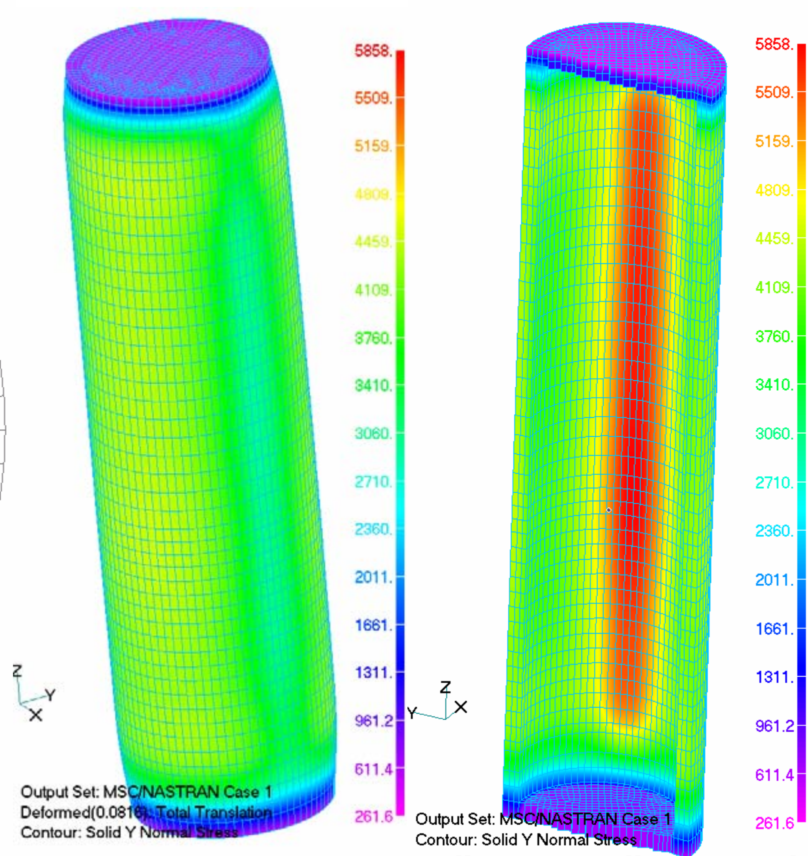


(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

- Mu Metal transition still causing asymmetric loading.
- Potting material causing higher peak stress on PMT inner wall than initial configuration (~5 ksi, approx. 16% increase) !!
- PMT outer surface stresses ~ 3.5 ksi.

Mu Metal on inside wall of housing, RTV-566 substitution for uralane potting (Case 4)





(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

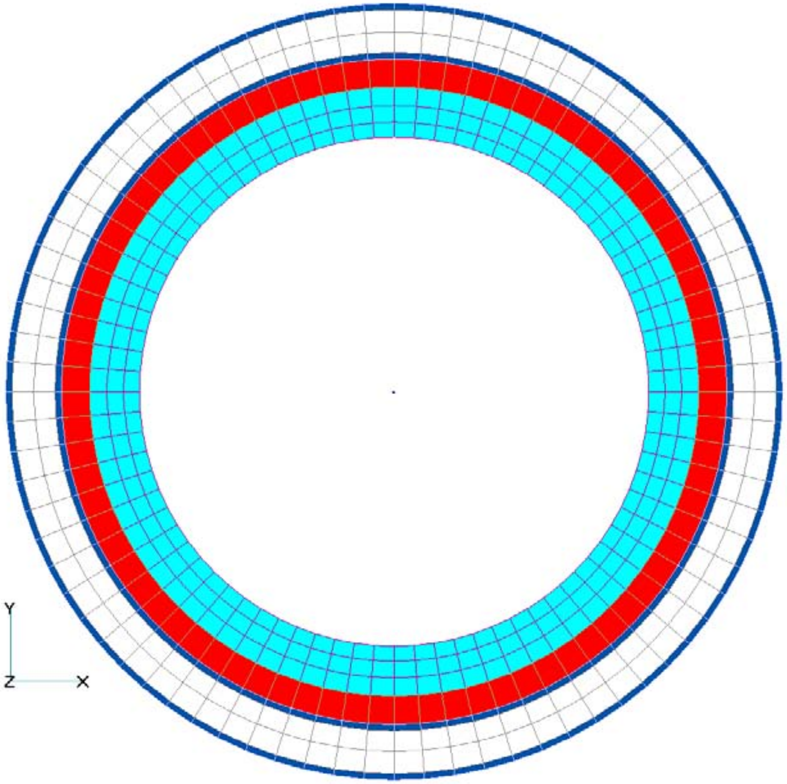
- Slight adverse reaction due to Mu Metal.
- Softer potting material "dampens" asymmetric effects.
- PMT inner surface peak stress ~ 850 psi.
- Outer surface peak stresses ~ 653 psi.

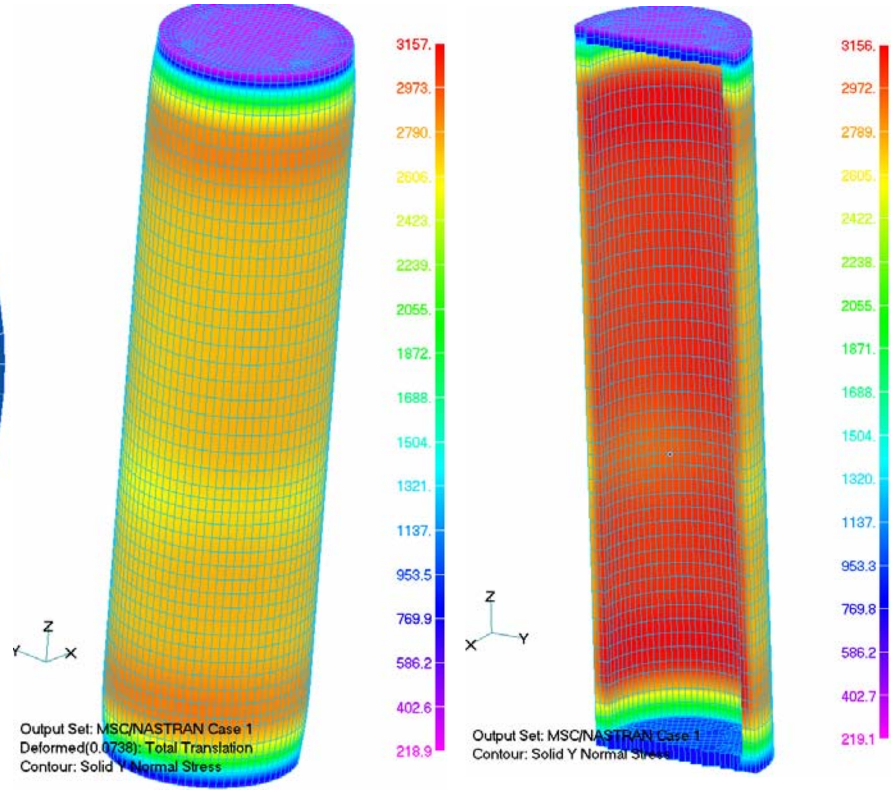
E_{rtv} = 609 psi

CTE_{rtv} = 233 ppm/deg C

Nu_{rtv} = 0.46

Nickel coated housing with RTV-566 potting (Case 5)





(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

• Inner wall stress ~ 458 psi.

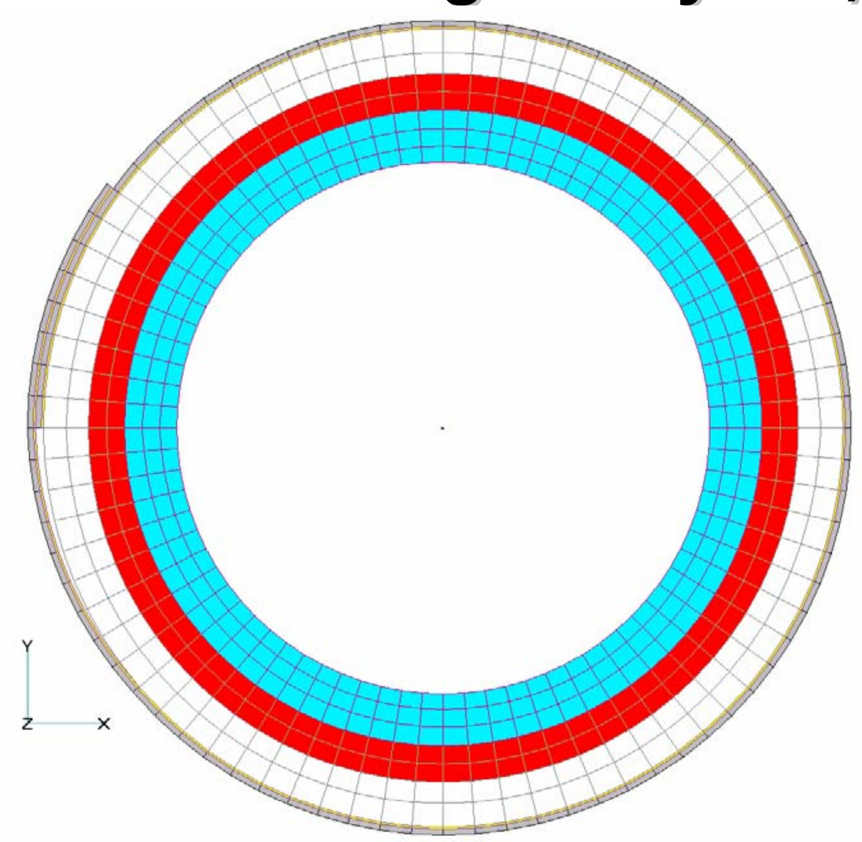
• Outer wall stress ~ 420 psi.

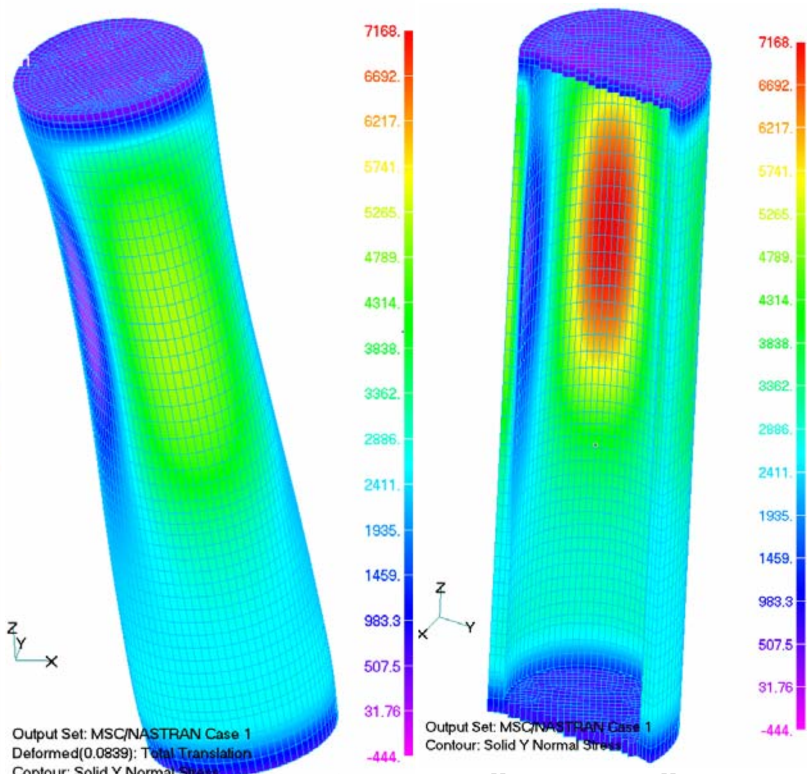
• Nickel coated housing with RTV-566 potting gives favorable results. However, Nickel coating did not meet magnetic shielding requirements.

• Also sensitive to Poisson’s ratio of potting compound (See Plot 1).

Plot 1 – Poisson's ratio sensitivity for Nickel Coated Housing PMT Assembly

Mu Metal attached to outside wall of housing with y966, RTV-566 potting (Case 6)





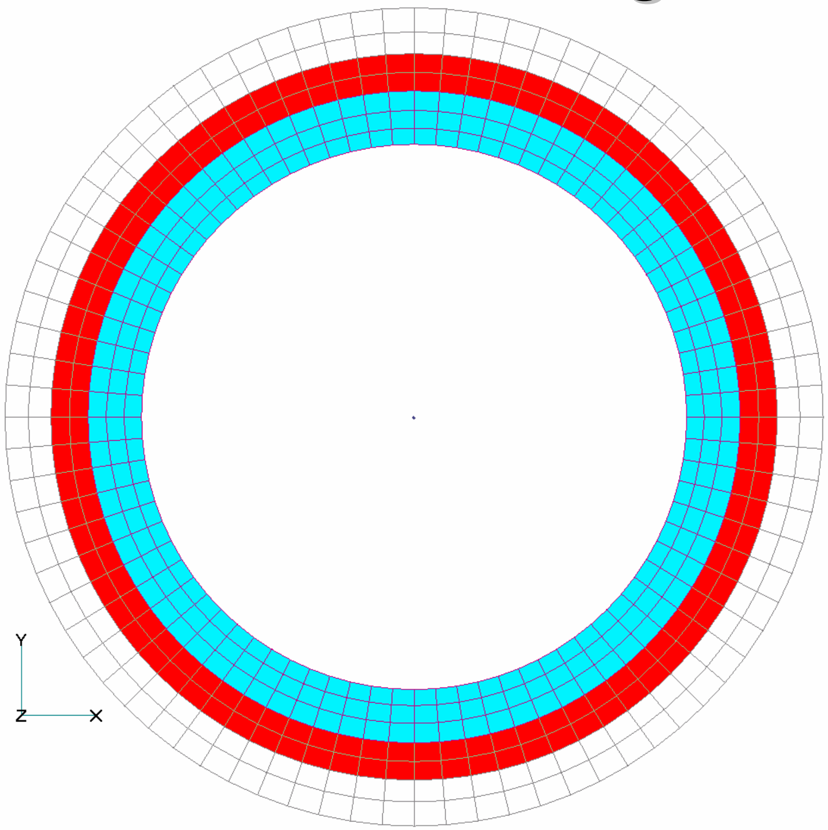
(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

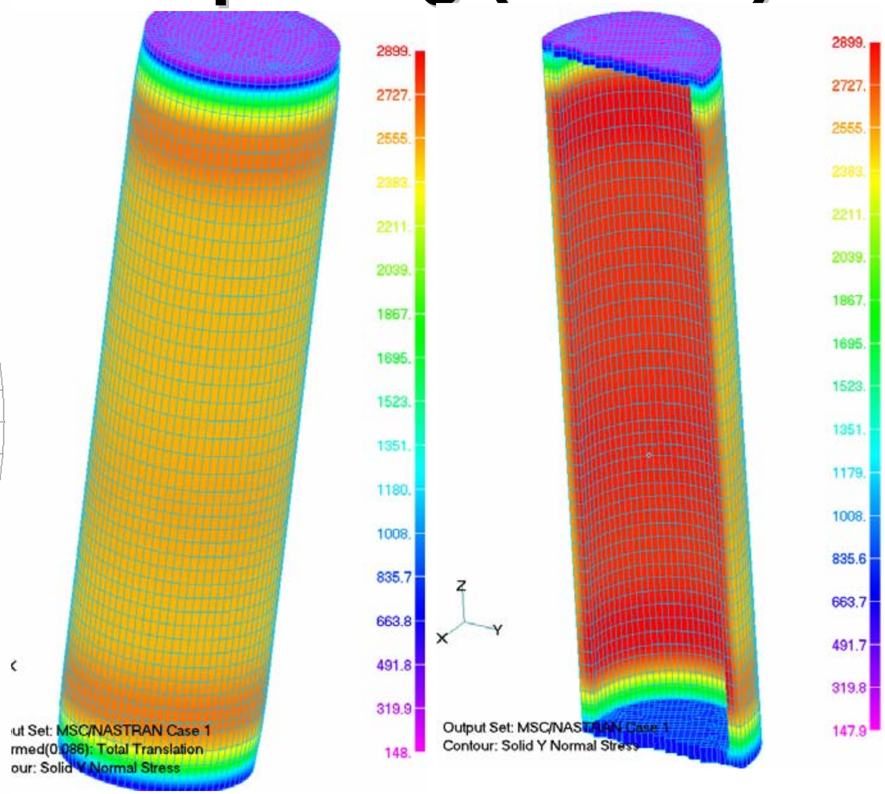
- Mu Metal adhered to outside wall of housing causes asymmetric deformation of PMT.

- PMT inner surface stresses ~ 1.03 ksi.

- PMT outer surface stresses ~ 771 psi

Mu Metal tacked to outside wall of housing, RTV-566 potting (Case 7)





(Hoop Stress)– Outer wall & inner wall, respectively. Results in kPa.

- Assuming tacked Mu Metal does not transfer much load into housing, PMT demonstrates uniform loading.
- PMT inner surface stresses ~ 419 psi.
- PMT outer surface stresses ~ 384 psi

Stress Reduction Analysis Summary

Case	Description	Inner Wall of Tube	Outer Wall of Tube	% From Nom.	% From Nom.
		psi	*psi*	*Inner Wall*	*Outer Wall*
1	ORIGINAL NOMINAL CONDITIONS - BASELINE	*4368.38*	*3202.32*	0	0
2	MU METAL with Double overlap, Y966, PMT ONLY. NO HOUSING OR POTTING (To see effects of Mu Metal on tube).	*816.53*	*691.81*	N/A	N/A
3	MU METAL ATTACHED TO INSIDE WALL OF HOUSING, URALANE POTTING.	*5061.64*	*3553.30*	*+15.87*	*+10.96*
4	MU METAL ATTACHED TO INSIDE WALL OF HOUSING, WITH RTV 566 SUBSTITUTION FOR 5753 POTTING.	*855.69*	*652.65*	*-80*	*-80*
5	NICKEL COATED HOUSING WITH RTV 566. Sensitive to poisson's ratio, see Plot 1.	*458.30*	*420.59*	*-90*	*-84*
6	MU METAL ATTACHED TO OUTSIDE WALL OF HOUSING, CONTINUOUSLY ATTACHED. Using RTV 566 potting.	*1039.88*	*770.12*	*-76*	*-71*
7	MU METAL ATTACHED TO OUTSIDE WALL OF HOUSING, NOT CONTINUOUSLY ATTACHED. Using RTV 566 potting.	*419.14*	*384.34*	*-90*	*-86*
8	MU METAL ATTACHED TO OUTSIDE WALL OF HOUSING, NOT CONTINUOUSLY ATTACHED. Using GASSED RTV 566 potting (nu=0.42, cte=318 ppm/degC, E=290psi).	*104.42*	*95.72*	*-98*	*-96*

SOLUTION IMPLEMENTATION

Path 2 Results

- **Ran into problems implementing our first solution choice.**
  - Nickel plated PMT housing (no Mu metal) with RTV potting
    - RTV-566 and similar Nusill availability, RTV availability solved
    - RTV Poison's ratio uncertainty not solved but improved, very hard to measure, manufacturers don't stand by quoted numbers, references vary some
    - Nickel worked in coating tests and thermal vac tests which was a concern
    - But test of magnetic nickel shielding properties failed. Phosphorous content the culprit. Probably solvable by testing other harder to get electroless solutions or trying very thick plating approach
    - In the interest of time, easier to switch to Mu metal on outside of housing, this allows easier implementation of secondary goal to increase potting thickness which turned out to be a good decision

Path 2 results

- <u>So the current solution is</u>
  - Existing Aluminum housings, we don't have to make new ones with lower CTE. This would have increased mass, delay, cost and not lowered stress much more.
  - 'Softer' RTV 566, similar Nusill as a backup if we run into supply issues which is now unlikely.
  - No inside Mu metal wrap. Also gets rid of Mu metal wrap handling step. No nickel, grounded Mu metal taped or tacked to outside of housing.
  - Centering step in potting procedure.
  - All flight and qualification PMTs will undergo full area microscope inspection looking for pre-existing flaws not associated with scores or for PMTs with particularly large (out of family) score microcracks.
  - Handling procedure for PMTs modified to add more precautions.
  - This solution reduces peak stresses by almost an order of magnitude. From 4300 to 420 psi inner wall and 3200 to 384 psi outer wall, reduces procedure variances and reduces PMT handling.

Path 2 results – Margin

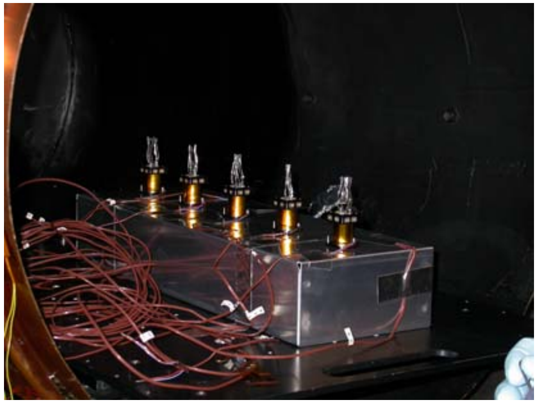
- Using the weakest Weibull strength curve we have this would meet the 1.5% reliability goal by a factor of almost 6.
- The Weibull curves have internal margin via the use of a conservative strength correction factor.
- This weakest curve is for the inner flaws, a weak area we must account for. But we know this curve does not necessarily apply to outer flaws which we now know has been our primary culprit so far.
- Do we need more margin due to some uncertainty in outer flaw strength?
  - Late discovery of likely origination regions is in higher stress region but lower stress than predicted by inside surface score strength curves.
  - We are finding smaller external flaws on the PMTs, subject to time dependent flaw propagation under exposure to moisture. We will be inspecting flight PMTs and rejecting ones with problematic flaws (still being defined) but this will not eliminate all flaws

Path 2 results

- **Ideas**
  - The latest reliability requirement is 3% drop out rate over 5 years, 100% higher than the the 1.5% goal we beat by a factor of 6.
  - This 3% requirement has a correction for uncertainty in for some items in the chain (i.e. ASIC reliability). Without this correction the reliability requirement is 6%.
  - Increase low temperature test temperature. Still qualify to -40C but lowest PMT predict is survival temp of ~-20C. Get an exception agreed to use a margin of 10 deg GEVS req or the 20 deg we are using. So flight PMTs would see -30 C in Chassis tests and -25C after that. Would effect LAT and observatory tests after ACD integration.
  - Further stress reduction is difficult to achieve but possible
    - Add bubbles to RTV, reduces Poison's ratio 8% and modulus by 50%. Reduces stress from 400 psi to under 200 psi. High voltage venting concerns, process not very controllable.
    - Additional stress reduction of a few hundred psi may also be achievable with new housings that are also larger (heavier, analysis ripple effect) or by adding slits to create turn the housing into mini- flexures so hoop stress is reduced (analysis, vibration epoxy concerns). But we are in the region of paying very large schedule and budget hits for small further improvements in stress.

Path 2 results

- Pictures of latest qualification units using solution design. These are being verified to qualification levels



- Initial verification results
  - Thermal vac (4 cycle +45° to –40°C) was successful!
  - Vibration being done this week.
  - Followed by more severe thermal test (possibly 2 cyc to –40°C then more cycles to –50°, -60°C) to check for more margin. Just in this morning – successful first cycle to -60C.
  - Repeat verification on 10 more NG units, plus bond strength test
  - Also Qualify 5 calibration units, this brings total qualified units to 20

Path 2 results

- **More on this outer flaw strength uncertainty**

- **Speculation – what if we used the failure data we have for outside surface failures (4 of 22 with a predicted peak stress in that region of ~3200 psi) and adjusted an the inside score Weibull strength curve match that data.**

- **Several problems with this. The biggest one is that we don't really know how different the curve could be given the wider distribution of flaws and the moisture exposure. However Weibull constant and ultimate strength prediction indicate this could be a conservative curve. If one does this we get a 1490 psi stress goal for a 1.5% failure rate or better which our new design beats by over a factor of 3 without any of the addition margins we just discussed.**

Correction for size (area) effect

$$(\sigma_1 / \sigma_2) = (S_2 / S_1)^{1/m}$$

S: Area with maximum tensile stress

m: Weibull modulus

For the PMT failed from *outside surface* (Kevin Dahya's estimation: S_{PMT} / S_{test}=15.2)

PMT	***m***	**σ_o, ksi**
Off-score, for PMT failed from outer surface	7.9	18.7
On-score, for PMT failed from outer surface	4.5	7.9

For σ = 2.6 ksi (max tensile stress on outer surface), the probability of failure from a score similar to the score on inside surface: 0.7%, far lower than the actual failure rate (4 out of 23, or 17%)

Fitting the Weibull function into actual probability of failure

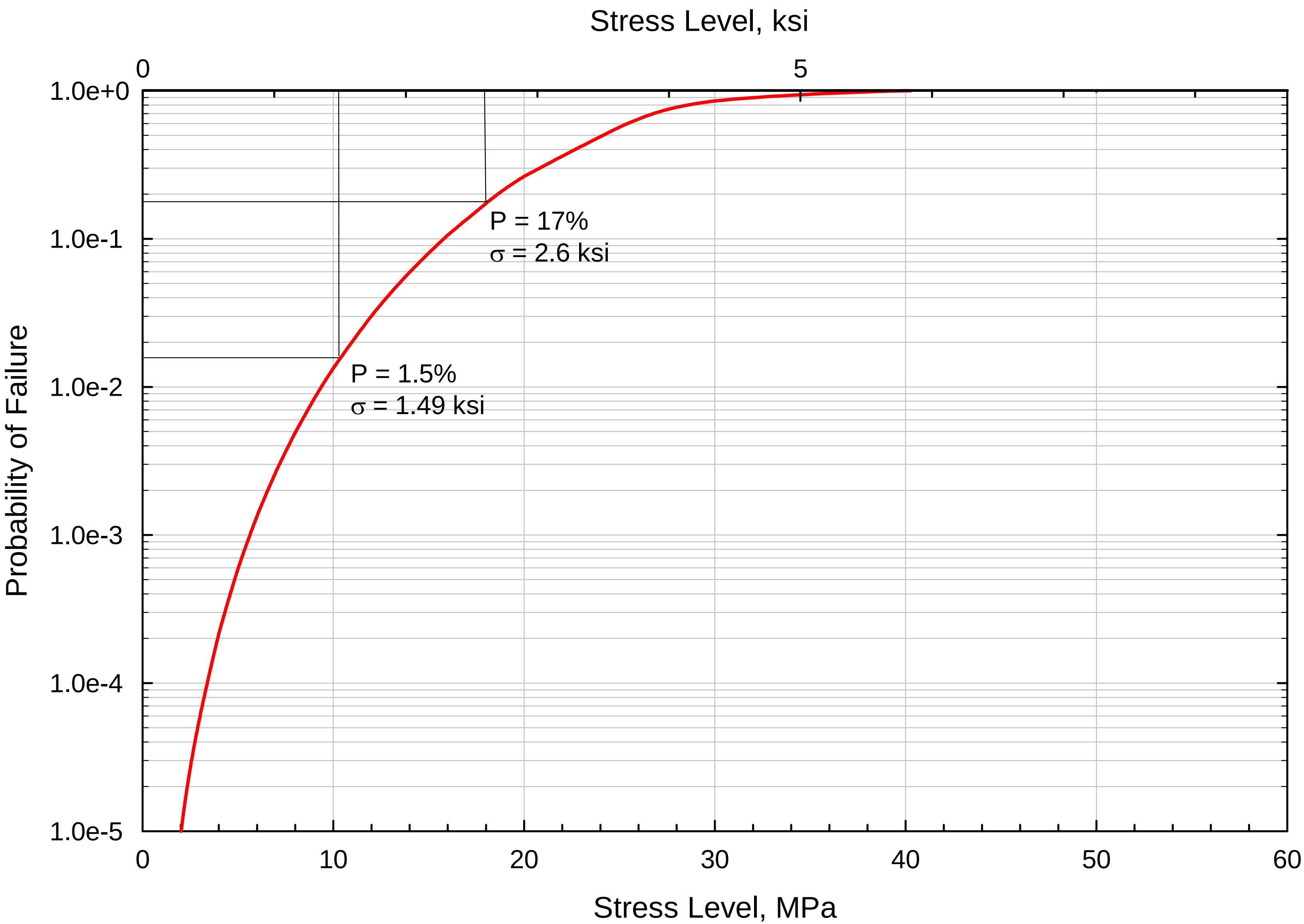
- The PMTs failed from outside
- Probability of failure 4 out of 23, or 17%
- The maximum tensile stress on outer surface = 2600 psi (K. Dahya's FEA results)

Assume P = 17%, *m* = 4.5 (for a score failure on outer surface, then σ_o = 3.77 ksi)

With the above *m* and σ_o , the stress level at 1.5% probability of failure (the goal) will be 1490 psi.

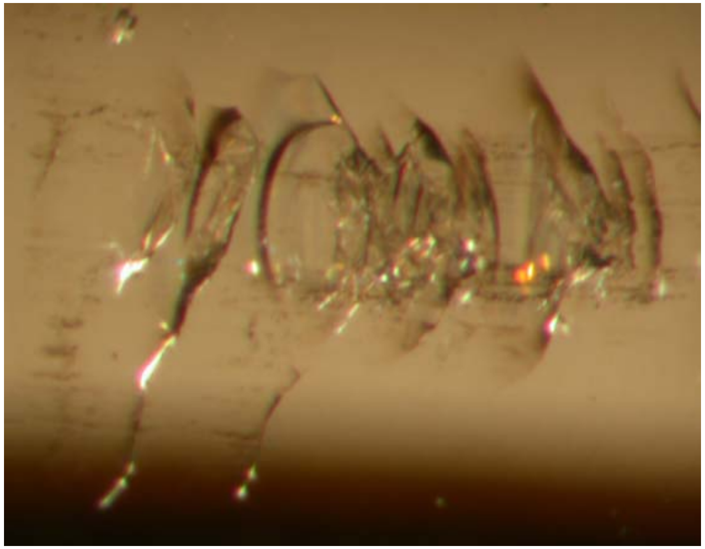
Weibull Distribution

(fitting the Weibull function into 17% probability failure at 2600 psi stress)

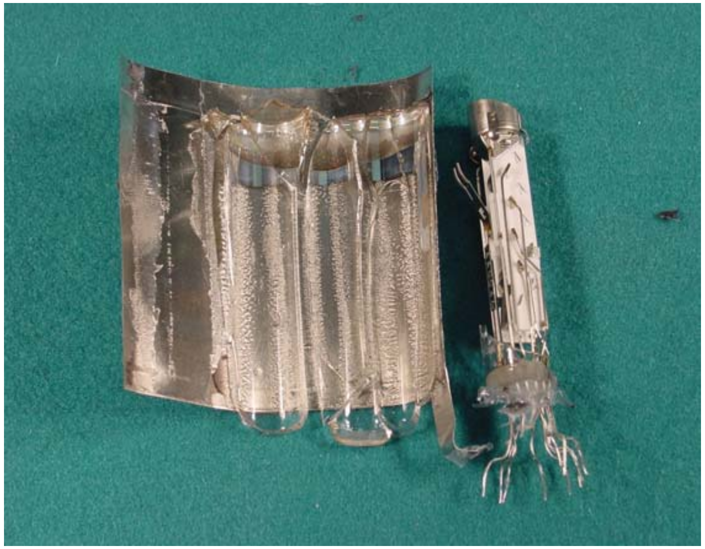


More Pictures

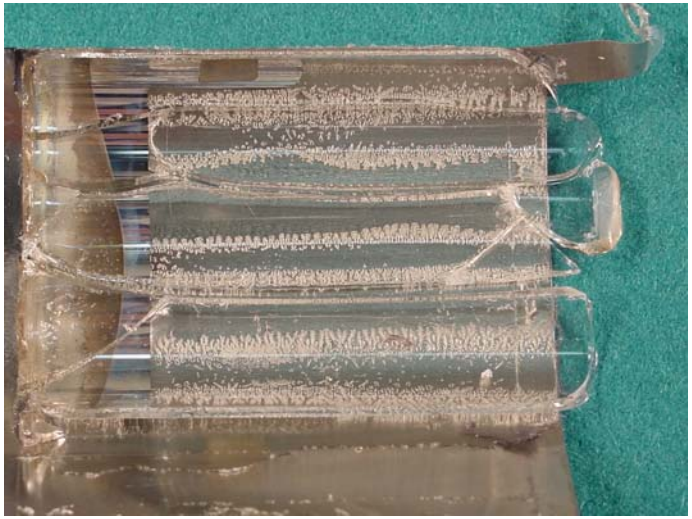
PMT pics – First failure and inside flaws



Score

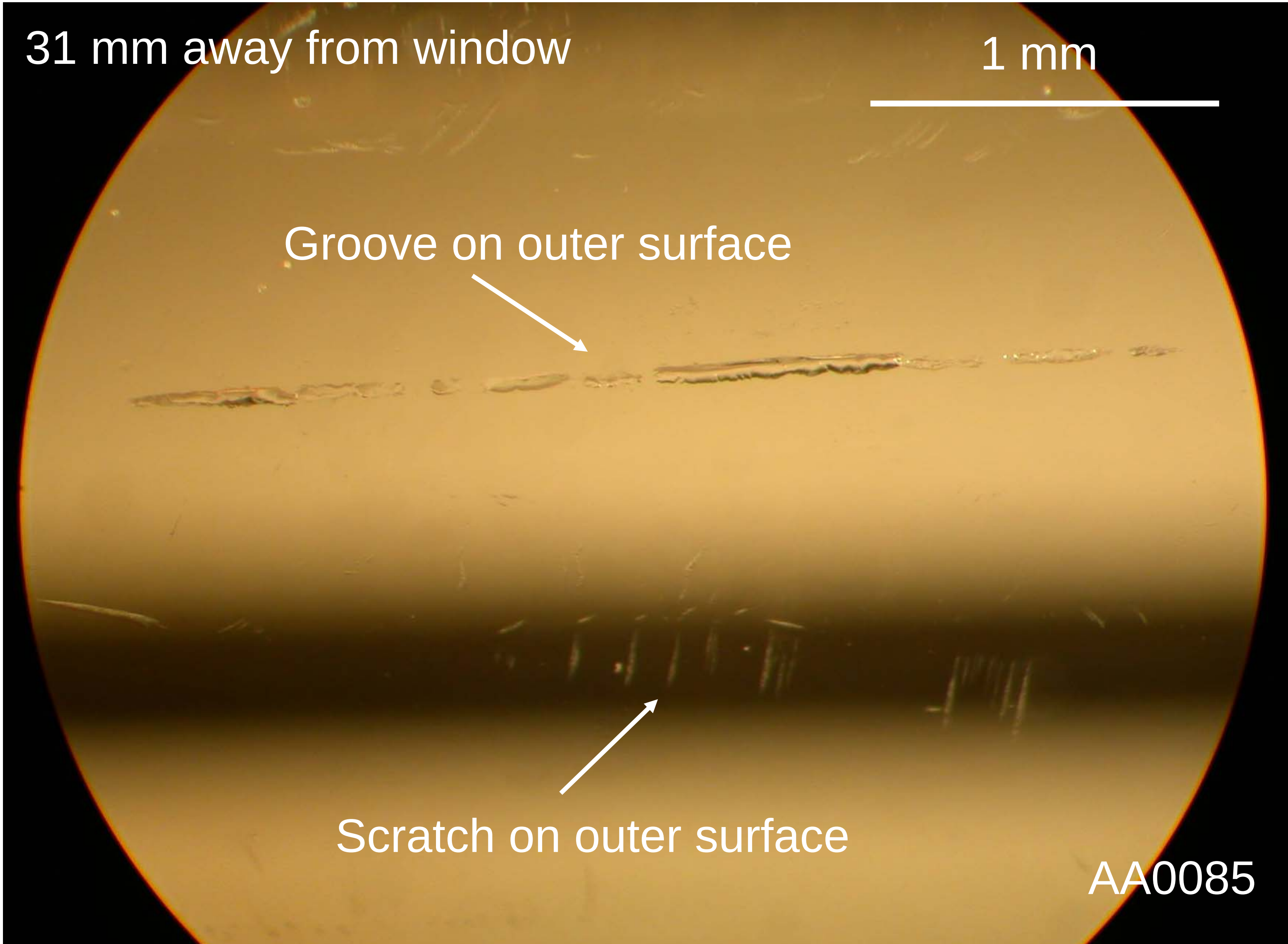


Weaknesses

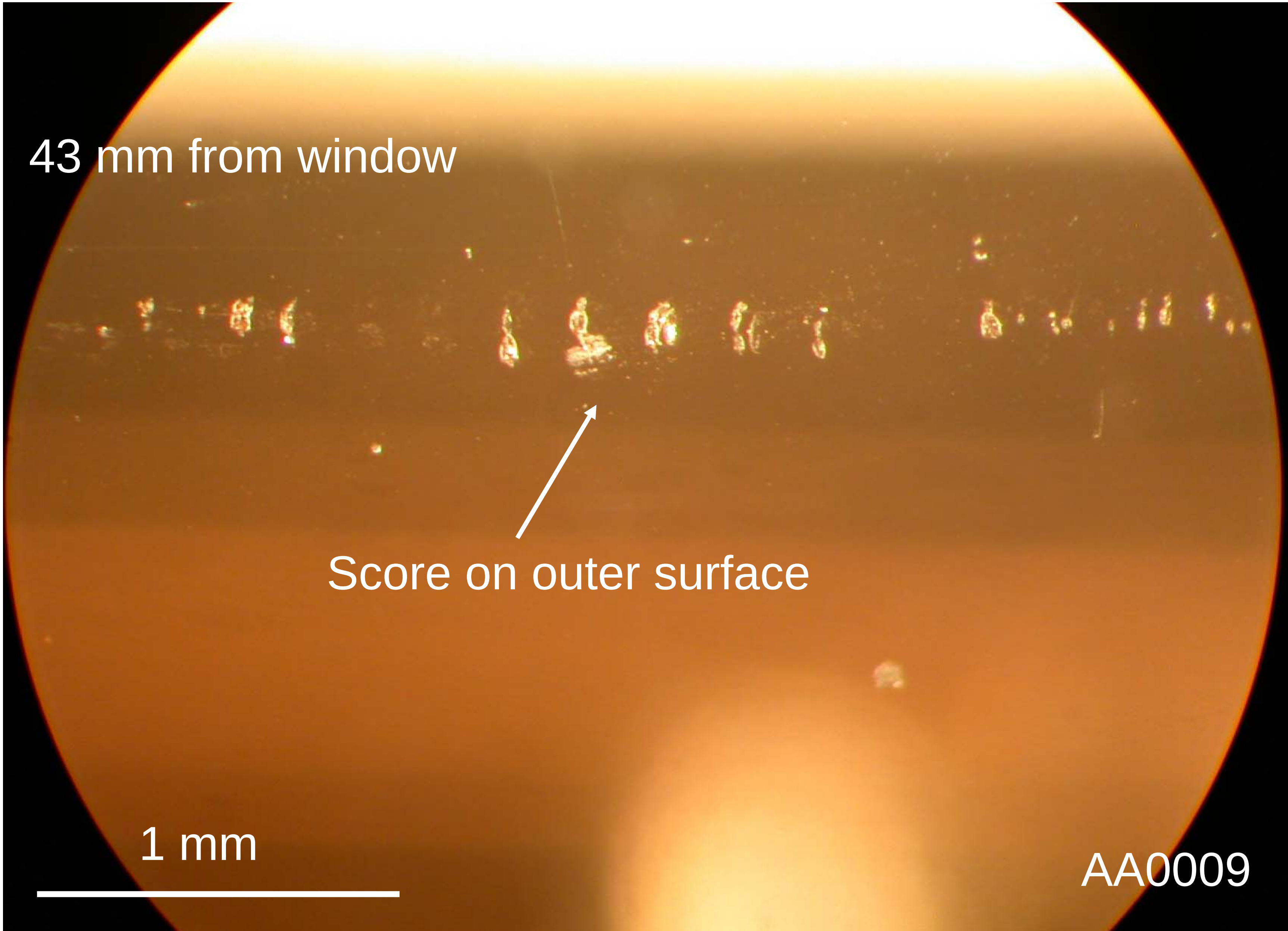


Failed PMT post removal

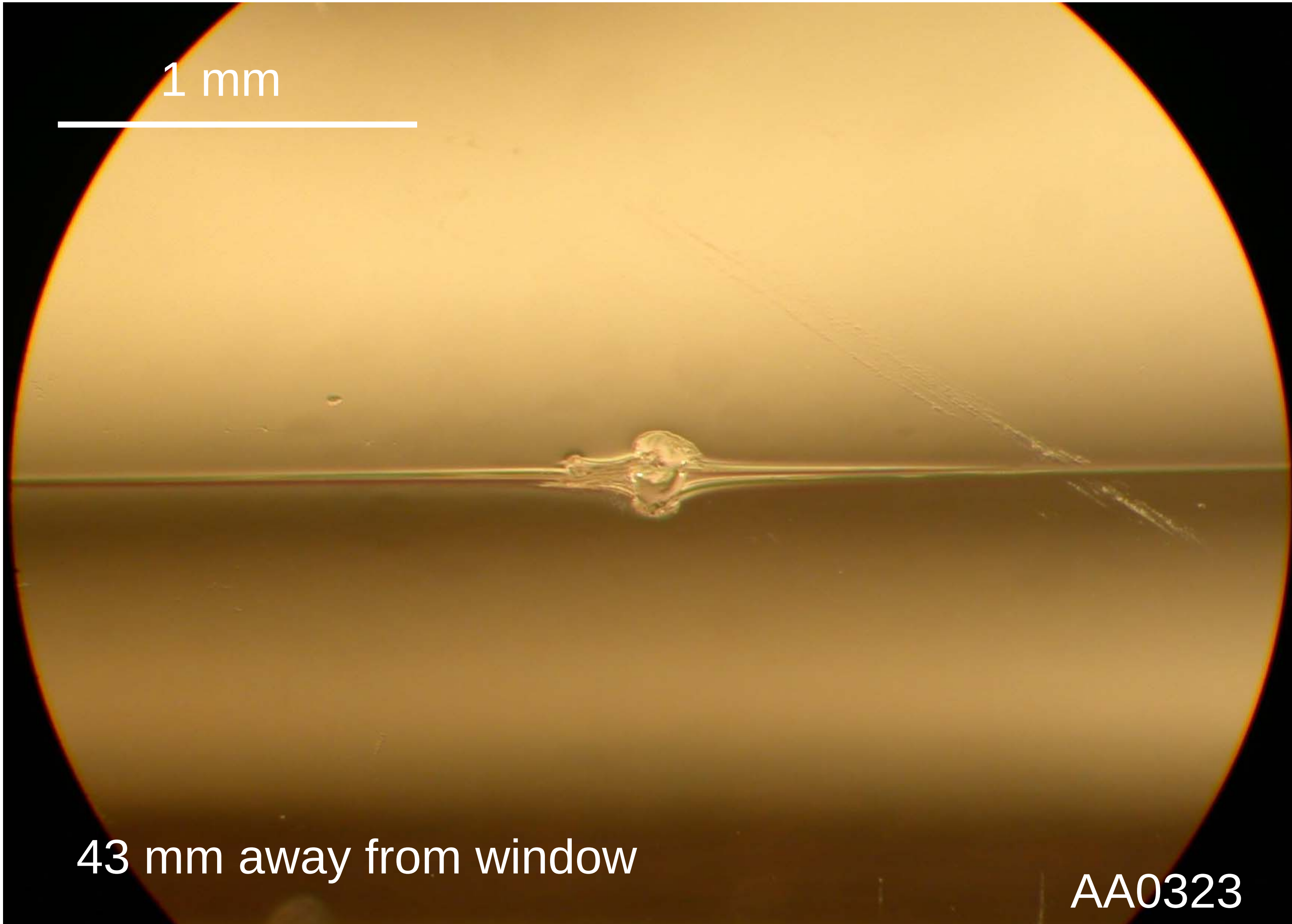
Outer surface flaws on NG and Cal tubes



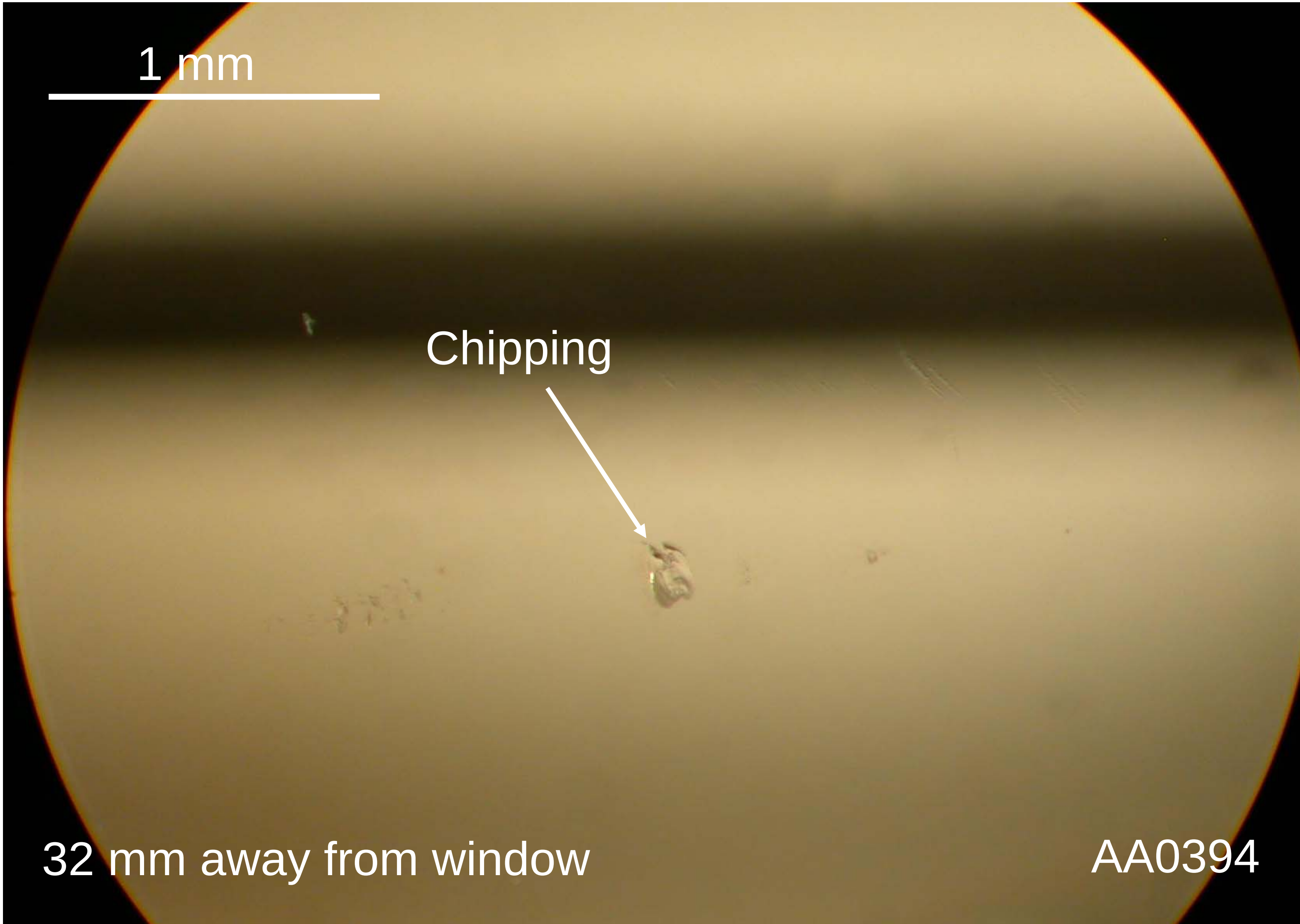
Outer surface flaws on NG and Cal tubes

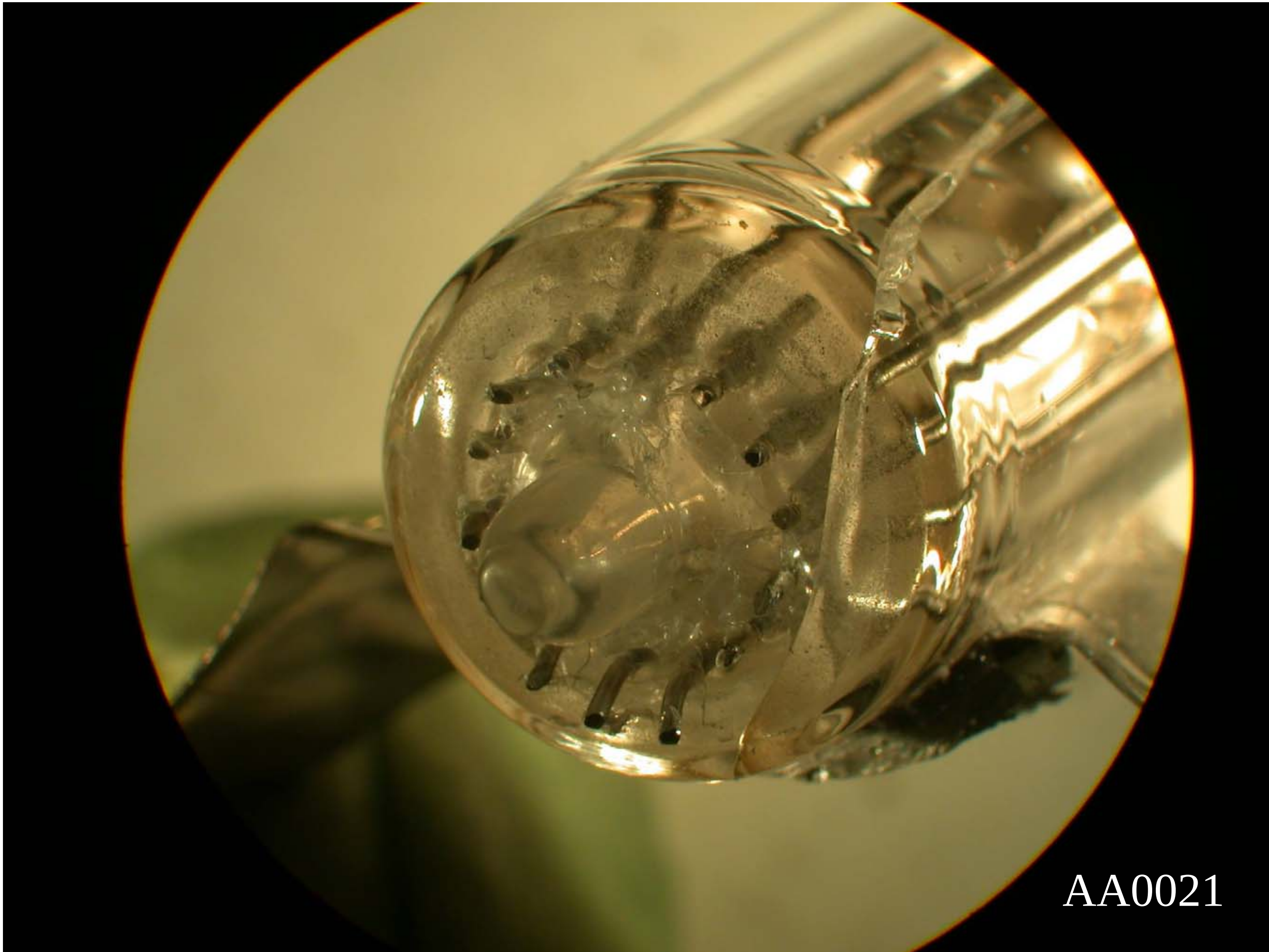


Outer surface flaws on NG and Cal tubes



Outer surface flaws on NG and Cal tubes




AA0021