HGTD module thermal cycle

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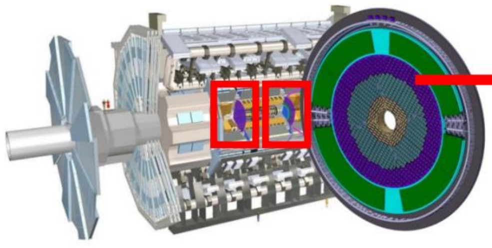
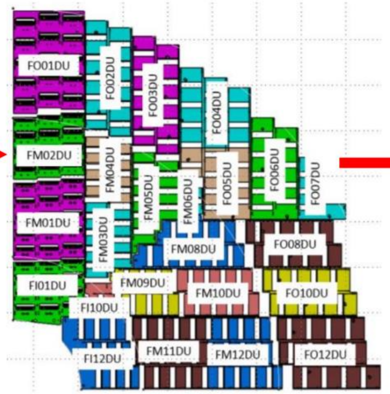
HGTD module

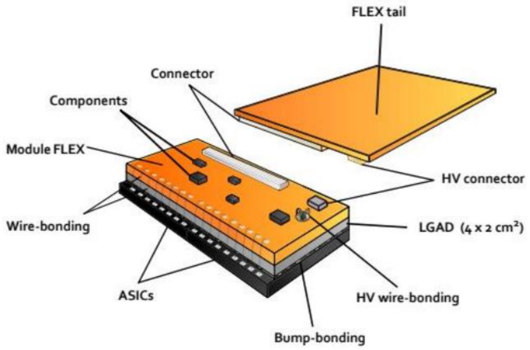
- HGTD module=2*sensor + 2*ASIC (2 hybrids) + module flex
- 1 hybrid=1*sensor bonded with 1*ASIC using flip-chip bonding technology
- 1 hybrid=15*15 pads (each pad has 1 bump)



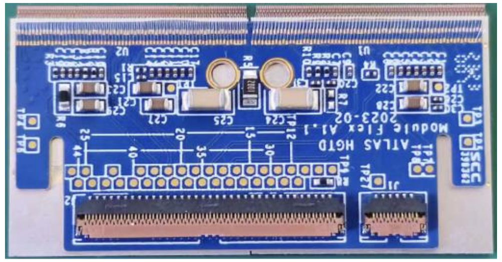
HGTD (one of two)

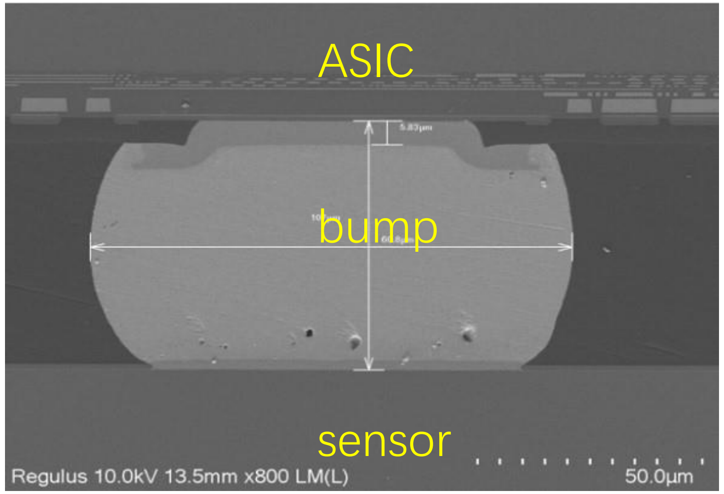


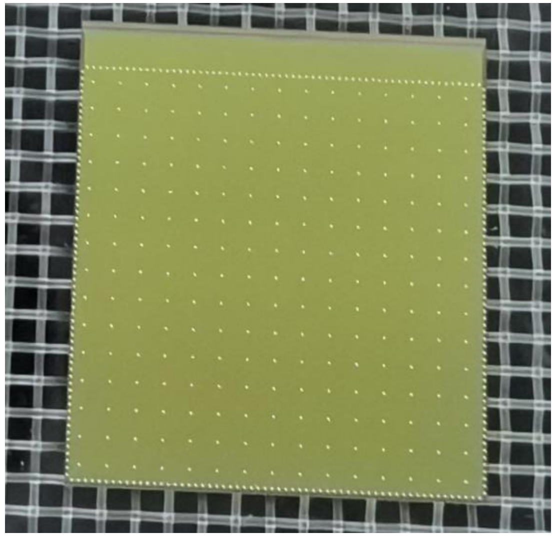
Detector units (a quarter)



Modules (8032 in total)







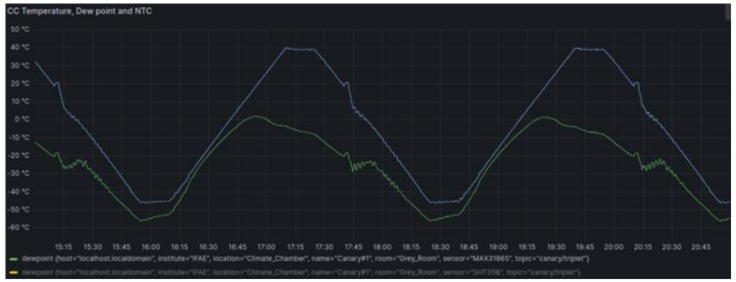
Thermal cycle

- HGTD is going to work in low temperature (-30℃) , a thermal cycle is a testing method to check module stability against temperature change
- During HGTD working time, estimated thermal cycles is 36 for those will never be replaced

- When we did thermal cycle on previous designed modules (thin sensor, ALTIROC-3 hybrid) they could not reach this standard
- Failures mainly happened on bumps connecting sensor and ASIC (disconnected or broke inside) in early time (mostly <30 cycles)
- This problem delayed HGTD module pre-production by one year

- This work were done to improve module design and make sure they survive enough thermal cycles

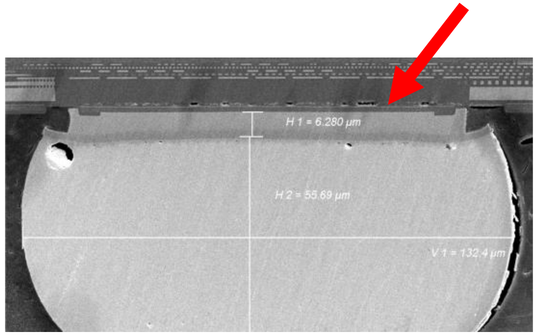
Temperature in thermal cycle (blue)



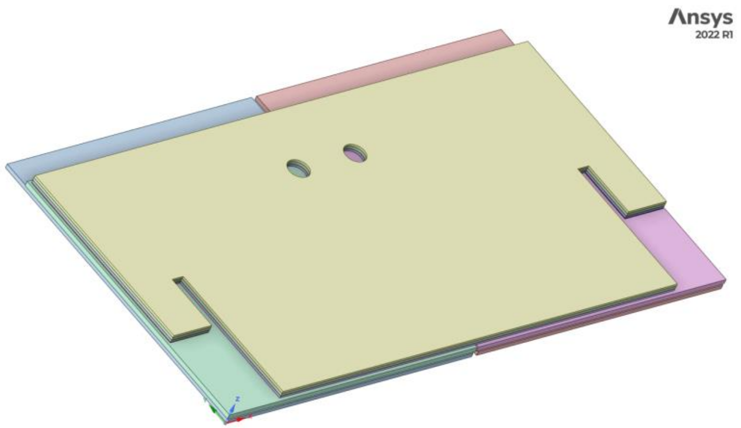
Total thermal cycles for modules which will never be replaced

	Estimated	Pessimistic
Surface (b180) commissioning	8	12
P1 commissioning	4	12
Nominal data-taking (9 years)	18	26
Replacement (3 times)	6	12
Total	36	62

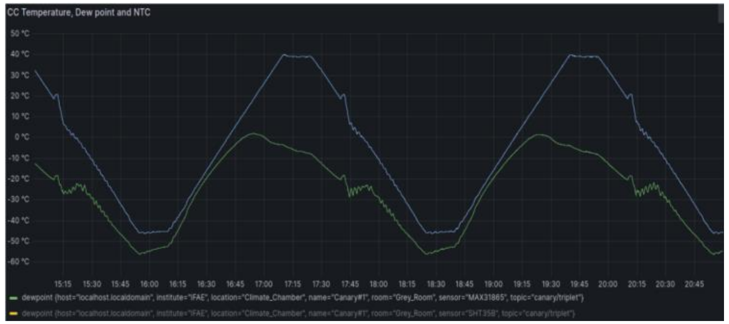
disconnect bump



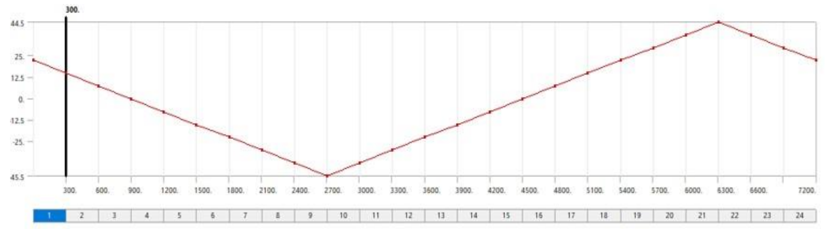
	Material	Thickness (um)
ASIC	Silicon	300
Bump	$Ag_{3.5}Sn$	50±5
Sensor	Silicon	775
Glue	Epoxy resin (Araldite 2011)	50±30
Module flex layer1	Kapton	175
Module flex layer2	Copper	200
Module flex layer3	Kapton	175

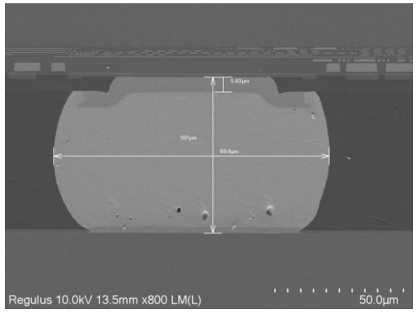


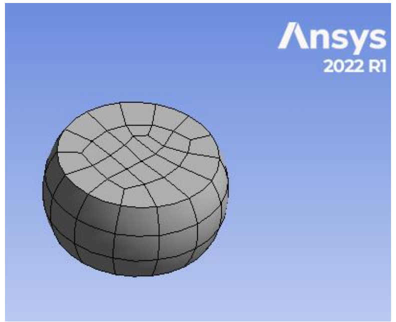
Real TC: -45~40℃, 2.5h



Simulated TC: -45.5~44.5℃, 2h





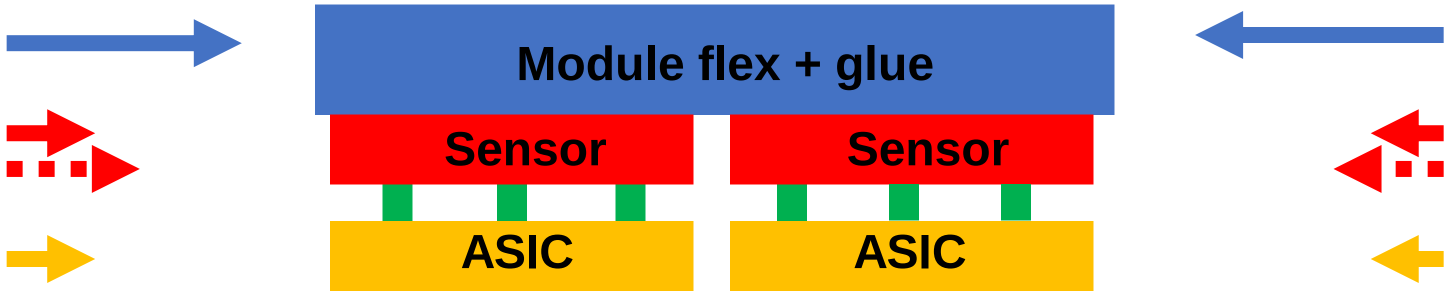


Lifetime prediction model

- Aim: predict bump connection lifetime during thermal cycle using simulation results in single cycle
- Modified Coffin-Manson equation: $N_f = \frac{1}{2}\left(\frac{\Delta\epsilon}{2\epsilon'_f}\right)^{1/c}$ reference
  - Commonly used in estimating solder joint reliability within certain temperature range
  - Parameter explanation:
    - N_f: average lifetime (50% probability failure in any bump on LGAD pad, unit in cycles)
    - $\frac{\Delta\epsilon}{2}$: cyclic strain amplitude/ half maximum total mechanical strain in one cycle
    - $\epsilon'_f = 0.325$, fatigue ductility coefficient
    - c: fatigue ductility exponent, relative to thermal cycle setup:
      - $c = -0.442 - 6 \times 10^{-4}\bar{T} + 1.74 \times 10^{-2}\ln(1+f)$
      - $\bar{T}$: average solder temperature in one cycle, -0.5℃ in our setup
      - f: frequency of thermal cycle, in unit cycles/day, 12 in our setup
      - ➢ c=-0.3971

Simulation results: hybrid thickness

	Both thin	Thick sensor	Thick ASIC	Both thick
Sensor thickness/um	300	775	300	775
ASIC thickness/um	300	300	425	425
Average lifetime/cycles	108	393	80	323



Consider low temperature (shrinking) situation
Length of arrow means deformation magnitude

Cause of bump failure: mechanical strain accumulated in thermal cycle due to mismatch in material CTE (coefficient of thermal expansion, thermal strain in 1℃ temperature change)

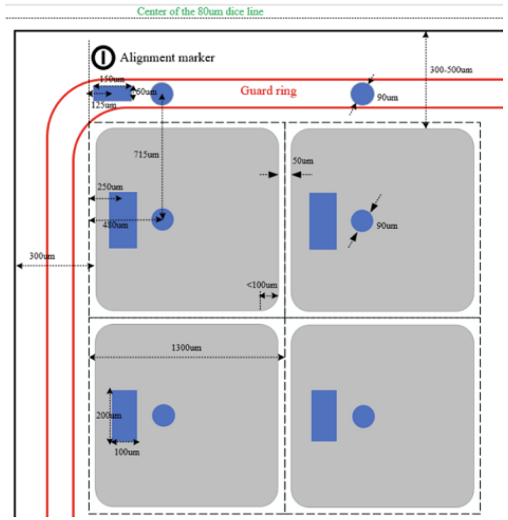
Although CTE of bump is also large, the dimension of a single bump is too small compared to Sensor/ASIC/module flex that bump almost does not deform during thermal cycle.

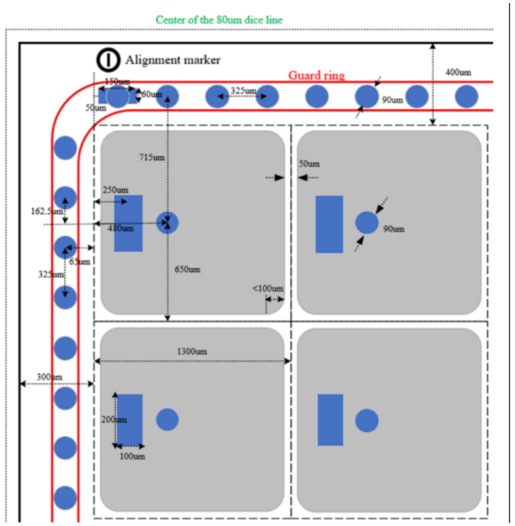
Mismatch of CTE in module flex and sensor is leading to shearing between them, finally leading to a larger shrinking to the middle in sensor. When bumps stay still and sensor shrinks to the middle, the larger sensor shrinks will produce larger shear stress/strain between sensor and bump. A thicker sensor reduces the effect from module flex and leads to smaller deformation in sensor.

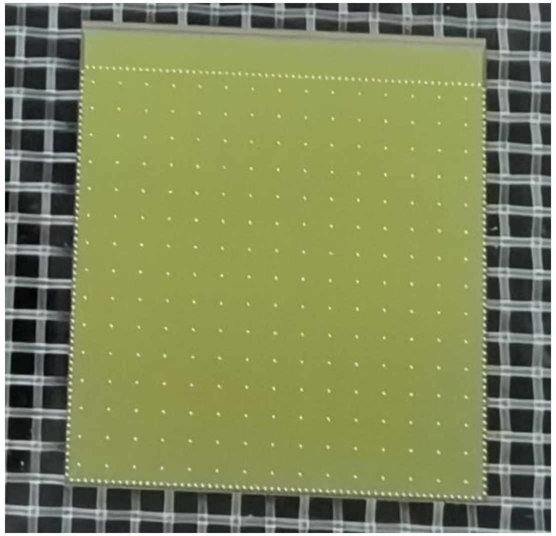
A thicker ASIC helps nothing on top side of bumps, the only effect is to shear the bottom of bump more which leads to larger stress in bumps.

Guardring bump design

- Major difference between pre-production (ALTIROC-A) hybrid design and previous design (ALTIROC-3)







- Purpose: protect bumps on LGAD pads

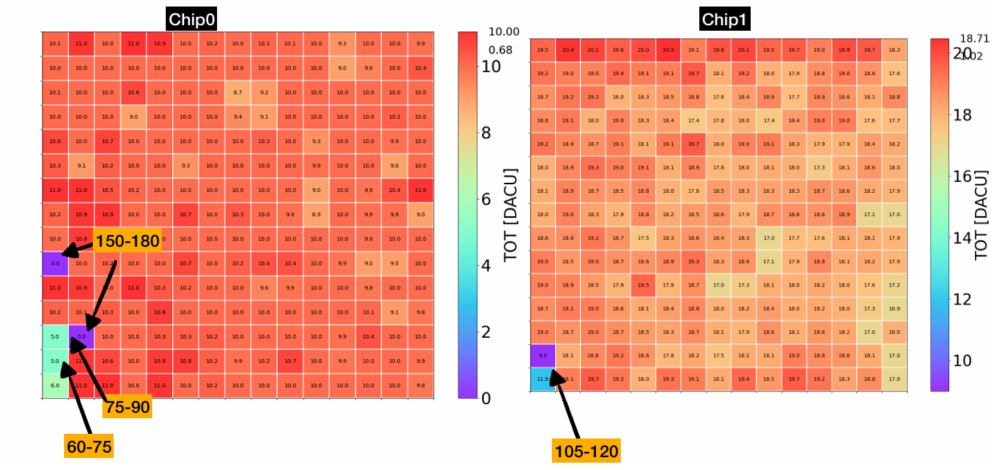
Simulation results: guardring bumps

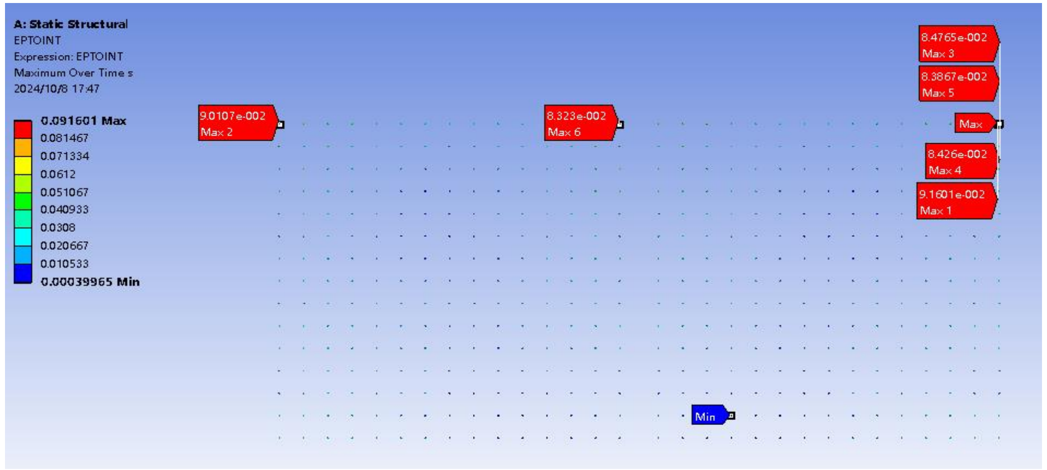
	Thin (300 um) sensor, more bumps	Thin (300 um) sensor, fewer bumps	Thick (775 um) sensor, more bumps	Thick (775 um) sensor, fewer bumps
	ALTIROC-A	ALTIROC-3	ALTIROC-A	ALTIROC-3
Average lifetime/cycles	**108**	**16**	**393**	**119**

- By adding more bumps on guardring, module lifetime increases a lot
- Results for thin ALTIROC-3 module (16 cycles) matches previous thermal cycle results
- Results for thick ALTIROC-3 module (119 cycles) also matches thermal cycle results well (discuss later)

Thermal cycle: ALTIROC-3, thick module

- Thermal cycle testing was done in different sites
- All the results were recorded and updated in a same shared document
- Results in different sites are similar:
  - First disconnect bump on average appears at ~110 cycles (agree with simulation prediction, 119)
  - Most disconnect bumps appear at corner part of hybrid (same as simulation prediction, right bottom plot)
  - After some disconnect bumps appear, the spread of the disconnection is slow





Statistical model: data pre-processing

- Data: ALTIROC-3, thick module thermal cycle results, 46 hybrids in total
- Lifetime assumptions:
  - Already failed hybrids (14 hybrids): average of last observed passing cycles and first observed failure cycles (**fair**)
  - ➢ Average lifetime of already failed hybrids: 90
  - Not yet failed hybrids:
    - 90, if not yet passed 90 cycles (20,20,75,75,75,75) (**fair**)
    - Last cycles done, if already passed 90 cycles (26 hybrids) (**conservative**)

  - Try to make conservative and reasonable lifetime assumptions

- Strategy: fit a distribution with data and then use the distribution to predict failure situation in all 8032 HGTD modules

- **Note: these models are based on ALTIROC-3 module thermal cycle results, believing the simulation results we are expecting a more than 3 times longer average lifetime when moving to pre-production ALTIROC-A modules (see slide 8)**

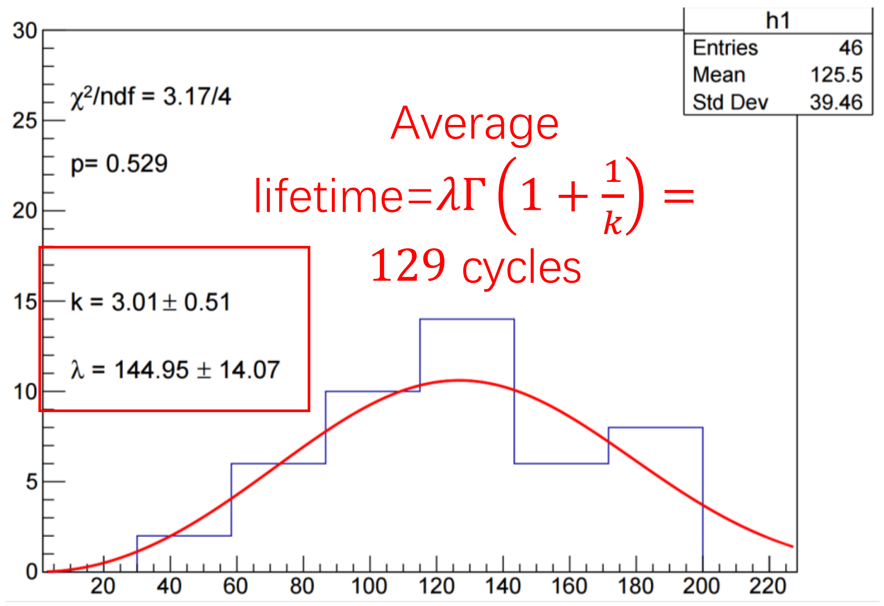
Statistical model: data pre-processing

Module	Hybrid	Site	First failure cycle	Last no failure cycle	Applied lifetime	Module	Hybrid	Site	First failure cycle	Last no failure cycle	Applied lifetime
	0		75	60	67.5	M130	0		120	120	120
FM028	1		120	105	112.5		0			120	120
	0			180	180	M131	1			120	120
FM029	1		75	60	67.5		0	IFAE		120	120
	0			180	180	M132	1		90	60	75
FM031	1	IHEP	120	105	112.5		0			120	120
	0		75	60	67.5	M133	1			120	120
FM033	1			180	180		0			20	90
	0		60	30	45	20WMO321000002	1			20	90
FM034	1			180	180		0			175	175
	0			150	150	IJCLab2	1			175	175
FM035	1			150	150		0			175	175
FM036	0			150	150	20WMO321000006	1		175	120	147.5
	0			150	150		0			75	90
M125	1			150	150	IJCLab4	1	IJCLab		75	90
	0			120	120		0			75	90
M126	1			120	120	IJCLab5	1			75	90
	0		240	150	180		0			120	120
M127	1	IFAE	90	60	70	20WMO3210000011	1			120	120
	0		120	90	105		0		90	75	82.5
M128	1			120	120	20WMO3210000012	1			120	120
	0		60	30	45		0			120	120
M129	1		120	90	100	20WMO3210000013	1			120	120

Weibull distribution

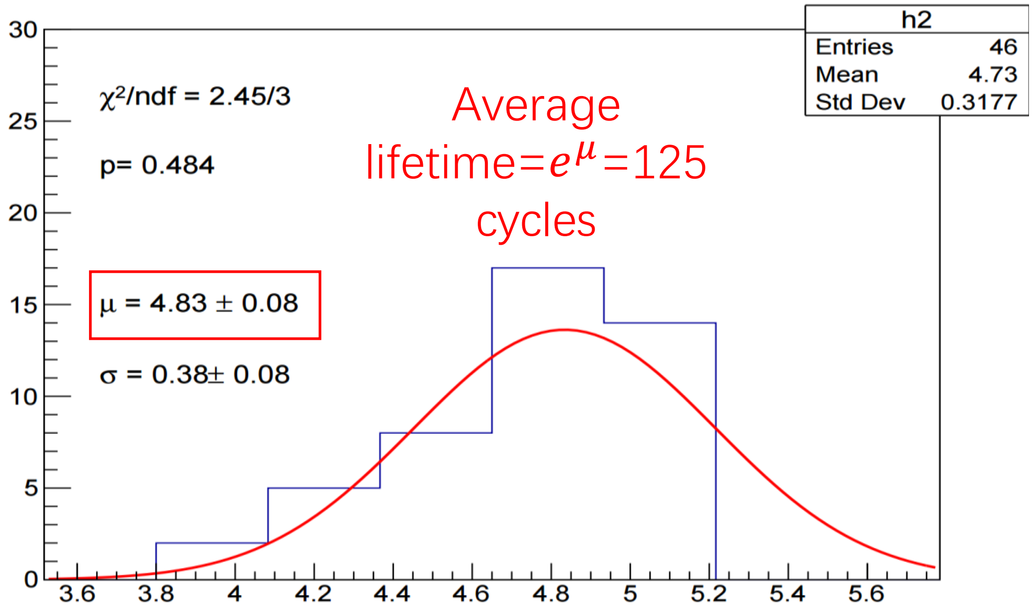
- Most commonly used reliability analysis distribution
- Flexible enough to fit into almost any distribution
- Probability density function given by:

$f(x,\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}$, shape parameter k and scale parameter λ given by fit

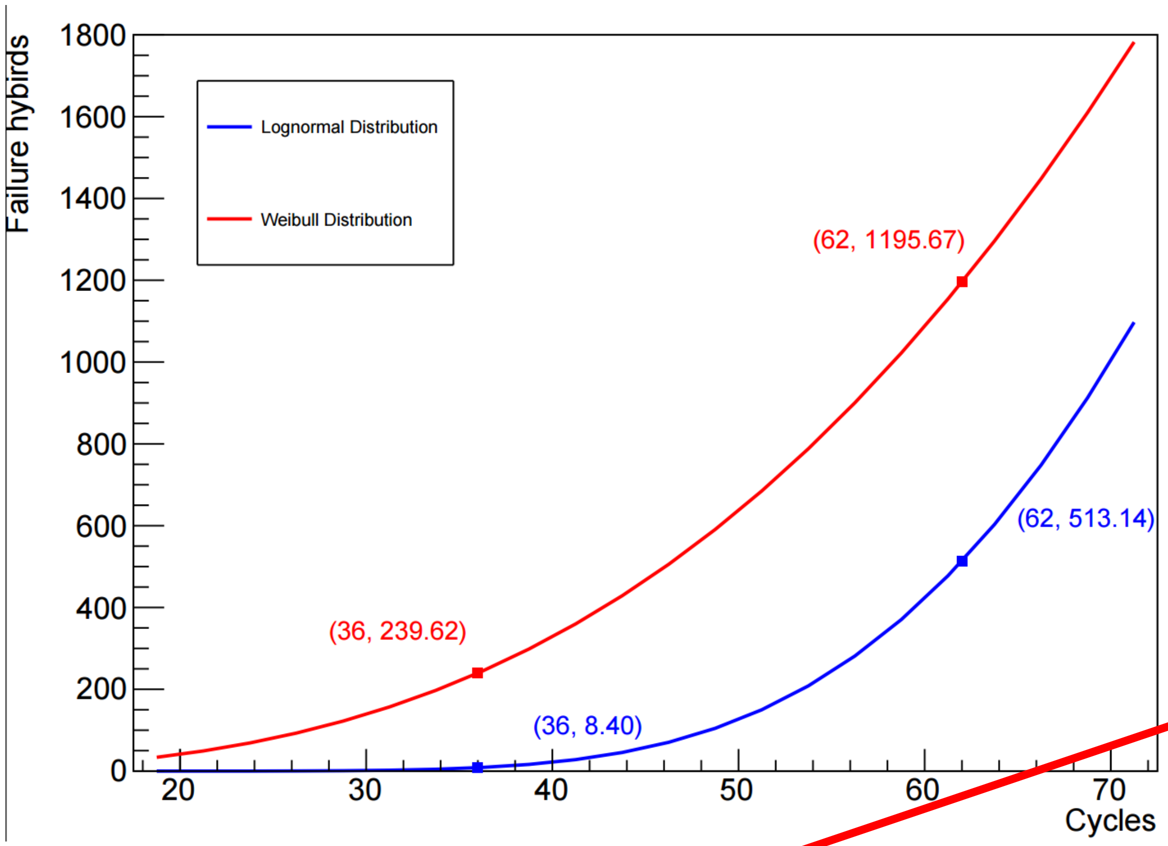


Lognormal distribution

- Logarithm of a variable is normal distributed
- Widely used for reliability analysis of semiconductor devices and fatigue life analysis of some mechanical components



Prediction of all 8032*2 hybrids



Failure hybrid defined as: any failure pad(s) out of 225 pads

Even if there are 1196 (240) failure hybrids, actual failure ratio in pad is:
1196/(8032*2*225)=0.03%
240/(8032*2*225)=0.007%

cycle	35	36 (estimated)	40	45	50	55	60	62 (pessimistic)	65
Weibull	221	240	329	467	637	844	1088	1196	1371
Lognormal	7	9	22	57	126	243	422	514	673

Summary

- Thermal cycle results based on 46 hybrids, indicate that ALTIROC3 modules with thick sensors can survive an average of more than 110 cycles without any disconnect pixel

- Simulation results agree well with current thermal cycle results, giving confidence to the approach

- Based on ALTIROC-3 thick module thermal cycle results, the number of pads expected to fail for the full HGTD before 36 cycles (240 or 9) is very small.

- The number of failures is expected from simulation to be even smaller with pre-production module design (thick sensors, more bumps in the guardring)

- ALTIROC-A design module has passed FDR and ready for pre-production

Thanks for attention!

Back up

Thin ALTIROC-3 module TC results

Module	Site	Before TC	5 TC	15 TC	30 TC
M105	IFAE	0	Mass		
		1	Mass		
M107	IFAE	0			2
		2			4
M112	IFAE	0			0
		0			1
M117	IFAE	0			0
		0			1
20WMO32100 0005	IJCLab	11	15		
		21	28		
FM021	IHEP	16	16	19	
		1	3	6	
FM023	IHEP	2		Mass	
		8		Mass	
FM025	IHEP	0			0
		0			0

Material mechanical property

Material	Component	Coefficient of linear thermal expansion (/℃)	Young's modulus (Mpa)	Poisson's ratio
Copper	Module flex	1.8×10^{-5}	110000	0.34
Kapton	Module flex	2×10^{-5}	2800	0.34
Epoxy resin	Glue	7×10^{-5}	3780	0.35
$Ag_{3.5}Sn$	Bump	1.9×10^{-5}	55000	0.4
Silicon	Sensor, ASIC	2.578×10^{-6}	169000(x,y) 130000(z)	0.064(xy) 0.36(xz,yz)

Viscoplastic (Anand) model for $Ag_{3.5}Sn$

$$\frac{d\epsilon}{dt} = Ae^{-\frac{Q}{RT}}\left[\sinh\left(\xi\frac{\sigma}{S}\right)\right]^{\frac{1}{m}}$$

$$\frac{d\epsilon}{dt} = \left\{h_0\left|1-\frac{S}{S^*}\right|^a \operatorname{sign}\left(1-\frac{S}{S^*}\right)\right\}\frac{d\epsilon_p}{dt}$$

$$S^* = \hat{S}\left[\frac{\frac{d\epsilon_p}{dt}e^{-\frac{Q}{RT}}}{A}\right]^n$$

Initial deformation resistance	S_0	2.3165 MPa
Activation enengy/Universal gas constant	Q/R	10279 °C
Pre-exponential factor	A	1.7702×10^5 s^{-1}
Multiplier of stress	ξ	7
Strain rate sensitivity of stress	m	0.207
Hardening/Softening constant	h_0	27782 MPa
Coefficient for deformation resistance saturation	$\hat{S}$	52.4 MPa
Strain rate sensitivity of saturation (deformation resistance)	n	0.0177
Strain rate sensitivity of hardening or softening	a	1.6

Explanation for hybrid thickness result

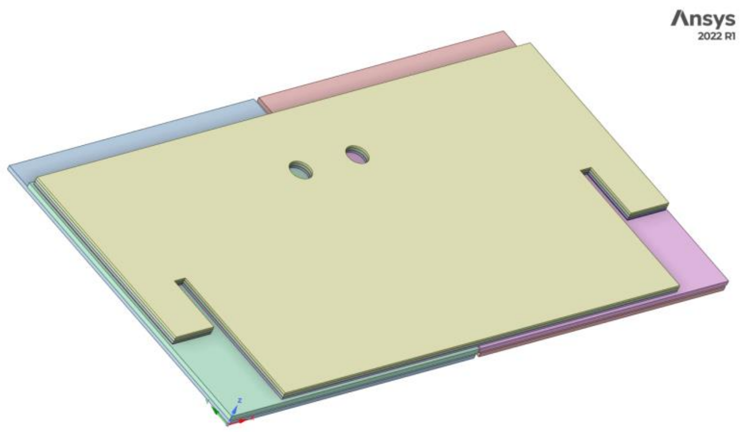
Consider low temperature (shrinking) situation
Length of arrow means deformation magnitude

Although CTE of bump is almost same as module flex, the dimension of a single bump is too small compared to Sensor/ASIC/module flex that bump almost does not deform during thermal cycle.

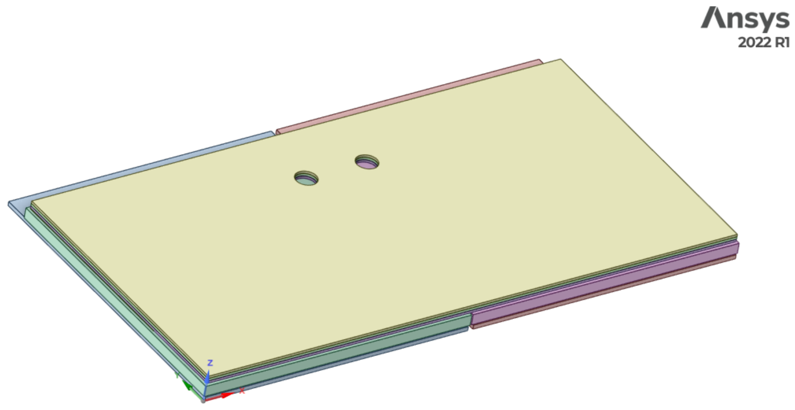
Mismatch of CTE in module flex and sensor is leading to shearing between them, finally leading to a larger shrinking to the middle in sensor. When bumps stay still and sensor shrinks to the middle, the larger sensor shrinks will produce larger shear stress between sensor and bump. A thicker sensor reduces the effect from module flex and leads to smaller deformation in sensor.

A thicker ASIC helps nothing on top side of bumps, the only effect is to shear the bottom of bump more which leads to larger stress in bumps.

Module flex shape



Easier to
manufacture



Lifetime: 393

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- Simulation shows that rectangle module flex makes module much weaker in thermal cycle

Simulation results: glue thickness

	20 um	50 um	80um
Maximum Von-Mises stress/MPa	50.61	51.52	51.53
Maximum equivalent plastic strain	0.02330	0.02642	0.02683
Average lifetime/cycles*	**535**	**393**	**378**

- Module with thinner glue can live a little longer
- Glue thickness within specification (20-80 um) does not make too much difference in lifetime

Thermal cycle to larger temperature range

- Current cycle: -45℃~40 ℃, 2 hours (simulated: -45.5 ℃~44.5 ℃, 2 hours)
- Longer cycle: -55 ℃~60 ℃ (simulated: -53 ℃~59.5 ℃, 2.5 hours)

	Current cycle		Longer cycle	
	ALTIROC-A, more bumps	ALTIROC-3, fewer bumps	ALTIROC-A, more bumps	ALTIROC-3, fewer bumps
Average lifetime/cycles	393	119	248	77

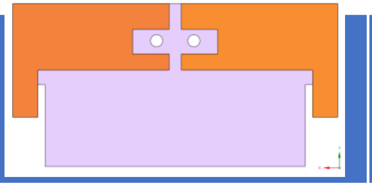
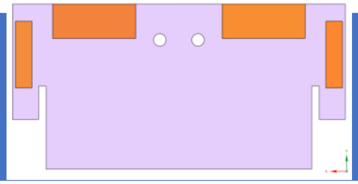
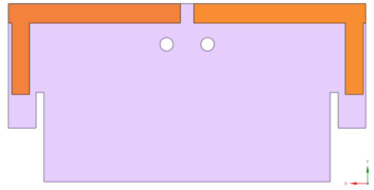
- During a longer cycle, average module lifetime decreases by about 1/3
- Testing results showed that a cycle to larger temperature range did not affect the results obviously

Module flex material

Middle layer	Copper	Copper	Tungsten	Tungsten
Outer layers	Kapton	½ CTE kapton	Kapton	Ceramic
Maximum Von-Mises stress/MPa	51.52	51.19	25.91	31.53
Maximum equivalent plastic strain	0.02642	0.02512	0.00286	0.00428
Average lifetime/cycles	393	445	83838	31565

- Just changing Kapton does not make a big difference
- Changing copper for tungsten can make module survive much longer, but:
  - Tungsten cannot be matched with Kapton for technical causes
  - Combination of tungsten and ceramic is much more expensive
  - Ceramic cannot be as thin as before for technical causes, requiring more vertical space

Glue pattern

			
Maximum Von-Mises stress/MPa	51.52	45.40	50.63
Maximum equivalent plastic strain	0.02642	0.01144	0.02538
Average lifetime/cycles	393	3029	566
Reference glue weight on hybrid/mg	9.41±5.45	3.32±1.99	3.37±2.02

- By reducing glue area lifetime can be much longer
- Glue pattern in the middle column has been tested by IFAE and did not cause wire-bonding problem
- Pattern between second and third one can be used

Testing results of longer cycle

- Thick module M126, M128 and M130 from IFAE
- Tested after 120 regular cycles of -45℃~40 ℃
- Continue doing some more cycles of -55 ℃~60 ℃

		120 cycles	+1 cycle	+1 cycle	+3 cycles	+1 cycle	+1 cycle	+1 cycle	+1 cycle	+1 cycle
M126	Chip 0	0	0	0	0	0	0	0	0	0
	Chip 1	5	5	7	7	7	8	7	8	9

		120 cycles	+1 cycle	+1 cycle	+3 cycle
M128	Chip 0	1	2	2	3
	Chip 1	0	1	1	1
M130	Chip 0	0	0	0	0
	Chip 1	No chip communication since beginning			

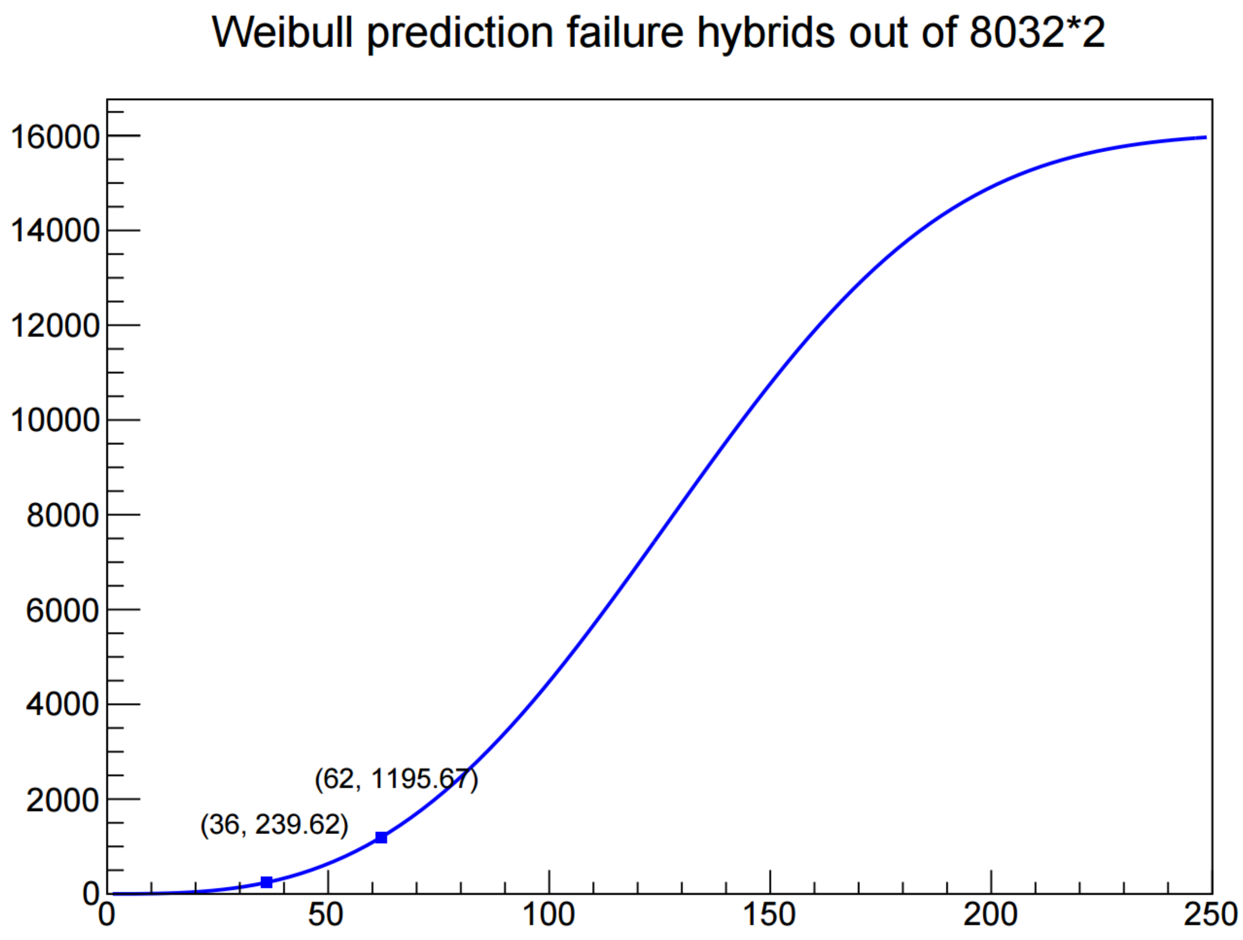
- Summary: no catastrophic failure with thermal cycle to larger temperature range

Statistical model: data pre-processing

Number of cycles for first disconnect	Bumps first disconnected	Total # cycles survived				Assumed lifetime
75	1	60				67.5
120	1	105				112.5
		180				180
75	4	60				67.5
		180				180
120	1	105				112.5
75	1	60				67.5
		180				180
60	1	30				45
		180				180
		150				150
		150				150
		150				150
x	x	x				x
		150				150
		150				150
		120				120
		120				120
240	3	150				180
90	3	60				70
120	1	90				105
		120				120
60	1	30				45
120	3	90				100
		120				120
x	x	x				x
		120				120
		120				120
		120				120
90	1	60				75
		120				120
		120				120
		20				90
		20				90
		175				175
		175				175
		175				175
175	1	120				147.5
		75				90
		75				90
		75				90
		75				90
		120				120
		120				120
90	1	75				82.5
		120				120
		120				120
		120				120

- No failures before 30 cycles
- Early failures: 45*2, observed to fail between 30 and 60 cycles, one from IHEP one from IFAE
- Normal failures: 67.5*3, 70, 75, 82.5, 90*6, 100, 105, 112.5*2 (16)
- Long lived: 120*14, 147.5, 150*5, 175*3, 180*5 (28)

Prediction- Weibull



Prediction- Lognormal