# Predictor Model … Round Robin

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**EXECUTIVE SUMMARY**

Solder joints tend to crack after extended thermal cycling, if the component and the circuit board are CTE mis-matched. Predicting this t-cycle lifetime is critical in optimizing product design or in-service conditions. Predictor models embody cyclic fatigue physics and math, and require inputs of the materials and geometry of the hardware, as well as the thermal conditions of the environment. The output is the predicted number of t-cycles to fail (i.e. to develop electrical-open cracks thru the solder-joint). Several predictor models are in use within the industry. All have strengths and weaknesses, and offer different results. This paper compares several models, rating them for ease of use, and for accuracy against actual test results and against each other. The study uses a round-robin approach; wherein each participant was given the same input data for ten different components, but the actual were withheld until the respective predictor results were in. Also, this paper describes a related study on the ability of each model to perform parametric analyses: i.e. to define the effect on t-cycle life of variations in hardware and environmental conditions. The results offer guidance on selecting models for t-cycle life prediction, as well as on understanding options for improving t-cycle life.

# PREDICTOR MODEL …
# ROUND ROBIN

TOM CLIFFORD

# CONTENT

1) WHAT IS A PREDICTOR MODEL?

2) WHY COMPARE PREDICTOR MODELS?

3) WHY USE A “ROUND ROBIN” ?

4) THIS STUDY: GROUND RULES

5) RESULTS , COMPARISONS , CONCLUSIONS

6) PARAMETRIC STUDY AND RESULTS

7) CONCLUSIONS, AND Q & A

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# WHAT IS A PREDICTOR MODEL?

PREDICTS THERMAL-CYCLE LIFE ( … CYCLES TO FAILURE…) FROM SCRATCH: INPUTS ARE HARDWARE DESCRIPTION AND CONDITIONS.

HANDLES CLASSIC CYCLIC-FATIGUE-FAILURE, THRU THE SOLDER-JOINT, DUE TO CTE-MISMATCH.

DOES NOT HANDLE PREMATURE FAILURES AT INTERFACES, LIKE BLACK-PAD OR VOIDS, etc ……. DOES NOT HANDLE OTHER FAILURE MODES SUCH AS IMPACT…. OR CONTRIBUTING FACTORS LIKE WARPING OF COMPONENT OR PWB.

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# WHY COMPARE PREDICTOR MODELS

1) DESIGNERS NEED TO PREDICT LIFE, TO ASSURE RELIABLE PRODUCT APPLICATION. THAT'S CRITICAL. PREDICTION, FROM SCRATCH, IS VERY DIFFICULT.

2) MOST DESIGNERS ARE DISTRACTED, IMMERSED IN A MILLION OTHER DETAILS, AND ARE NOT EQUIPPED OR FUNDED TO DEVELOP EXPERTISE.

3) THEY NEED A DESK-TOP, INTUITIVE, USER-FRIENDLY RESOURCE TO TO ARRIVE AT A T-CYCLE LIFE PREDICTION.

4) SEVERAL MODELS AND RESOURCES ARE IN USE AND AVAILABLE, COMMERCIAL AND IN-HOUSE. MOST REQUIRE HIGH SKILL LEVEL.

5) MUST SELECT AND COMMIT TO ACQUISITION AND TRAINING.

6) COMPARISON OF AVAILABLE MODELS IS A GOOD START.

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# WHY USE A “ROUND ROBIN” ?

**A “ROUND ROBIN” IS THE CLASSIC METHOD TO COMPARE LABS, OR INSTRUMENTS, OR SKILLS.**

**ALL PARTICIPANTS ARE GIVEN THE SAME “UNKNOWN”. THEY ANALYZE THIS “UNKNOWN” INDEPENDENTLY.**

**(THE “ACTUAL” VALUE IS NOT PROVIDED TO THE PARTICIPANTS  UP-FRONT)**

**RESULTS ARE THEN SHARED, COMPARED. …. AND DISCUSSED.**

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# THIS STUDY: GROUND RULES

* TEN WELL-CHARACTERIZED COMPONENTS WERE CHOSEN, FOR WHICH THERE WAS CREDIBLE ACTUAL T-CYCLE LIFE.
* THESE COMPONENTS SPANNED A WIDE RANGE OF GEOMETRIES.
* ALL WERE MOUNTED ON MULTILAYER POLYIMIDE PWB.
* ALL INVOLVED Sn63 PLATINGS AND FINISHES.
* ALL WERE TESTED AT THE SAME TIME.
* PROPER STATISTICS, SAMPLE-SIZE, DATA-REDUCTION
* "FAILURE TIME" IS DEFINED AS NUMBER OF CYCLES AT THE POINT THAT CRACKS PROPAGATED THRU 100% OF THE FRACTURE-PLANE AREA.

# THIS STUDY: GROUND RULES (contd)

* PARTICIPANT VOLUNTEERS SPANNED SEVERAL MIL-AERO ORGANIZATIONS AND LABS.

* EACH PARTICIPANT WAS TO USE HIS OWN PREDICTOR MODEL. SEVERAL PREDICTOR MODELS WERE INCLUDED.

* THE STUDY MANAGER (ME), HAD NO INTEREST OR INPUT INTO THE TYPE, DETAILS, OR OPERATION OF THE PARTICIPANTS' MODELS.

* EACH PARTICIPANT WAS PROVIDED THE SAME SUITE OF AVAILABLE INFORMATION ON EACH COMPONENT.

* EACH PARTICIPANT WAS PROVIDED THE SAME SET OF CONDITIONS (TEMPERATURE EXTREMES AND RAMPS AND DWELLS): IDENTICAL TO THE T-CYCLE TEST CONDITIONS USED TO OBTAIN THE ACTUAL TEST DATA.

* STUDY WAS INITIATED … RESULTS OBTAINED … AND COMPARED

## GROUND RULES (contd) NOTE THE PREMISES:

1) A PREDICTOR MODEL THAT CAN ACCURATELY PREDICT THE LIFE IN AN ACCELERATED T-CYCLE TEST (ie -10C to + 125C, 30 minute ramps and 30 minute dwells) SHOULD BE ABLE TO SIMILARLY PREDICT THE FIELD-SERVICE LIFE (example 10 C to 30 C, 120 minute ramps, 240 minute dwells).

2) IT'S VIRTUALLY IMPOSSIBLE TO DO A RATIONAL, STATISTICALLY-VALID, REAL-WORLD, T-CYCLE "TEST"… SPANNING MANY YEARS AND MANY TENS OF THOUSANDS OF CYCLES.

3) THEREFORE, WE COMPARE THE MODELS BASED ON THEIR ABILITY TO PREDICT ACTUAL KNOWN <u>TEST</u> T-CYCLE LIFE.

| | Details of Components É. Predictor Model Round Robin Table 1 | | |
|---|---|---|---|
| # | description | dimensional details (dims in mils) | CTE (1) |
| -0- | circuit board | 135 thick 20-layer polyimide / glass | 17.5 |
| 1 | 0402 SMR | 19X39, 9caps, 29X35 lands, 28X35 foot, 24X30 fracture plane, fillet to cap, 1.2 mil sldr thick, 21 toe. | 6.4 |
| 2 | 2010 SMR | 99X196X 21, 20 caps, 65X121 lands, 51X110 foot, 40 X115 fracture plane, 1.1 mil solder film, 9 toe. | 6.4 |
| 3 | 52 I/O LCCC | 750X750 , 950 cas diag, 25 cas-land width, 34x96 lands, fillet3/4up .85 solder, 36 toe | 7.5 |
| 4 | little Plastic FP 28 I/O 50 pitch | 273X774X90, 490landtoe-toe, 655 body-attach diagonal, 715 foot-center diagonal, 10X16 leads, 35X121lands, 75 degree angle,15 radius, 28 straight lead-length, 11shoulder, 11X40 foot, 30X94 wetted foot, 28x55 fracture plane, toe fillet to top of lead, heel fillet 23 up heel, 23 heel fillet , 23 toe fillet, 0.9 mil sldr film thick | 14.0 |
| 5 | big Plastic QFP 144 I/O 25 pitch | 1089X1089X140 body, 1320X1320 land toe-toe, 1382 body-attach diag, 1490 foot diagonal, 6X11 leads, 18X120 lands, 80 angle, 20 radius, 60 straight H, 15 shoulder, 10X38 foot, 18X93 foot, 11x50 fracture plane, toe filletto top, heel fillet, 15 up heel, 20 heel fillet length, 38 toe fillet length, .8 mil sldr thick | 14.0 |
| 6 | little ceramic FP 28 I/O 50 pitch | 393X720X90 body, 696 landtoe-toe, 720 bodydiag, 875 foot diag, 5X17leads, 35X12lands, 70 angle, 21 radius, 30 straight lead-length, 23 shoulder, 17X44 foot, 35X90 wetted foot, 25x50 fracture plane, toe fillet to top, heel fillet18 up, 30 heellength, 35 toe length, .8 mil sldr thick | 7.5 |
| 7 | Big ceramic QFP 192 I/O 25 pitch | 950X950X94 body, 1495X1495 landtoe-toe, 1521 bodydiag, 1740 foot- diag, 4.5X6leads, 20X120 lands, 85angle, 20 radius, 80 straight lead-length, 40 shoulder, 6X45 foot, 15X80 wetted , 6.6x13 fracture plane, toe fillet to top, heel 15 up, 33 heel length, 36 toe length, .8 mil sldr thick | 7.5 |
| 8 | Big P-BGA, Amkor 1517, 1mm | 1572 sq body, 2068 ball diag, 16 collaps ht, 28 fattest, 25at fracture plane, 20.5 dia land NSMD on PWB, 22.5 land slite SMD on package, | 15.0 |
| 9 | Big C-BGA 625 full, 1.0mm | 1281 sq body, 1692 ball diag, 36 assembled ht, 35 dia fattest part, 29 dia at fracture plane, 37 dia land NSMD on PWB, 35 land on package, 1 mil thinnest film, fillet covers land and 8 mils up ball sides, 75% fails at bottom fillet. | 5.3 |
| 10 | Big Ceramic ColGA, 625, 1.27mm | 1281sq body, 1692 ball diag, Raychemcolumns, 88 ht, 21coldia, 29 dia at f plane, 37land NSMD on PWB, 35 land on package, 1 mil film base, fillet 10 up column sides, and down 5 mils from package, 75% fails at bottom fillet. | 5.3 |
| | (1) CTE (weighted average from -10 to + 125). | | |

## ROUND ROBIN ÉÉÉÉ PREDICTOR MODEL TABLE 2 SUMMARY

| PREDICTOR MODELS | COMPONENTS / DESCRIPTIONS (see Details). AND PREDICTED F50s | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | 0402 SMR | 2010 SMR | 52 I/O LCCC | 28 I/O P-FP | 144 I/0 C-QFP | 28 I/0 C-FP | 192 I/O C-QFP | big P-BGA | big C-BGA | big CCol-GA |
| Cliff (Engel) 100% | 1844 | 25 | 1 | 20 | 541 | 63 | 607 | 2819 | 0.2 | 6469 |
| Cliff (Engel w 'correct' solder) 100% | 15380 | 256 | 13 | 332 | 11540 | 1349 | 12960 | na | 26 | na |
| D (Clech) | 1728 | 2646 | 762 | 29320 | 40,140 | 38840 | 14400 | 963 | 244 | 6228 |
| B (Engel) | 31981 | 632 | 37 | 209 | 85814 | 5669 | 132560 | | | |
| G (CALCE) | 33025 | 811 | 431 | 29215 | 130000 | 4611 | 3019 | 1451 | 961 | 1294 |
| K (Engel) | 1844 | 25 | 1 | 869 | 60621 | 1086 | 166 | 7066 | 175 | 1482 |
| K (Clech) | 4325 | 9078 | | 79110 | 21790 | 49030 | 3164 | | | |
| N (SIP) | 2237 | 502 | 119 | 1361 | 2258 | 944 | 792 | 2059 | 1089 | 1328 |
| N (CM) | 1667 | 82 | 310 | 561 | 2631 | 330 | 1844 | 1365 | 271 | 441 |
| **ACTUAL TEST RESULTS** | | | | | | | | | | |
| Cracks begin, (est) | 2500 | 300 | 75 | 1500 | 1400 | 1000 | 1200 | 250 | 50 | 500 |
| Cracks at 50% thru fracture plane area (est) | 8000 | 900 | 360 | 4800 | 3800 | 3600 | 3700 | 400 | 60 | 2500 |
| Cracks at 100% thru fracture plane area (est) | 10000 | 2800 | 500 | 5600 | 5000 | 4000 | 4600 | 550 | 75 | 3225 |

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# RESULTS , COMPARISONS

**THE FOLLOWING GRAPHICS SHOW THE COMPARATIVE NUMERICAL RESULTS OF ALL PARTICIPANTS' PREDICTIONS, FOR EACH COMPONENT.**

**NOTE THAT <u>EASE-OF-USE</u> DIFFERED SIGNIFICANTLY:**

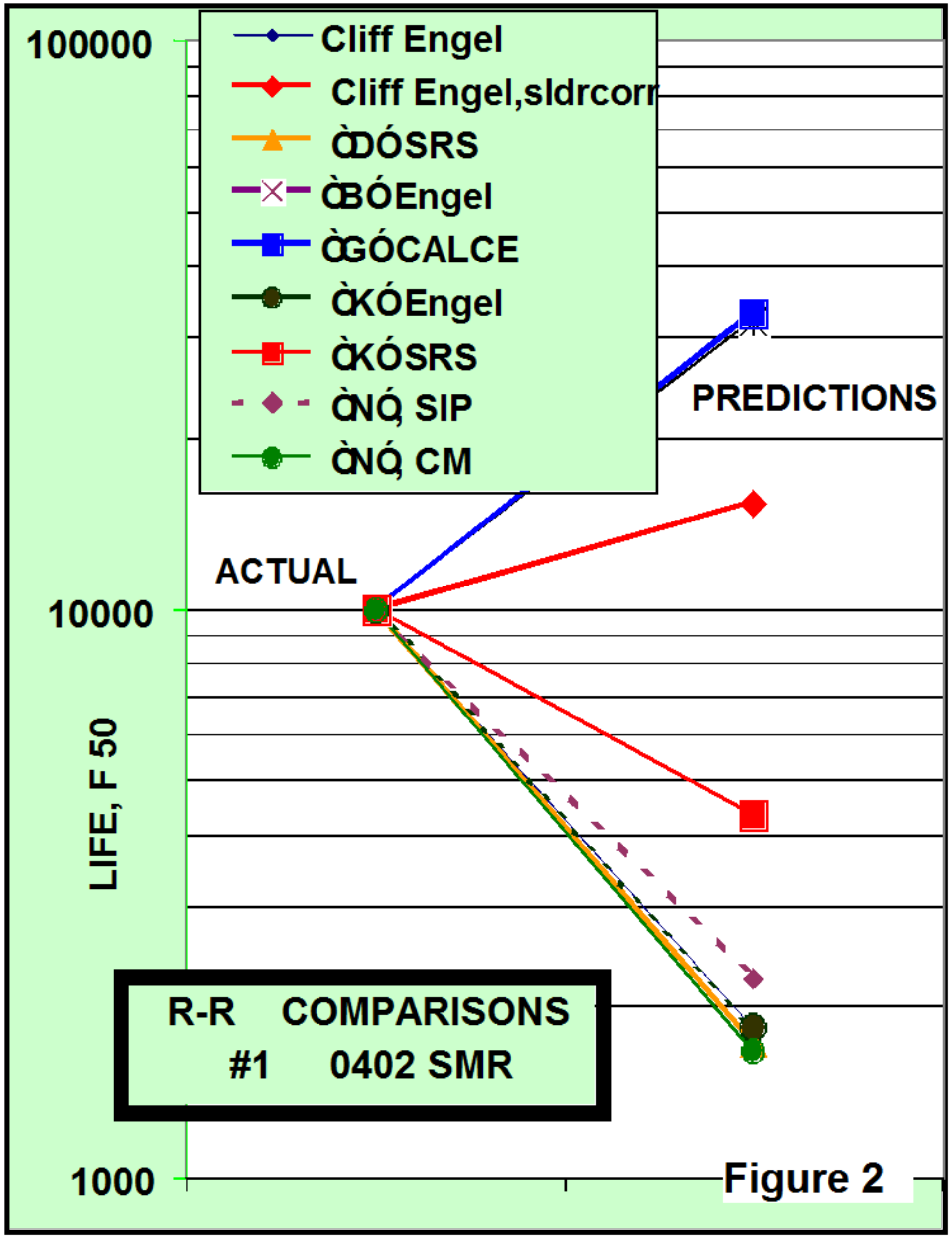
**1) THE ENGELMAIER-BASED MODEL IS AN EXCEL SPREAD-SHEET THAT IS KEY-STROKE-SIMPLE, WITH ONLY 20-30 INPUTS.**

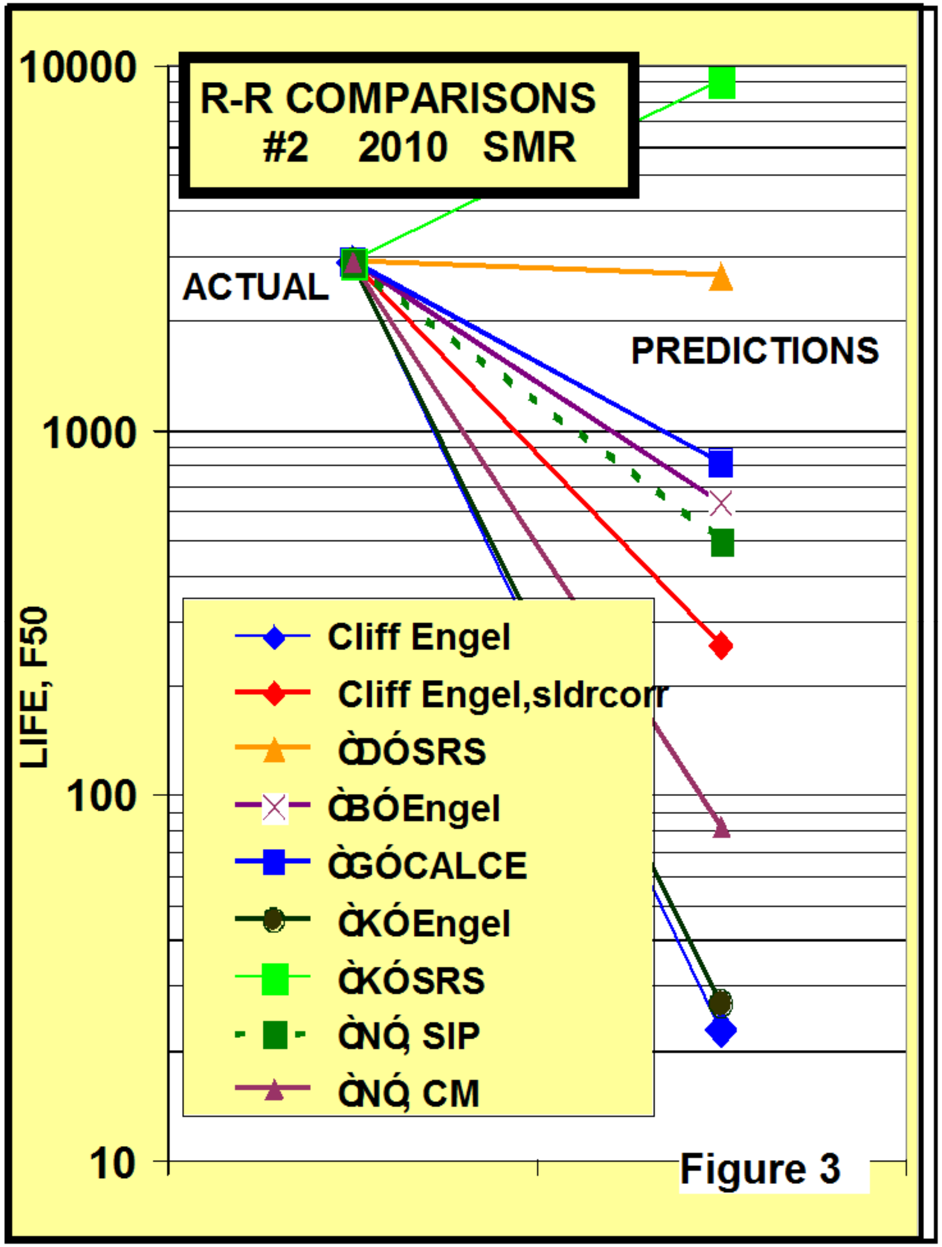
**2) THE "N-CM" IS MAIN-FRAME, ARCANE, COMPLEX AND VERY SLOW.**

**3) THE "N-SIP" IS DESK-TOP, BUT RELATIVELY SLOW.**

**4) THE CALCE AND CLECH/SRS MODELS ARE MID-RANGE, DEPEND ON SKILLS, AND ARE VERY CAPABLE.**

# RESULTS


100000
10000
1000
LIFE, F 50
Cliff Engel
Cliff Engel,sldrcorr
ÒDÓSRS
ÒBÓEngel
ÒGÓCALCE
ÒKÓEngel
ÒKÓSRS
ÒNÓ SIP
ÒNÓ CM
ACTUAL
PREDICTIONS
R-R COMPARISONS
#1 0402 SMR
Figure 2


10000
1000
100
10
LIFE, F50
R-R COMPARISONS
#2 2010 SMR
ACTUAL
PREDICTIONS
Cliff Engel
Cliff Engel,sldrcorr
ÒDÓSRS
ÒBÓEngel
ÒGÓCALCE
ÒKÓEngel
ÒKÓSRS
ÒNÓ SIP
ÒNÓ CM
Figure 3

# RESULTS

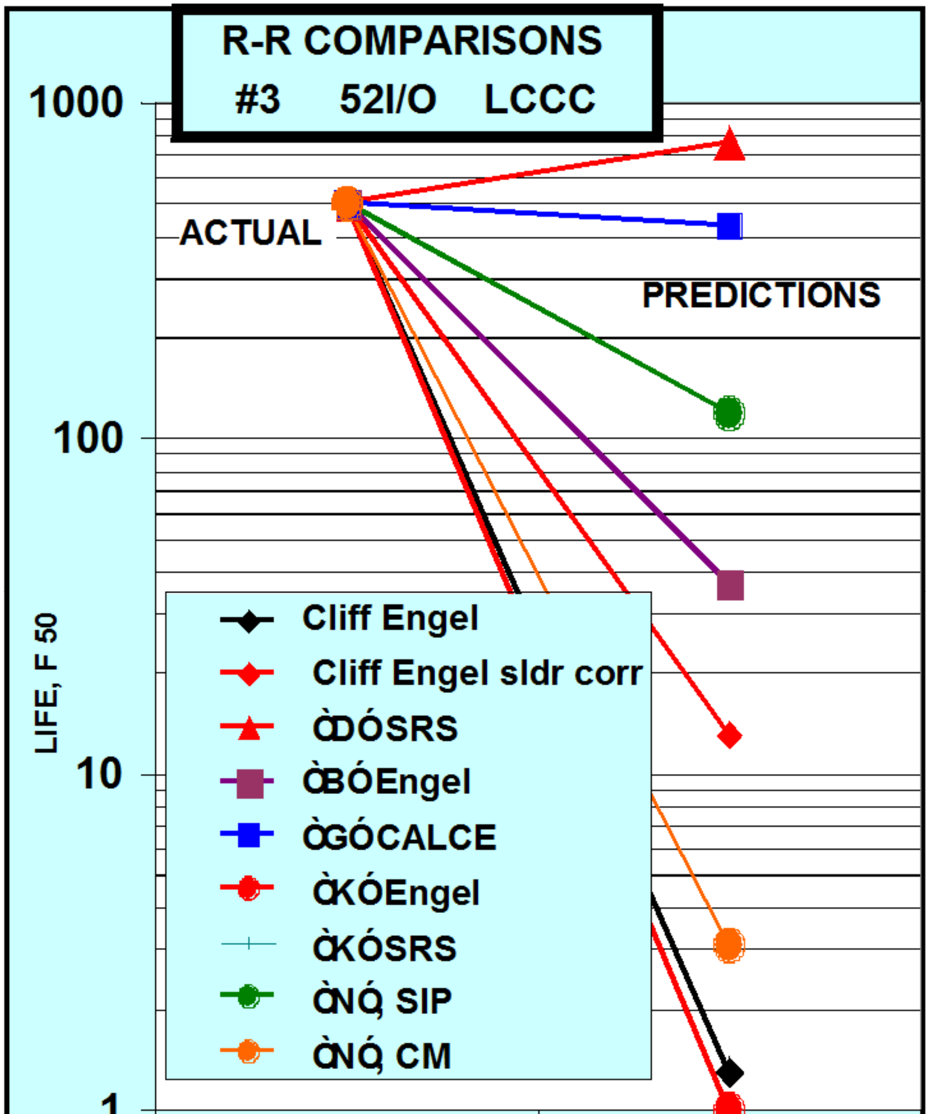



Figure 4

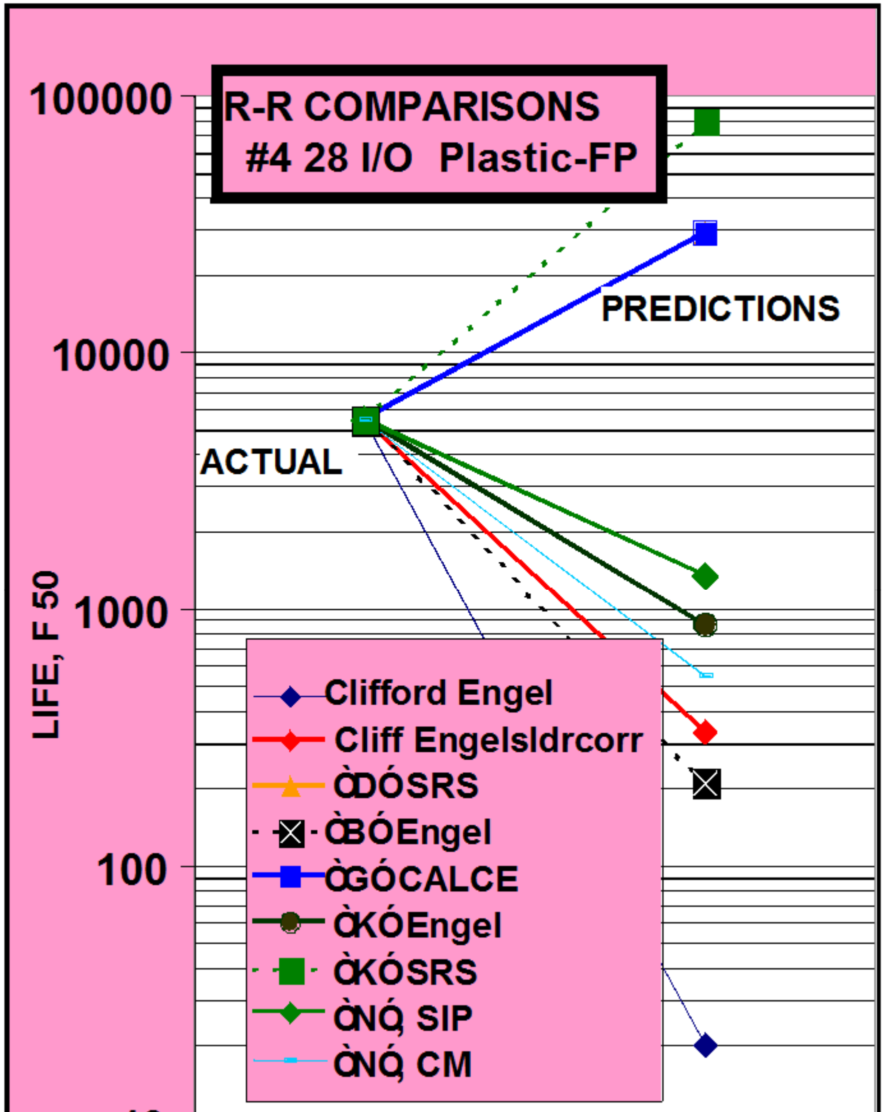



Figure 5

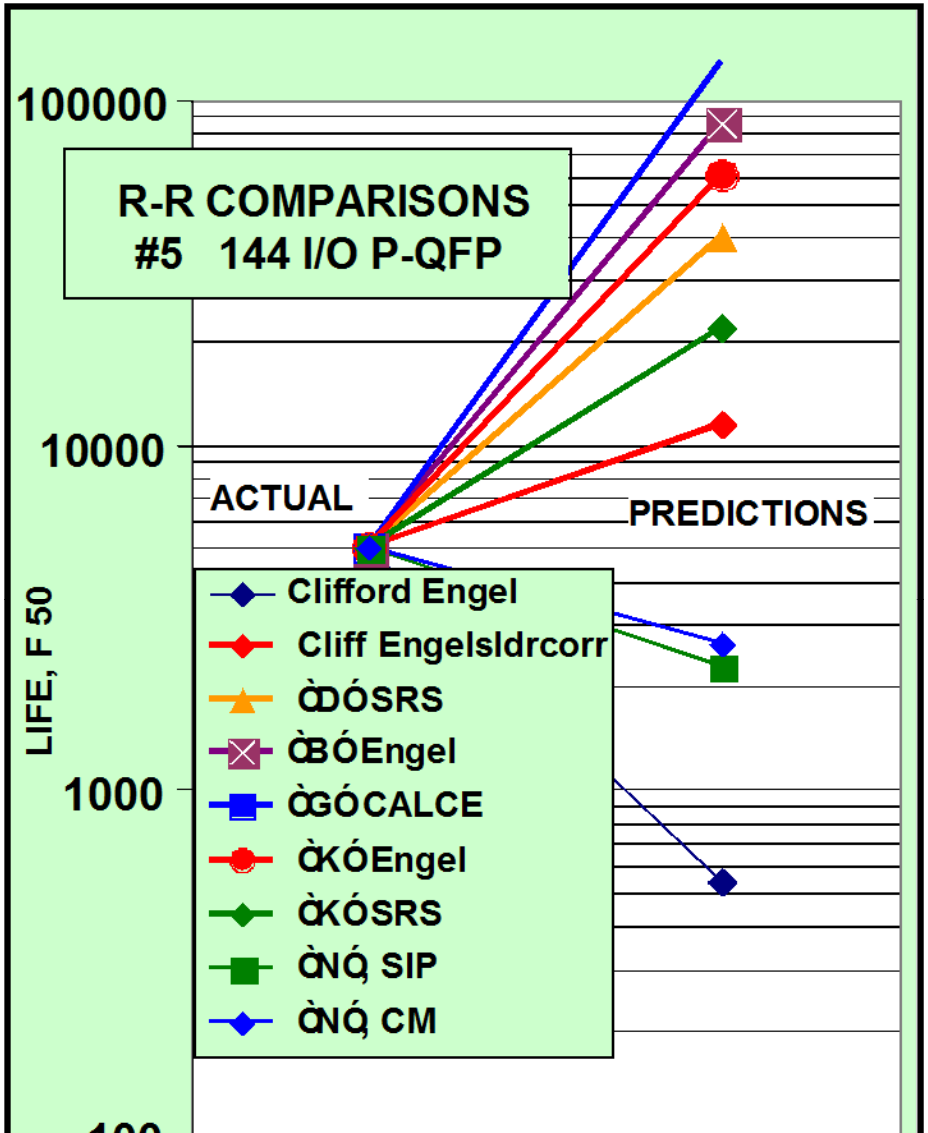


Figure 6

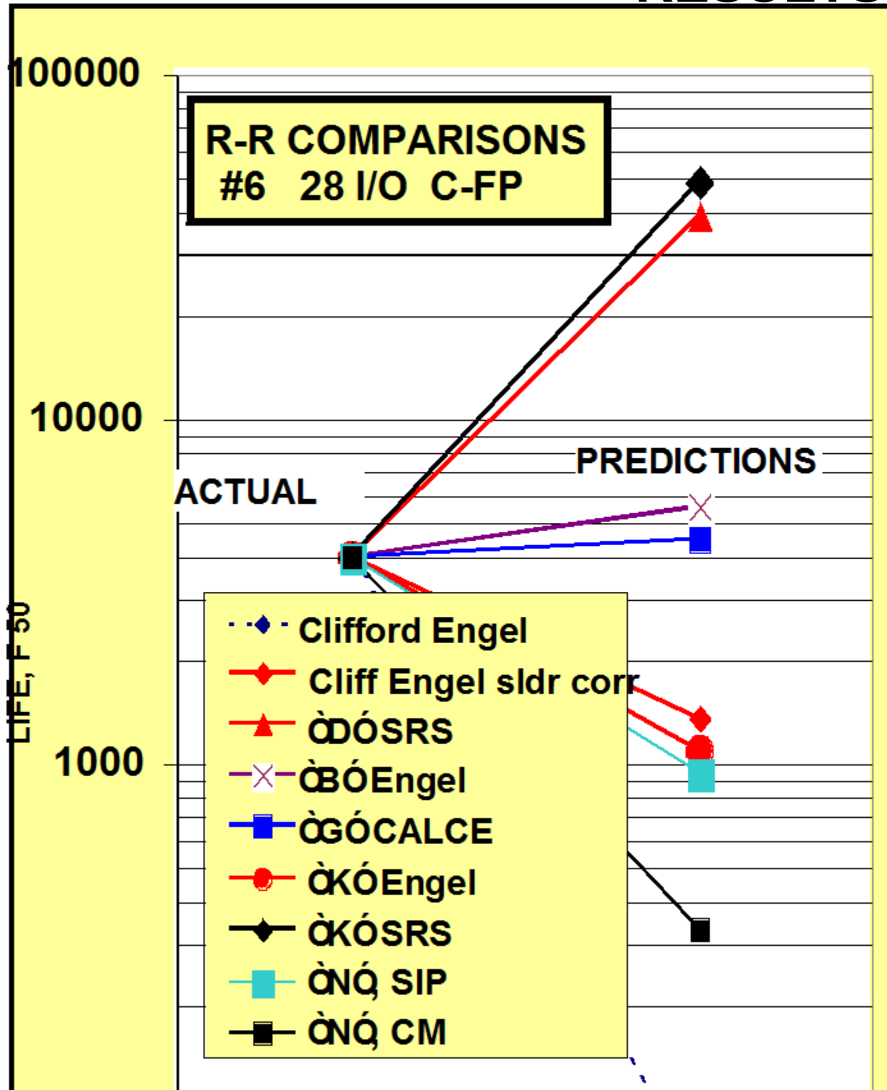


Figure 7

# RESULTS

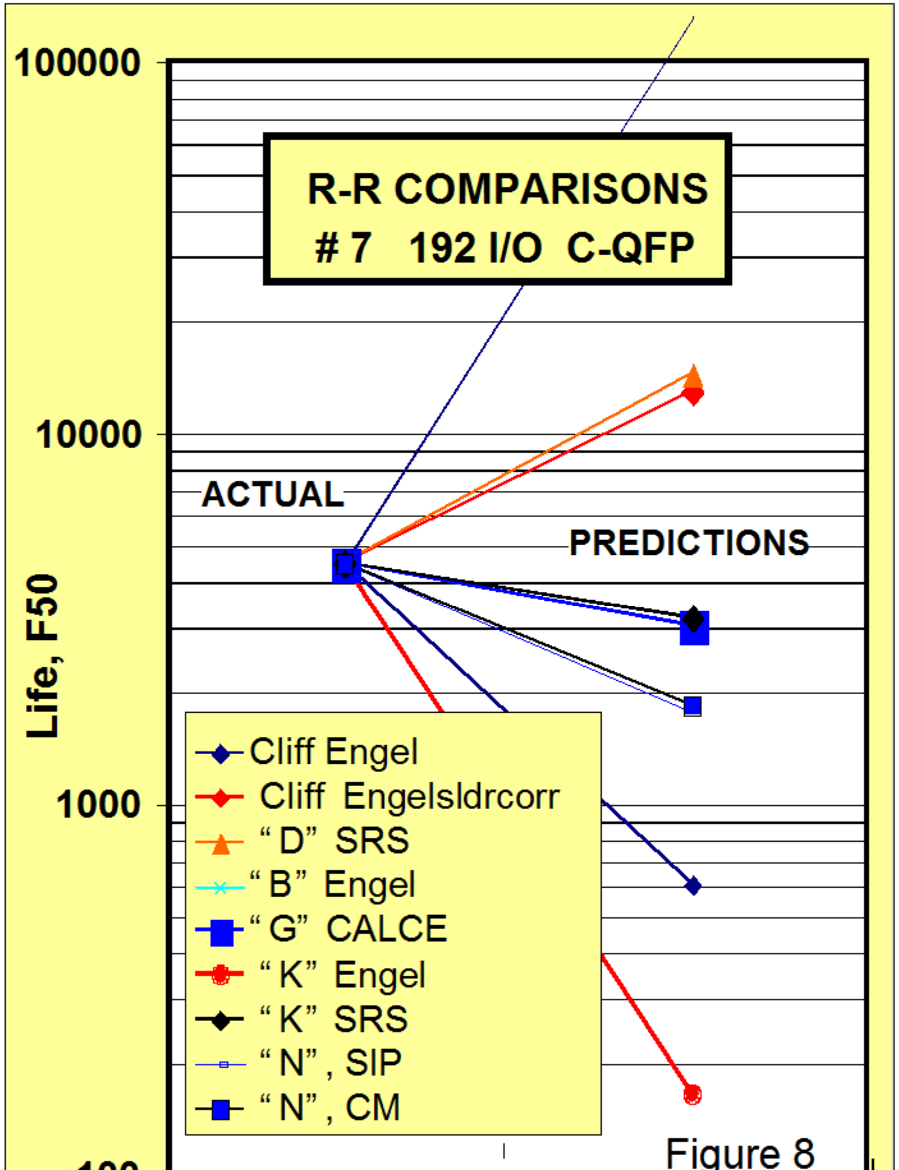



Figure 8

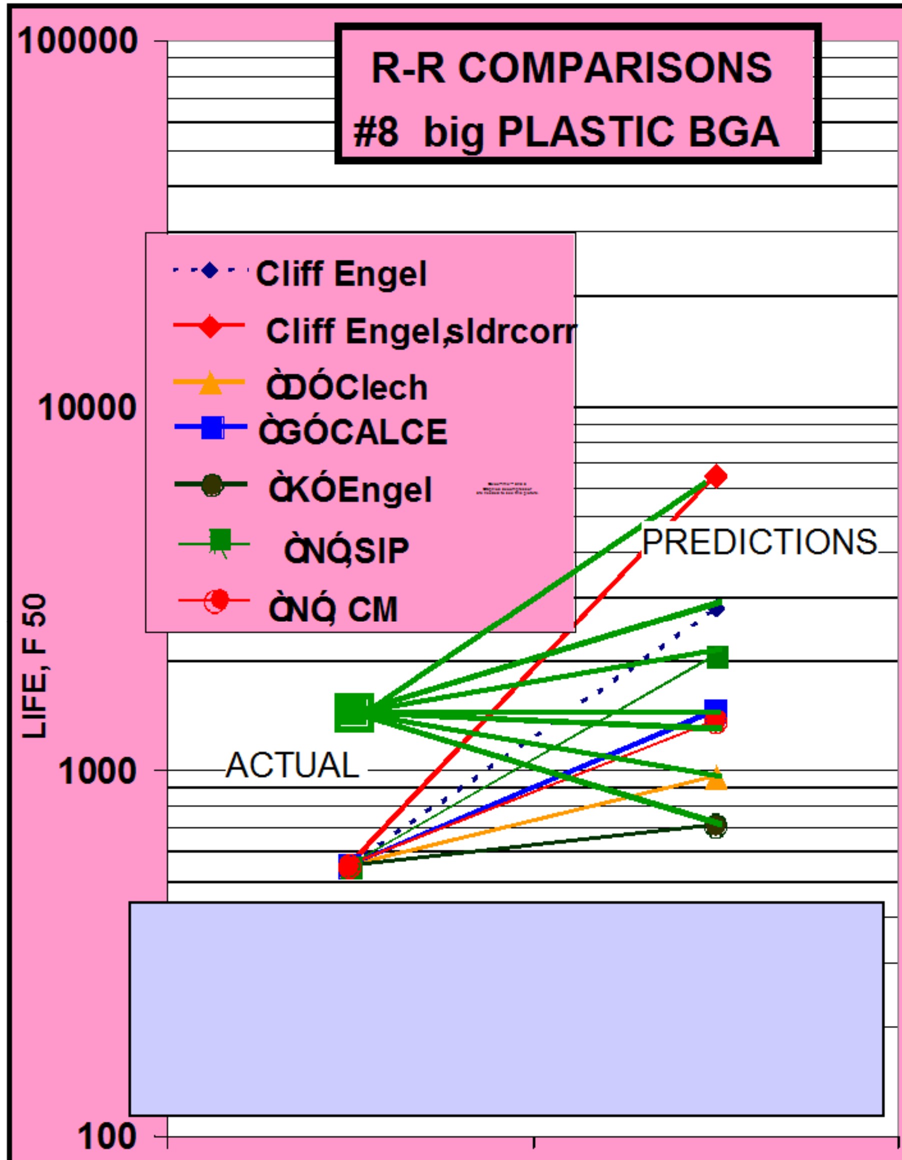



Figure 9

# RESULTS

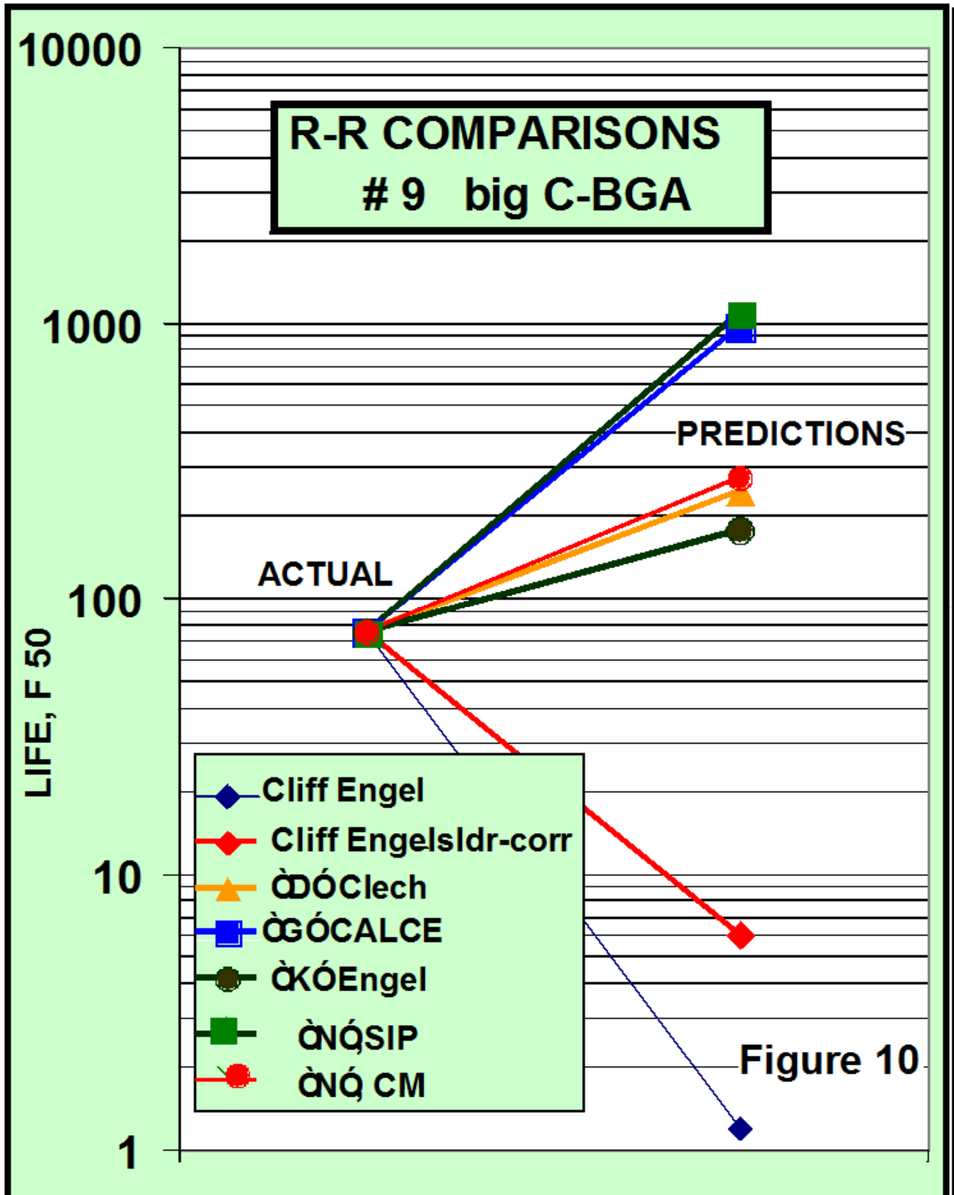



Figure 10

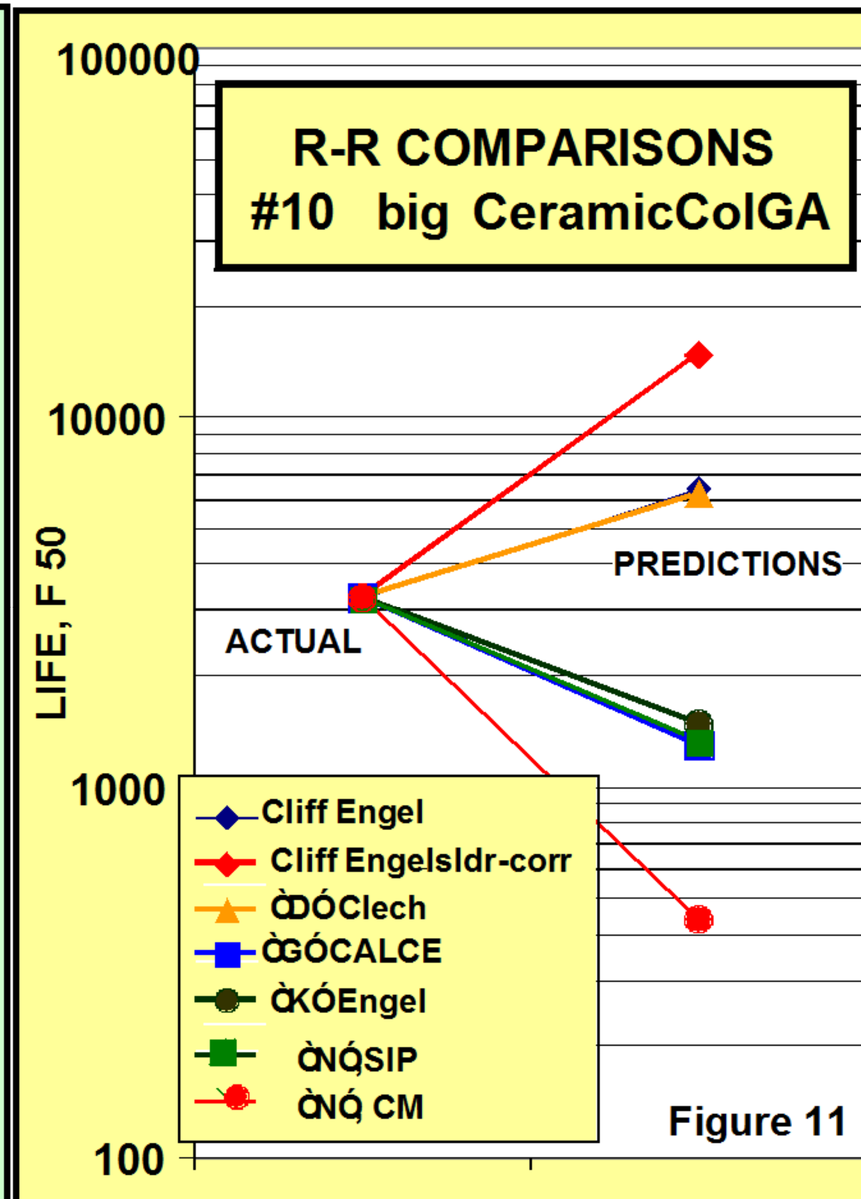



Figure 11

# CONCLUSIONS

**THE ACTUALS FALL IN THE MIDDLE OF ALL THE PREDICTIONS. THAT'S REASSURING, FOR TESTING CREDIBILITY.**

**SOME MODELS PREDICT "HIGH" FOR SOME COMPONENTS, AND VICE VERSA. NO CONSISTENT PATTERN, BY MODEL OR BY COMPONENT.**

**YOU CAN COUNT ON PREDICTING WRONG BY A FACTOR OF 2-5X EITHER SIDE. FOR ANY COMPONENT, USING ANY MODEL. THAT'S NOT GOOD …..… BUT NOT UNEXPECTED.**

**SOME MODELS ARE MORE COMPLEX AND ALL-INCLUSIVE, PLUS PERHAPS MORE AMENABLE TO "TWEAKING" AND "FUDGE". >>>> THAT IS LEGIT, IF IT'S BASED ON PROPER SCIENCE <<<<<**

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# PARAMETRIC VARIANCE, OR TRANSFORM ……
# THE OTHER WAY TO "PREDICT" T-CYCLE LIFE

- …. NOT TO PREDICT LIFE FROM SCRATCH (THE PREDICTOR MODEL) … BUT TO "TRANSFORM" FROM A KNOWN SITUATION TO A NEW SET OF CONDITIONS. FOR INSTANCE:
- IF A CERTAIN COMPONENT IF FELT TO BE "OK" IN A GIVEN APPLICATION, HOW MUCH WORSE WILL BE A COMPONENT THAT IS 0.5" BIGGER, ALL ELSE EQUAL?
- IF A COMPONENT WITH A PACKAGE CTE OF <u>16.5</u> HAS AN F50 OF 2250 CYCLES IN A GIVEN TEST, WHAT WOULD THE F50 BE IF THE CTE IS <u>6.8</u>, INSTEAD?
- IF A GIVEN COMPONENT/PWB IS KNOWN TO BE BARELY OK IN AN APPLICATION WITH A DELTA T OF <u>15</u> DEGREES, HOW MUCH WORSE WILL IT BE IF THE DELTA T IS <u>22</u> DEGREES?

**THIS PARAMETRIC STUDY WAS AN ADD-ON BONUS.**

**…… ONCE THE PARTICIPANTS GOT THEIR MODELS SET UP , THEY WERE ALL ASKED TO RUN SOME STANDARD CASES: VARY ONE FACTOR AT A TIME; SEE WHAT EFFECT THAT HAS ON T-CYCLE LIFE.**

**FACTORS INCLUDED HARDWARE PARAMETERS, AS WELL AS EXPOSURE CONDITIONS.**

**THIS EXERCISE WAS TO COMPARE "TRANSFORM" CAPABILITIES, AMONGST THE VARIOUS MODELS.**

**TABLE 3 ROUND-ROBIN, PARAMETRIC ANALYSIS** AOVs, response surfaces

| AOVs É . hardware | 1) Use component 2, vary the solder thickness, mils | | | | 2) Use component 8, vary the diagonal dim, | | | | 3) Use component 7, vary the lead thickness @ constant width = .01 | | | | 4) use component 9, vary the component CTE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| parameter value | 0.5 | 2.0 | 5.0 | 20.0 | 0.5 | 1.0 | 2.0 | 3.0 | 3.0 | 5.0 | 8.0 | 10.0 | 3.0 | 6.0 | 9.0 | 12.0 |
| C Engel, | 4 | 100 | 834 | 20680 | 89240 | 16710 | 3238 | 1253 | 2870 | 133 | 13 | 5 | 4336 | 7417 | 14940 | 40920 |
| K Clech | 7691 | 11260 | 16990 | 47070 | 102 | 21 | 8 | 3 | 3612 | 3048 | 2556 | 2345 | | | | |
| B Engel | 107 | 510 | 19350 | 443474 | 102 | 21 | 8 | 3 | 288725 | 132596 | 20036 | 736 | | | | |
| D Clech | 2461 | 2962 | 4326 | 13509 | 5754 | 3168 | 1856 | 716 | 16140 | 13920 | 11770 | 11078 | 186 | 267 | 429 | 853 |
| G CALCE | 164 | 400.0 | 1700.0 | 7534.0 | | | | | 3745.0 | 3019.0 | 1558.0 | 118.0 | 311.0 | 600.0 | 1500.0 | 8000.0 |
| N-CM | 44 | 530 | 2095 | 14282 | 15059 | 8525 | 4029 | 2248 | 1763 | 1264 | 674 | 381 | 216 | 373 | 795 | 2905 |
| N-SIP- | 361 | 1231 | 2469 | 5466 | 5644 | 4614 | 3413 | 2592 | 1787 | 1667 | 1373 | 1101 | 1053 | 1315 | 1805 | 3035 |
| | | | | | | | | | | | | | | | | |
| AOVs É . conditions | 5) use component 5 ...vary the delta @ Tave=40 | | | | 6) 5, vary the average temp, @delta=120 | | | | 7) 5, vary dwells, minutes | | | | 8) 10, vary F.xxx, @ beta 7 | | | |
| parameter value | 180 | 135 | 50 | 8 | -10 | 20 | 50 | 80 | 5 | 30 | 240 | 1000 | 63.0 | 0.1 | 0.010 | 0.001 |
| C Engel, | 164 | 1126 | 30220 | 558000 | 2035 | 1412 | 1010 | 743 | 912 | 541 | 350 | 302 | 2968 | 1107 | 797 | 543 |
| D Clech | 28480 | 33020 | 123700 | 433000 | 33960 | 35250 | 38860 | 66900 | 42780 | 40140 | 36680 | 35590 | 6228 | 1970 | 1342 | 914 |
| B Engel | | | | | | | | | | | | | | | | |
| K Clech | 15580 | 17760 | Crash | Crash | 17840 | 18690 | 20920 | 36650 | 23220 | 21790 | 20040 | 19450 | | | | |
| G CALCE | 274 | 431.0 | 2488.0 | 92000.0 | | | | | 2408.0 | 811.0 | 114.0 | 26.0 | | | | |
| N- CM | 2593 | 4819 | 33403 | 1E+06 | 8068 | 6860 | 5566 | 3857 | 4753 | 4003 | 3160 | 2438 | | | | |
| N-SIP | 2726 | 5772 | 30579 | 229800 | 43924 | 15701 | 5334 | 1623 | 4063 | 2794 | 1464 | 522 | | | | |

# RESULTS

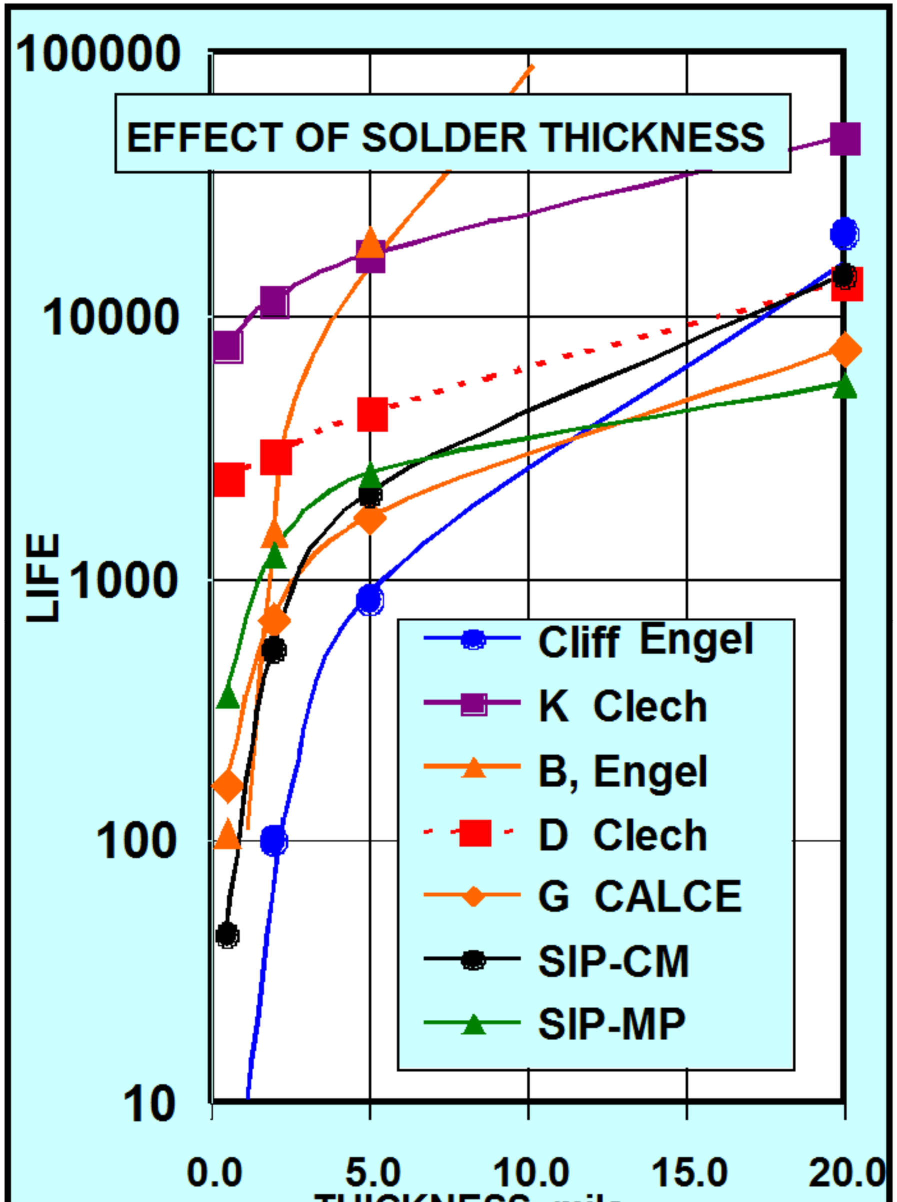


Figure 12

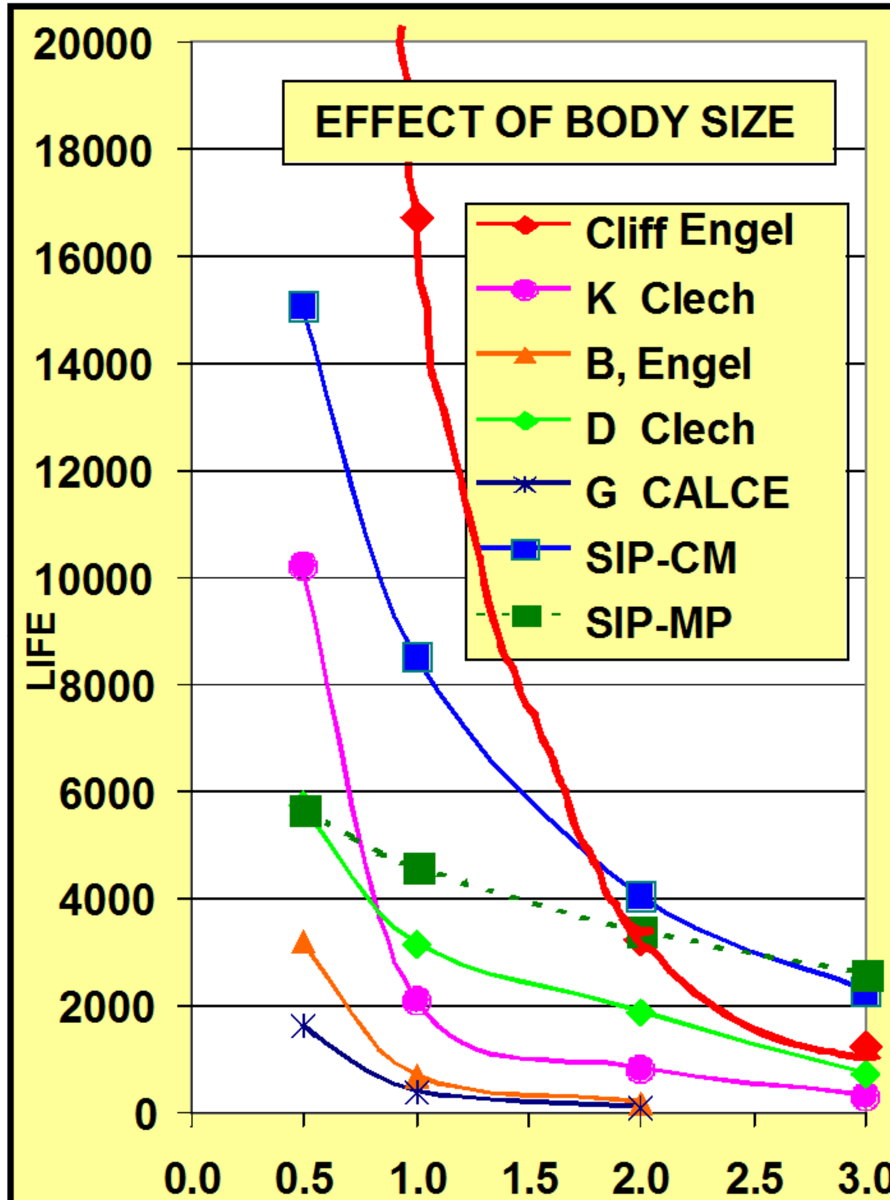


Figure 13

# RESULTS

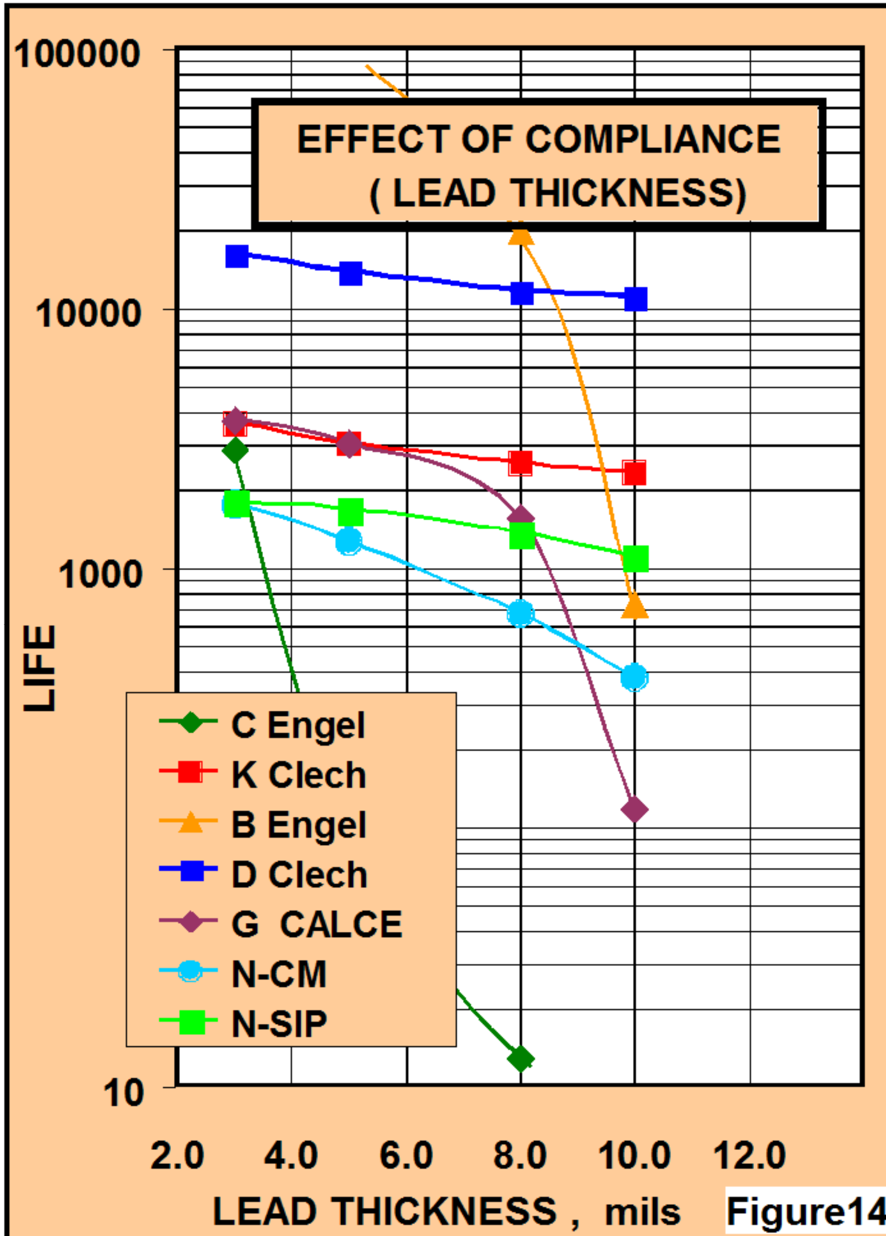

Figure14

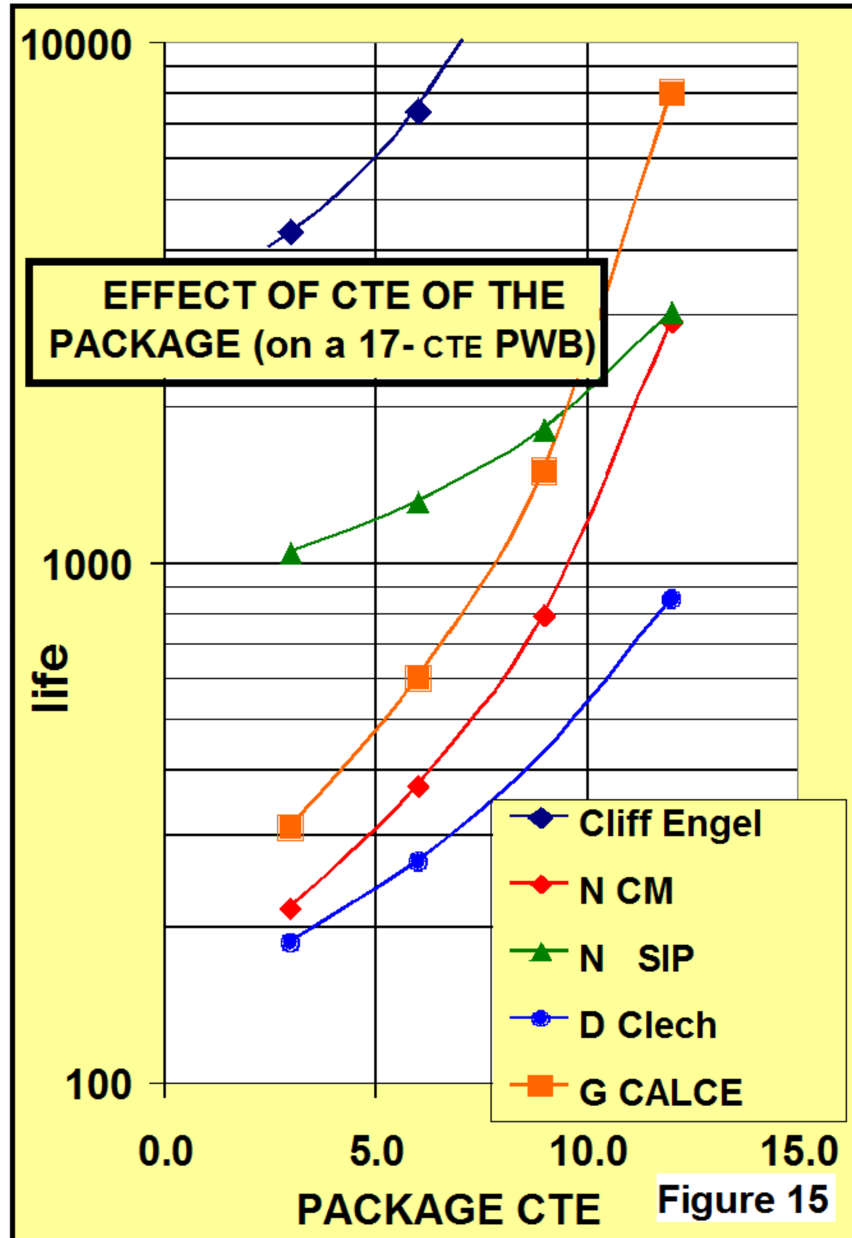

Figure 15

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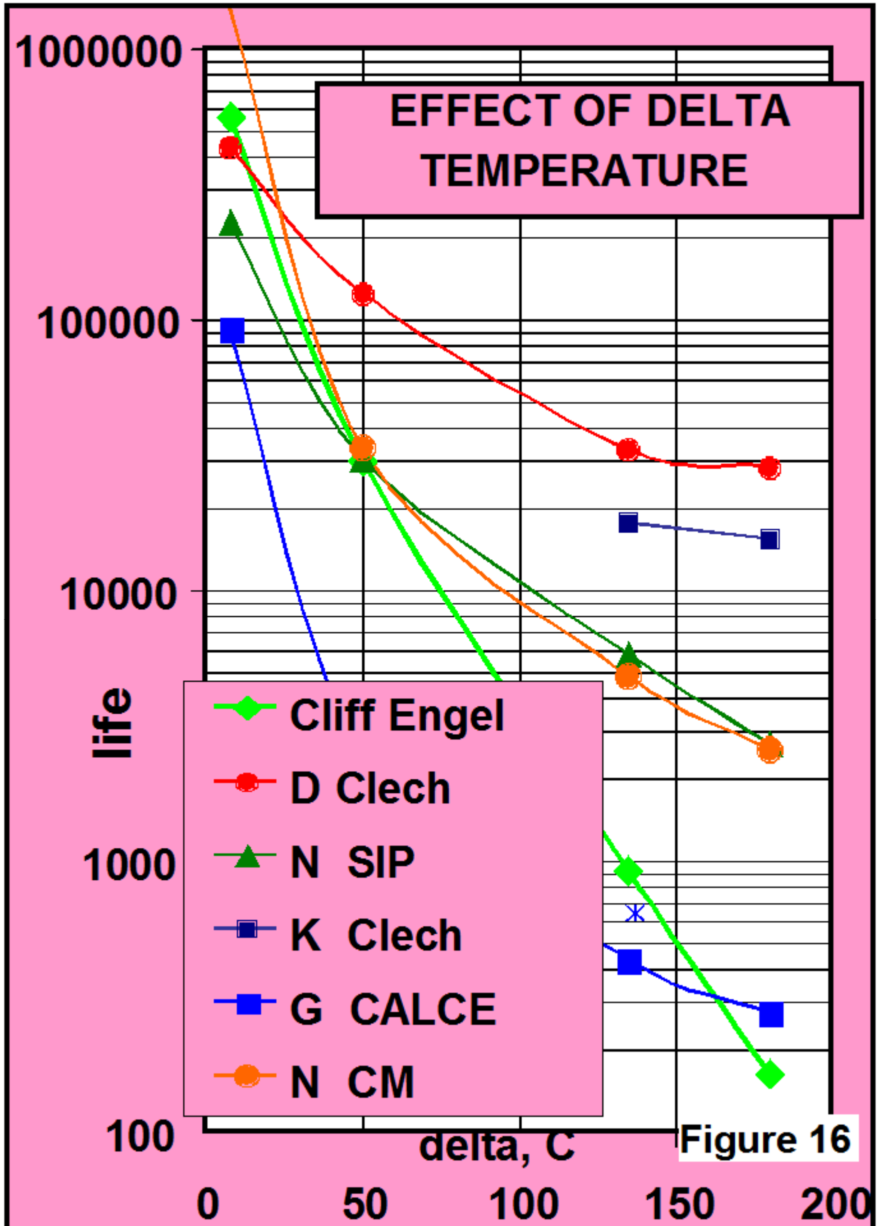


Figure 16

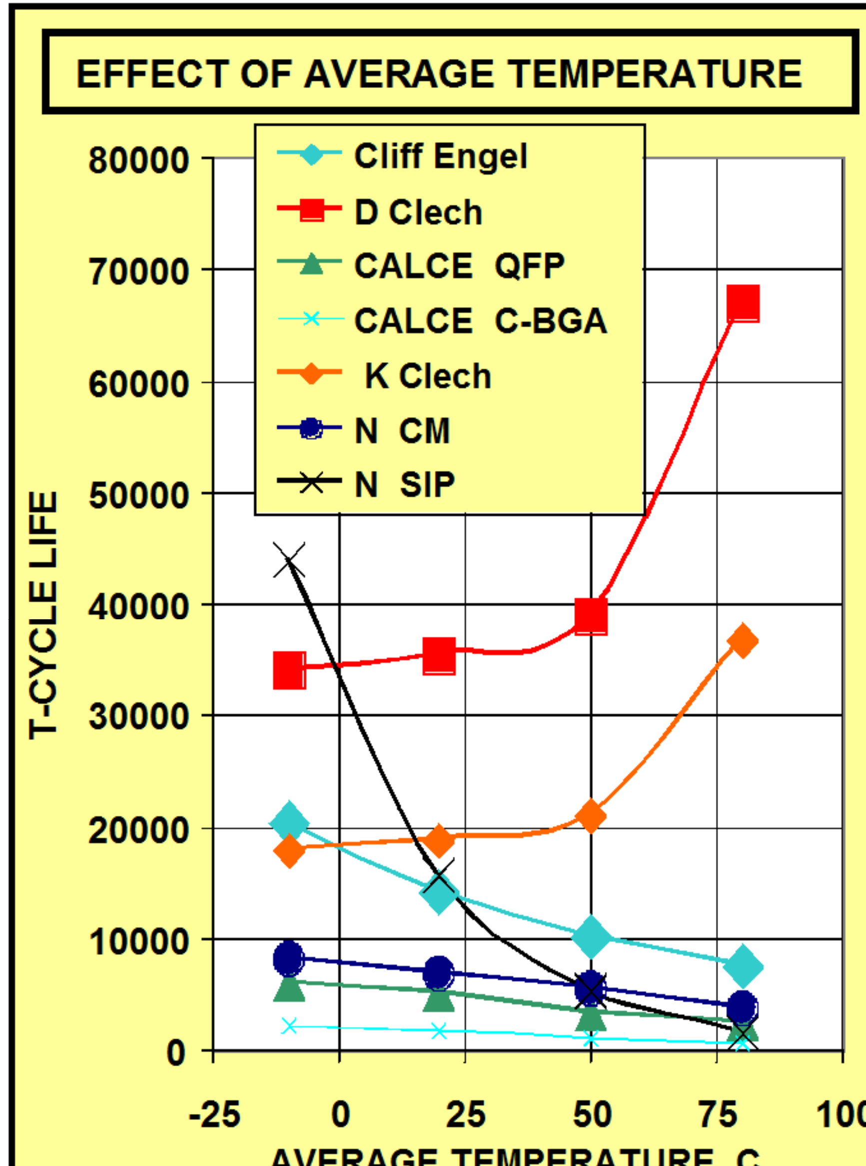


Figure 17

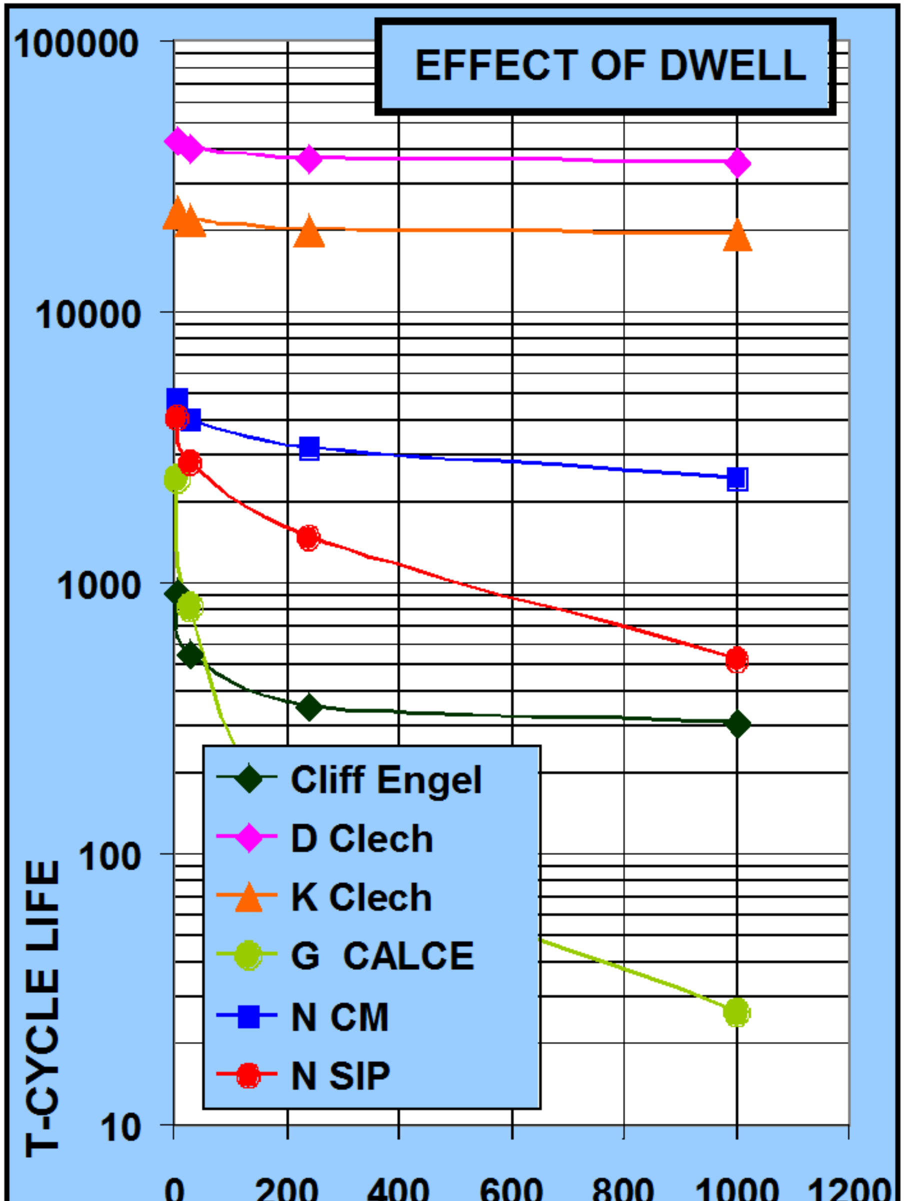

Figure 18

ALL THE MODELS AGREE …. ON ALL THE HARDWARE PARAMETERS. EVEN THOUGH THE ABSOLUTE VALUES DIFFER, THE SLOPE OF THE CURVE IS ESSENTIALLY THE SAME.

THAT MEANS IF ANY MODEL IS ASKED WHAT IS THE IMPACT OF A SMALL CHANGE IN ONE PARAMETER, THE CALCULATED IMPACT WILL BE APPROXIMATELY THE SAME.

THE ODD RESPONSE TO AVERAGE TEMPERATURE VARIANCE (FIGURE 17) IS UNEXPLAINED, AT THIS POINT

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# CONCLUSIONS

1) PREDICTIONS OF ABSOLUTE T-CYCLE LIFE REMAINS PROBLEMATIC.

2) SOURCES OF DIFFERENCES MIGHT INCLUDE THE MODELS' DEFINITION OF FAILURE, THE INCLUSION OF DIFFERENT FACTORS, AS WELL AS DIFFERENT INTERNAL MATH AND PHYSICS.

3) TRANSFORMS …. STARTING WITH SOME KNOWN SITUATION, THEN VARYING THE PARAMETERS …. LOOKS LIKE THE BEST BET, AT LEAST AS A FIRST CUT.

4) MUCH MORE WORK … DIFFERENT MODELS, MORE HARDWARE CASES, INCLUSION OF LEAD-FREE ALLOYS, etc, WOULD BE USEFUL.

5) FEEL FREE TO TRY YOUR FAVORITE MODEL USING THE TEN ACTUAL CASES DESCRIBED. NO FAIR PEEKING AT THE RESULTS, FIRST, THOUGH.

# AKNOWLEDGEMENTS

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**THE AUTHOR IS EQUALLY GRATEFUL FOR THE ENCOURAGEMENT BY INDUSTRY EXPERTS, TO DO THE STUDY AND TO DRAMATIZE THE IMPORTANCE OF HARDWARE FACTORS AND EXPOSURE CONDITIONS ON SOLDER-JOINT RELIABILITY.**

**THE WORKERS AT LOCKHEED MARTIN, WHO HELPED RUN THE T-CYCLE TESTS AND CHARACTERIZE THE SPECIMENS, WERE THE STRENGTH OF THIS ENDEAVOR. ANY ERRORS ARE ALL MINE.**

# Application guide -cycle life summary

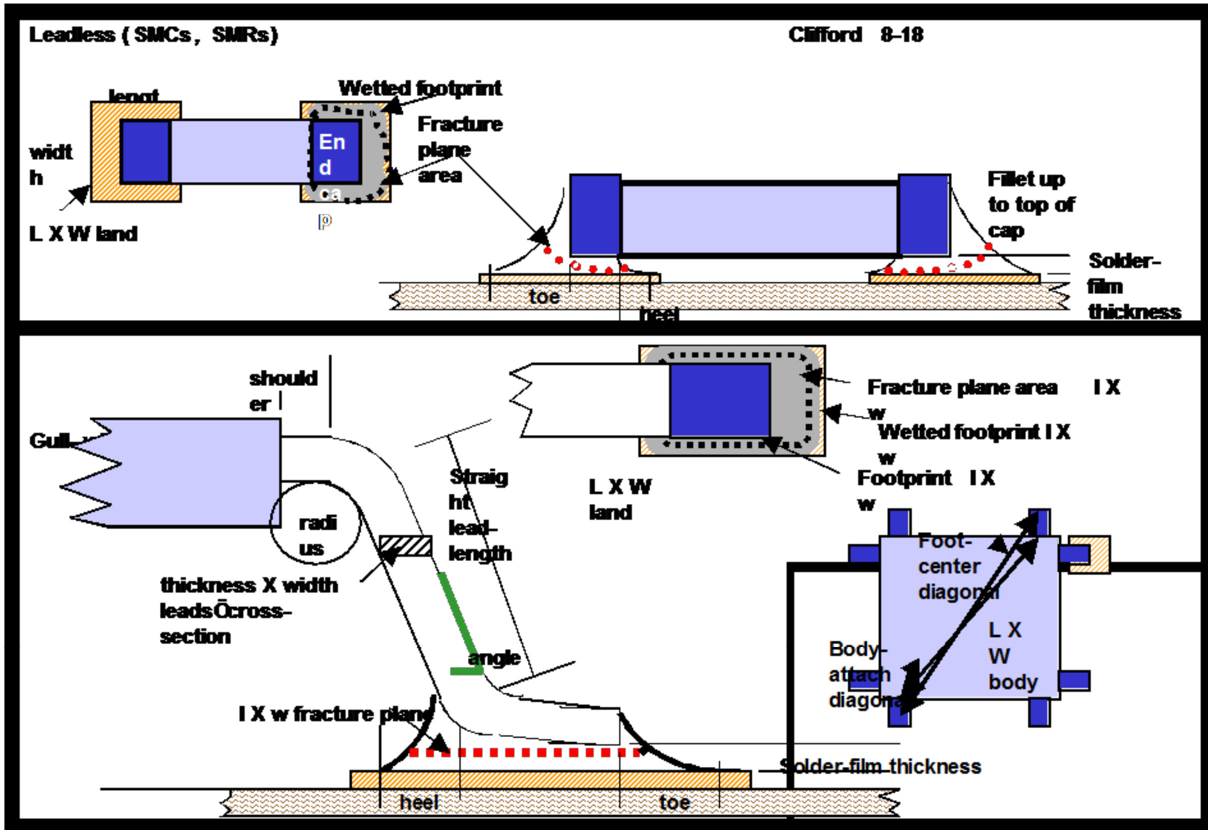
## Typical SMT components, on conventional poly/glass PWBs

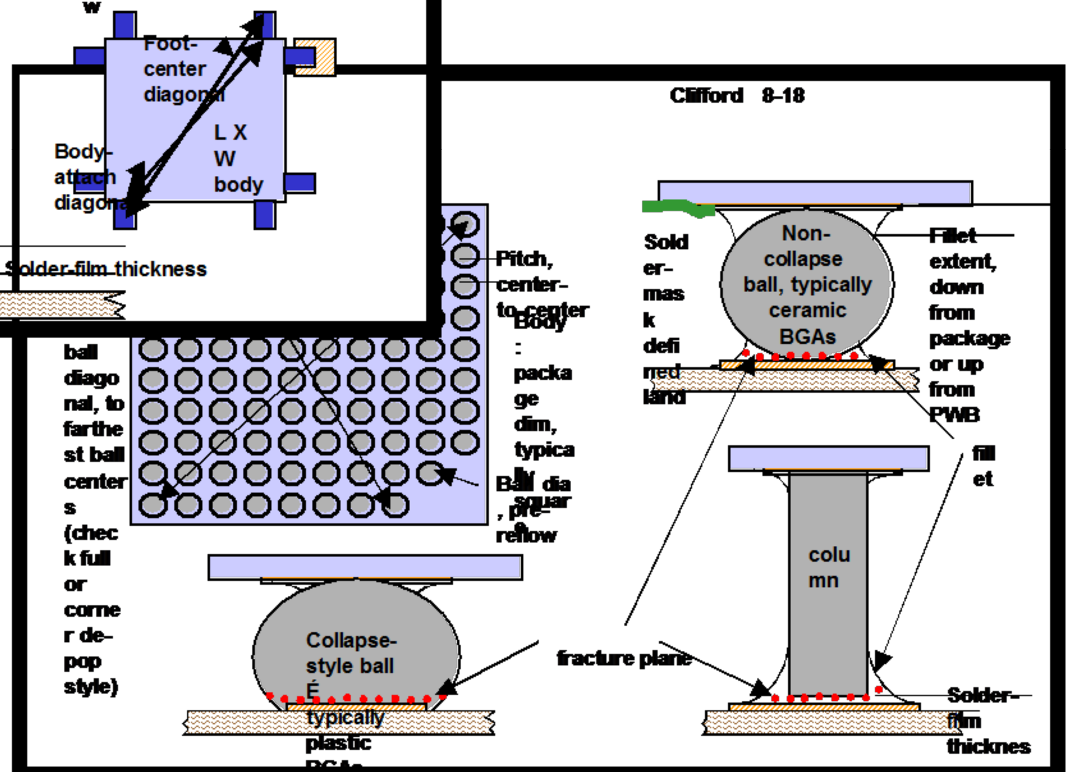
clifford 5-25-06

| typical parts' t-cycle life, in our standard test | | | | Extrapolated to likely LEO mission conditions | | |
|---|---|---|---|---|---|---|
| Examples of SMT parts' t-cycle life, on Poly/Glass PWBs, based on Phase 1 data, @ delta 135, ave 57 C. | F 50 at delta 135, from Phase 1, corrected to est all at 75% fracture plane | test data @ F.001 (from Phase 1) | F.001 test data, converted to 35 C | mild: 50,000 cycles @ F.001, 20 min. dwell, 35 C average, delta 11 C | medium: 75,000 cycles @ F.001, 20 min. dwell, 35 C average, delta 13C | severe: 100,000 cycles @ F.001, 20 min. dwell, 35 C average, delta 15 C |
| big C-BGA 1.9" diag | 65 | 13 | 17 | 5349 | 3642 | 2621 |
| small C-BGA .8" diag | 130 | 27 | 33 | 10698 | 7285 | 5242 |
| big LCCC 68 I/O * | 195 | 40 | 50 | 16046 | 10927 | 7863 |
| medium LCCC 52 I/O | 320 | 66 | 82 | 26332 | 17932 | 12903 |
| small (20 I/O) LCCC | 750 | 155 | 193 | 61717 | 42028 | 30241 |
| big MELF | 900 | 185 | 232 | 74060 | 50433 | 36289 |
| big plastic BGA, 1.9" diag | 950 | 196 | 245 | 78175 | 53235 | 38305 |
| big chip cap or res, typ 2512 | 1250 | 258 | 322 | 102861 | 70046 | 50402 |
| big ceramic QFP 25 mil pitch | 1350 | 278 | 348 | 111090 | 75650 | 54434 |
| CCoIGA 1.6", IBM cols | 1500 | 309 | 386 | 123433 | 84056 | 60482 |
| CCoIGA 1.6", NTK cols | 1600 | 330 | 412 | 131662 | 89659 | 64514 |
| little chip cap or res (typ 1206) | 2300 | 474 | 592 | 189265 | 128885 | 92739 |
| CCoIGA 1.6", Ray cols | 2700 | 556 | 695 | 222180 | 151300 | 108868 |
| small ceramic FP 28 I/O | 3400 | 700 | 876 | 279783 | 190526 | 137093 |
| big Plastic QFP | 4800 | 989 | 1236 | 394987 | 268978 | 193542 |
| mBGA 3/4" diag* | 5000 | 1030 | 1288 | 411445 | 280185 | 201607 |
| tiny chip res (typ 0201) | 6000 | 1236 | 1545 | 493734 | 336222 | 241928 |

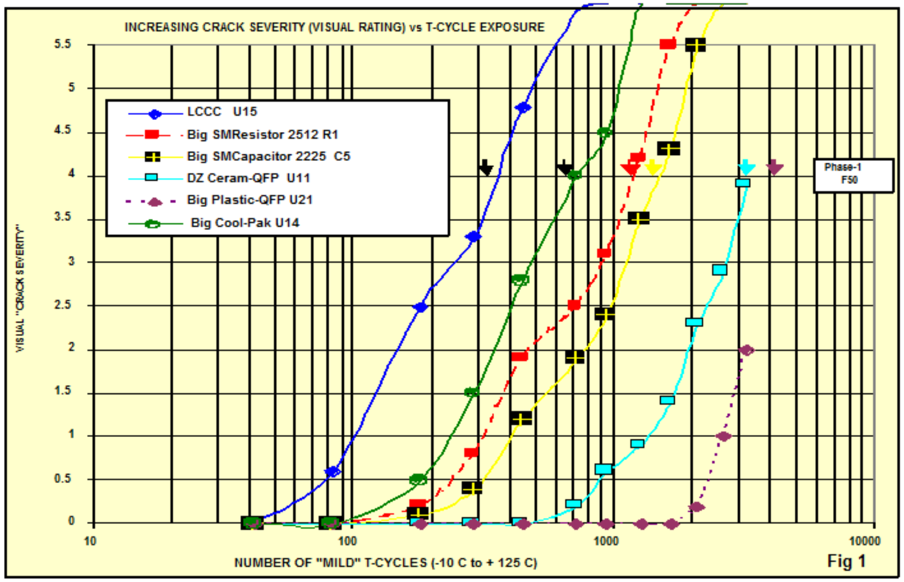
This chart shows which common SMT components are likely to survive a typical LEO mission

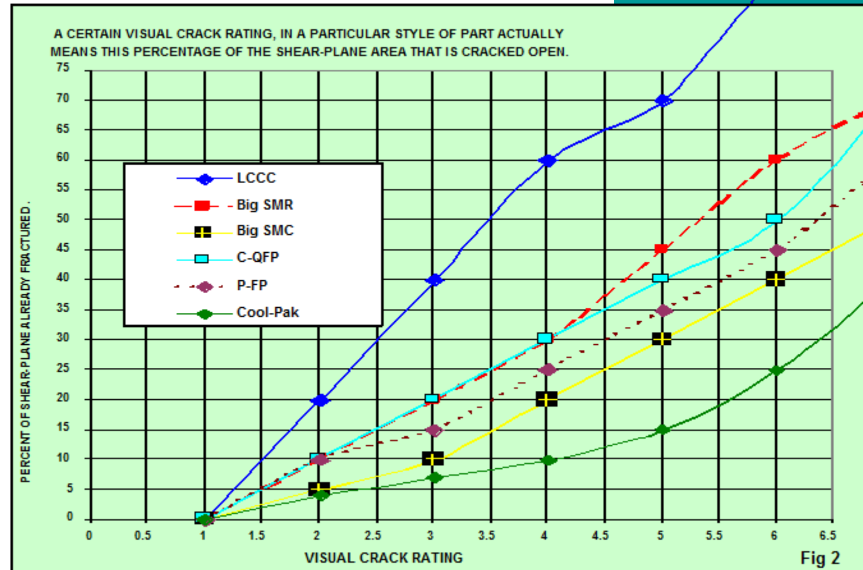
Cartoons, suggesting some of the hardware details necessary, when creating and using a predictor model. .

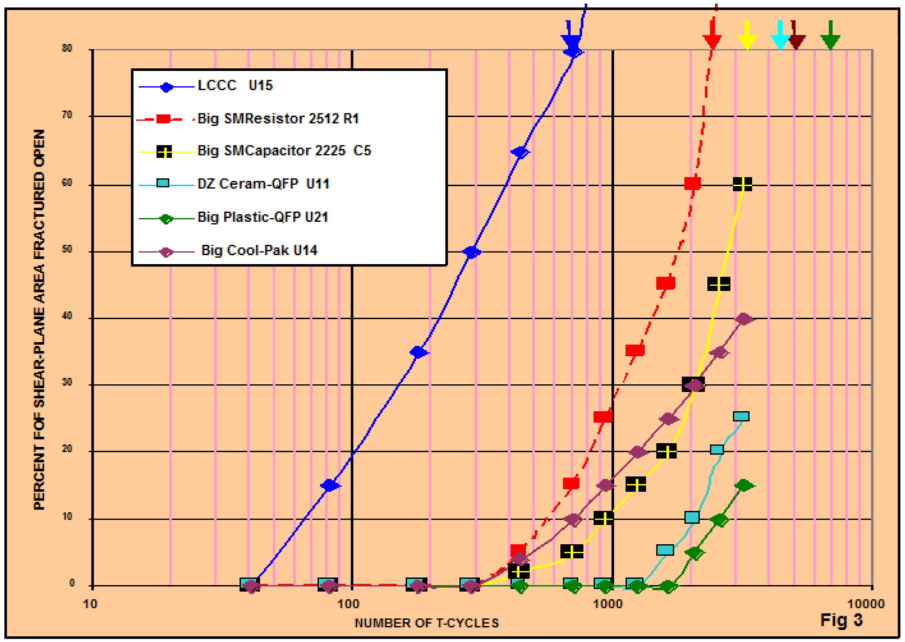


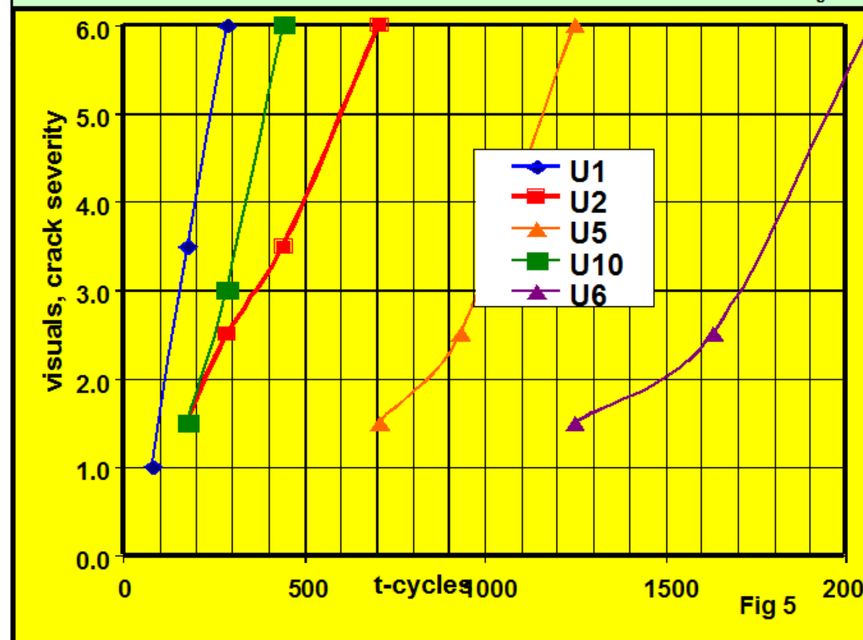



# APPENDIX C


INCREASING CRACK SEVERITY (VISUAL RATING) vs T-CYCLE EXPOSURE
VISUAL "CRACK SEVERITY"
NUMBER OF "MILD" T-CYCLES (-10 C to + 125 C)
LCCC U15
Big SMResistor 2512 R1
Big SMCapacitor 2225 C5
DZ Ceram-QFP U11
Big Plastic-QFP U21
Big Cool-Pak U14
Phase-1
F50
Fig 1


A CERTAIN VISUAL CRACK RATING, IN A PARTICULAR STYLE OF PART ACTUALLY
MEANS THIS PERCENTAGE OF THE SHEAR-PLANE AREA THAT IS CRACKED OPEN.
PERCENT OF SHEAR-PLANE ALREADY FRACTURED.
VISUAL CRACK RATING
LCCC
Big SMR
Big SMC
C-QFP
P-FP
Cool-Pak
Fig 2


PERCENT FOF SHEAR-PLANE AREA FRACTURED OPEN
NUMBER OF T-CYCLES
LCCC U15
Big SMResistor 2512 R1
Big SMCapacitor 2225 C5
DZ Ceram-QFP U11
Big Plastic-QFP U21
Big Cool-Pak U14
Fig 3


visuals, crack severity
t-cycles
U1
U2
U5
U10
U6
Fig 5