ECSS-Q-ST-70 Materials and Processes

Adrian J Graham

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Contents

ECSS-Q-ST-70C

INTRODUCTION

Adrian J Graham MSc DIC BEng CEng MIMMM

Year	Organisation	Role	Industries
1984	Queen Mary College, London	BEng Material Science and Engineering	
1988	BNF Technology Centre	Metallurgist: Mechanical and Corrosion testing, Failure Analysis	Metals, Building, Aerospace, Defence
1992	ERA Technology	Metallurgist: Failure Analysis, Corrosion testing, Consultancy	Power generation, Petrochemical, Building, Aerospace
1994	Institute of Materials	Professional Member (MIMMM), Chartered Engineer (CEng)	
1996	AEA Technology	Metallurgist: Corrosion, Consultancy	Nuclear, Power generation, Defence, Petrochemical, Building, Aerospace
1998	Imperial College, London	MSc Corrosion Science and Engineering	
2000	Nortel Networks	Project Manager	Telecommunications
2001	ERA Technology	Metallurgist: Failure Analysis, Corrosion testing, Consultancy	Power generation, Petrochemical, Building, Aerospace
2003	ESA	Metallurgist	Aerospace

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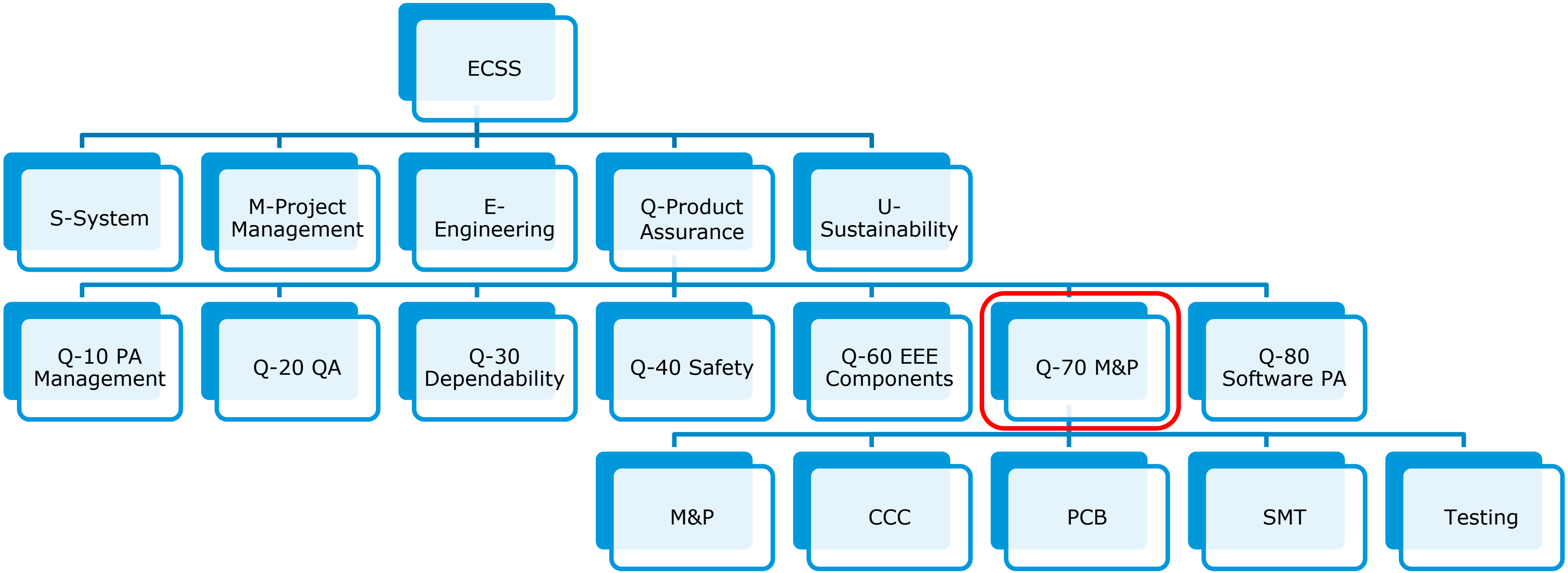
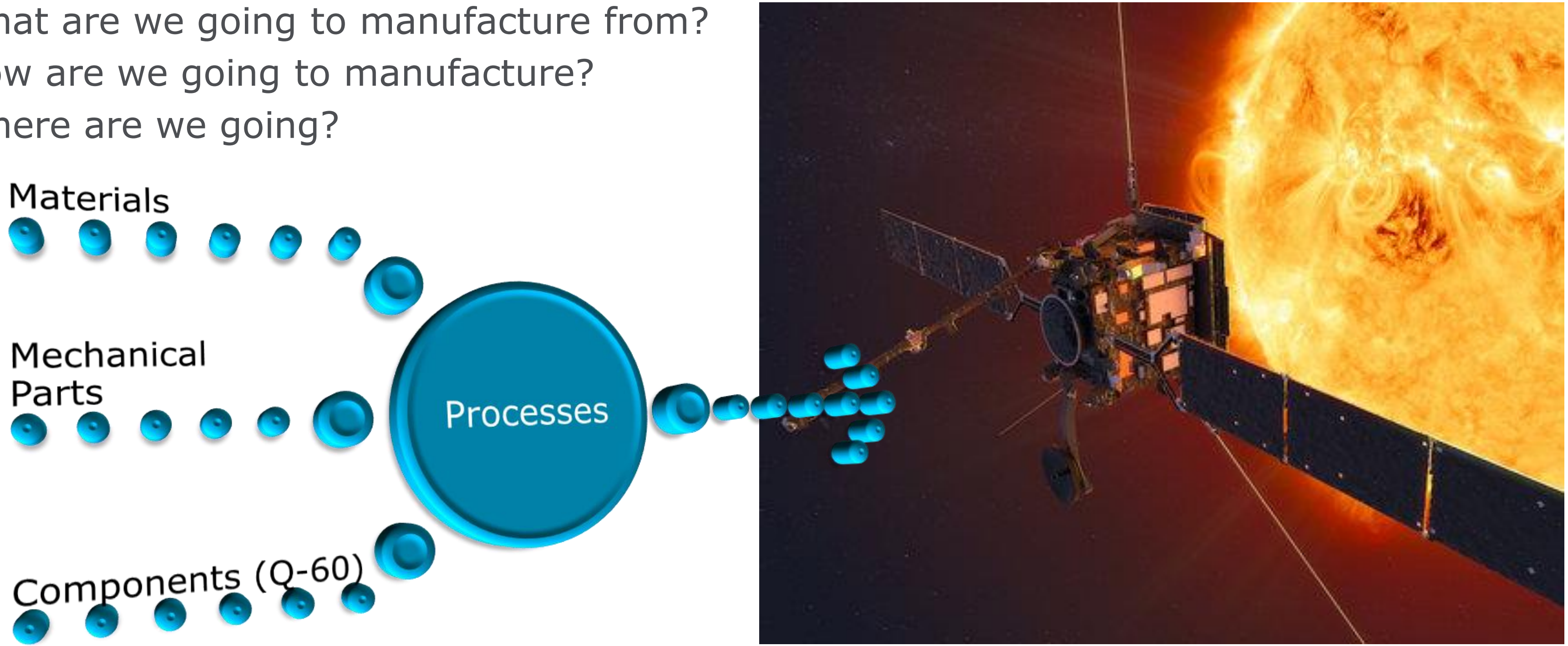
ECSS


ECSS
S-System
M-Project Management
E-Engineering
Q-Product Assurance
U-Sustainability
Q-10 PA Management
Q-20 QA
Q-30 Dependability
Q-40 Safety
Q-60 EEE Components
Q-70 M&P
Q-80 Software PA
M&P
CCC
PCB
SMT
Testing

ECSS-Q-ST-70C Rev.2 Materials and Processes

- What are we going to manufacture from?
- How are we going to manufacture?
- Where are we going?



Materials and Processes

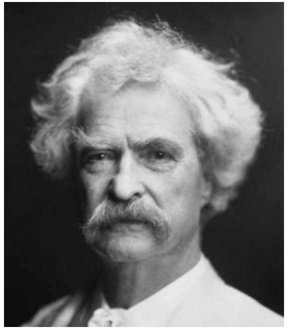
"M&P shall provide confidence that the materials, mechanical parts and processes used to assemble a spacecraft shall be fit for purpose over the life of the mission."

ECSS-Q-ST-70C Rev. 2 *Materials, mechanical parts and processes* and associated third tier standards govern M&P for European spacecraft.

For ESA programmes the PA manager is responsible for M&P

Confidence is the feeling you have before you fully understand the situation

Mark Twain



ECSS-Q-ST-70

- ***Prime is responsible for M&P***
    - Customer reviews and approves
- ECSS-Q-70-71C Data for selection of space materials and processes
    - Provides requirements for M&P
    - Preferred materials have been moved:
    - http://esmat.esa.int/Services/Preferred_Lists/preferred_lists.html
    - Preferred materials have extensive space heritage
    - **Space heritage with one manufacturer does not mean another will not have problems**

European Co-operation for Space Standardisation

ECSS-Q-ST-70-01C	Cleanliness and contamination control
ECSS-Q-ST-70-02C	Thermal vacuum outgassing test for the screening of space materials
ECSS-Q-ST-70-03C	Black-anodising of metals with inorganic dyes
ECSS-Q-ST-70-04C	Thermal Cycling test for the Screening of space materials and processes
ECSS-Q-ST-70-05C Rev.1	Detection of organic contamination of surfaces by IR spectroscopy
ECSS-Q-ST-70-06C	Particle and UV radiation testing for space materials
ECSS-Q-ST-70-07C	Verification and approval of automatic machine wave soldering
ECSS-Q-ST-70-08C	The manual soldering of high reliability electrical connections
ECSS-Q-ST-70-09C	Measurement of thermo-optical properties of thermal control materials
ECSS-Q-ST-70-12C	Design rules for printed circuit boards
ECSS-Q-ST-70-13C Rev.1	Measurement of the peel and pull-off strength of coatings and finishes using pressure-sensitive tapes
ECSS-Q-ST-70-14C	Corrosion
ECSS-Q-ST-70-15C	Non-destructive testing
ECSS-Q-ST-70-17C	Adhesive bonding for spacecraft and launcher applications

ECSS Page 2

ECSS-Q-ST-70-18C	Preparation, assembly and mounting of RF coaxial cables
ECSS-Q-ST-70-20C	Determination of the susceptibility of silver-plated copper wire and cable to plague corrosion
ECSS-Q-ST-70-21C	Flammability testing for the screening of space materials
ECSS-Q-ST-70-22C	The control of limited shelf-life materials
ECSS-Q-ST-70-26C Rev.1Corr.1	Crimping of high-reliability electrical connections
ECSS-Q-ST-70-28C	Repair and modification of PCB assemblies
ECSS-Q-ST-70-29C	Determination of offgassing products from materials and assembled articles to be used in a manned space vehicle crew compartment
ECSS-Q-ST-70-30C	Wire-wrapping of high reliability electrical connections
ECSS-Q-ST-70-31C Rev.1	Application of paints on space hardware
ECSS-Q-ST-70-36C	Materials selection for controlling stress corrosion
ECSS-Q-ST-70-37C	Test method for stress corrosion cracking
ECSS-Q-ST-70-38C Rev.1 Corr.1	High-reliability soldering for surface mount and mixed technology
ECSS-Q-ST-70-39C	Welding of metallic materials for flight hardware

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ECSS-Q-ST-70-40C	Processing and quality assurance requirements for brazing of flight hardware
ECSS-Q-ST-70-45C	Mechanical testing of metallic materials
ECSS-Q-ST-70-46C Rev.1	Requirements for manufacturing and procurement of threaded fasteners
ECSS-Q-ST-70-50C	Particle contamination monitoring for spacecraft systems and cleanrooms
ECSS-Q-ST-70-53C	Materials and hardware compatibility tests for sterilization processes
ECSS-Q-ST-70-54C	Ultracleaning of flight hardware
ECSS-Q-ST-70-55C	Microbial examination of flight hardware and cleanrooms
ECSS-Q-ST-70-56C	Vapour phase hydrogen peroxide bioburden reduction for flight hardware
ECSS-Q-ST-70-57C	Dry heat bioburden reduction for flight hardware
ECSS-Q-ST-70-58C	Bioburden control of cleanrooms
ECSS-Q-ST-70-71C Rev.1	Materials, processes and their data selection
Two additional technical memoranda:	
ECSS-Q-TM-70-51A	Termination of optical fibres
ECSS-Q-TM-70-52A	Kinetic outgassing of materials for space

Terms specific to the present standard

- Critical material:
  - material that is new to an individual company or non-validated for the particular application and environment, or that has caused problems during previous use that remain unresolved

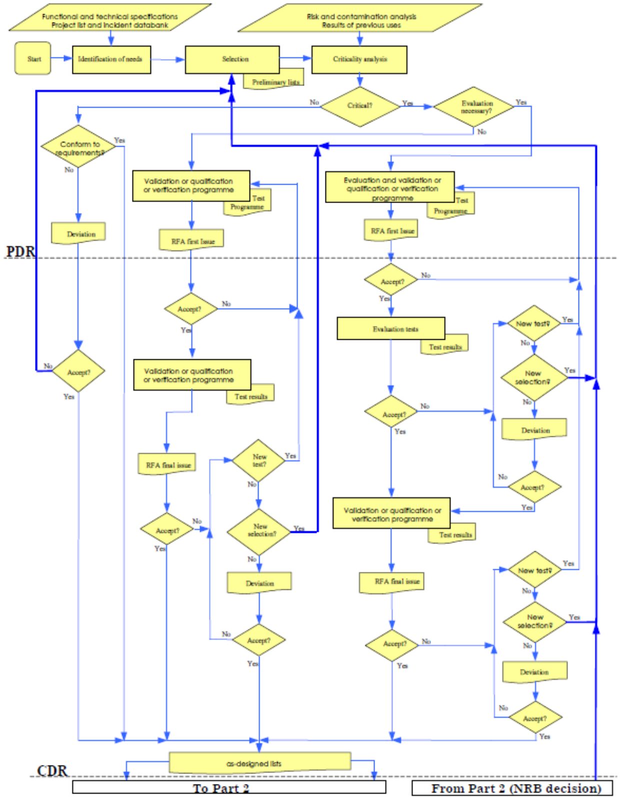
- Critical mechanical part:
  - mechanical part that requires specific attention or control due to fracture mechanics aspects and limited-life aspects, or with which the supplier has no previous experience of using the mechanical part in the specific application and environment or that are new or non-qualified, or that has caused problems during previous use that remain unresolved

Terms specific to ECSS-Q-ST-70

- Process:
    - set of inter-related resources and activities which transforms a material or semi-finished product into a semi-finished product or final product
- Critical Process:
    - process new to an individual company or non-verified for the application in question or has caused problems during previous use that remain unresolved
- Special Process:
    - process where quality cannot be completely ensured by visual inspection of the end article only

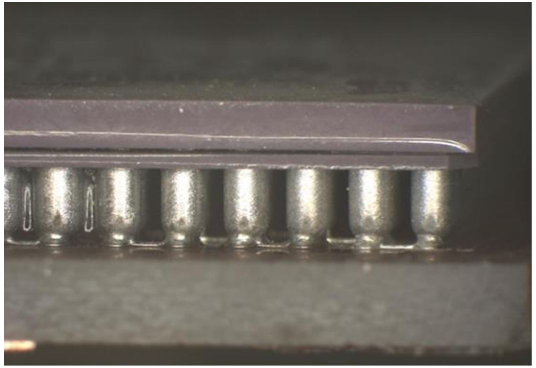
MMPP Management requirements

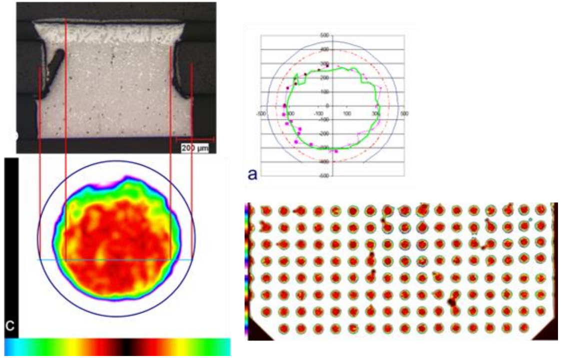
- Assign MMPP Manager
  - Ensure MMPP meet ground and flight requirements
  - Obtain validation, qualification and verification status
  - Organise MPCBs
- Prepare a plan
  - Risks, Verification, RfA/W/D
  - Should be ready for PDR
- Execute the plan
  - Ready for CDR



Review

- Does the system we built meet the:
  - requirements
  - standards
  - good engineering practice
- Did we build the right system?
- Design Reviews
  - PDR, CDR, etc
- MPCB:
  - Materials and Process Control Board





Timetable for M&P

Review	
SRR	Definition of mission requirements Tailoring of ECSS requirements Identification of key technologies/equipment
PDR	Planning of MPCB process Identification of RfD/W/As as required
CDR	Completion of MPCB review 90%-95% of line items approved Clear path to approval for outstanding items
QR	Conformation previous reviews & MPCBs closed All ongoing qualifications closed
FAR	Final check, generally little M&P involvement

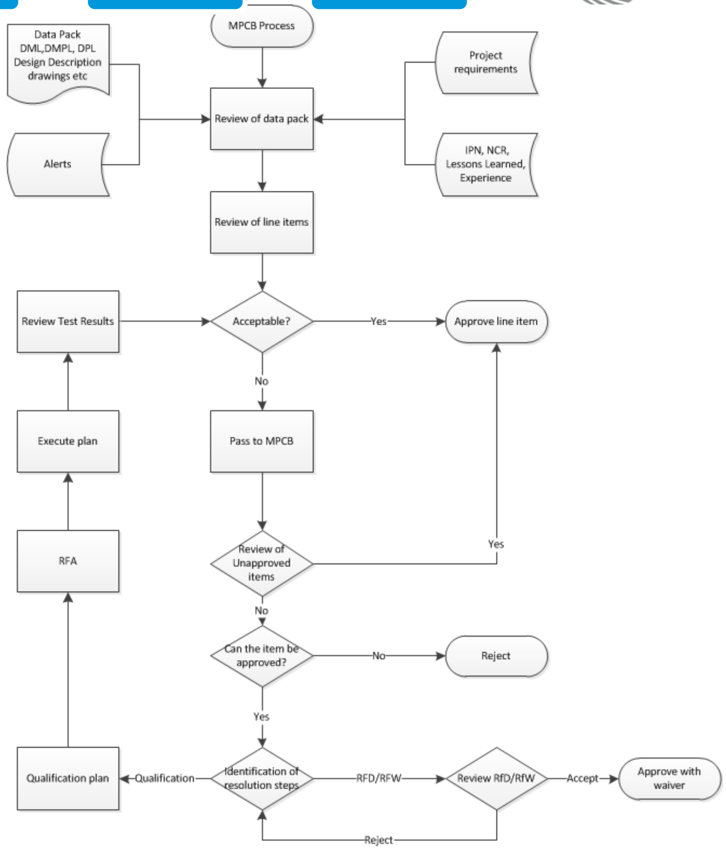
- SRR
  - System Requirements Review
  - Definition of mission requirements
  - Tailoring of ECSS requirements
  - Identification of key technologies/equipment
- EQSR
  - Equipment Qualification Status Review
  - Critical review of Equipment Status
    - Do we need any additional qualification?
    - *Rebuild with new components is not Cat. A*
  - Identification of Equipment and Subsystems requiring attention

Category	Description	Qualification programme
A	Off-the-shelf product without modifications and • subjected to a qualification test programme at least as severe as that imposed by the actual project specifications including environment and • produced by the same manufacturer or supplier and using the same tools and manufacturing processes and procedures	None
B	Off-the-shelf product without modifications. However: It has been subjected to a qualification test programme less severe or different to that imposed by the actual project specifications (including environment).	Delta qualification programme, decided on a case by case basis.
C	Off-the-shelf product with modifications. Modification includes changes to design, parts, materials, tools, processes, procedures, supplier, or manufacturer.	Delta or full qualification programme (including testing), decided on a case by case basis depending on the impact of the modification.
D	Newly designed and developed product.	Full qualification programme.

- Preliminary Design Review
- M&P Planning
  - Identification of where M&P effort should be concentrated
    - Risks in Subsystems and Equipment
    - SMT/PCB Qualification
    - New processes
    - New Technologies
    - COTS Issues
  - Identification of CAT. A items
    - **NB Not uncommon for units identified as Cat. A at EQSR to be reclassified once the complete dataset is available**
      - ***Nothing has changed, we've only improved it***
      - ***Component changes often result in issues***
  - Avoid surprises at CDR or MRR

- Material Process Control Board
- Customer Side
  - Establish review parameters with PA
  - Identify recurrent and new items (Cat. A or D)
  - Agree with PA the subsystems/equipment with technical risks
  - Decide which units to follow at MPCB and which to leave to industry
    - Decisions subject to review/change
  - Item by item review
    - Aim to identify key issues, clear out easily approved items
    - Major concern of time spent housekeeping rather than technical review
      - Looking at automation rules for easily approvable items
        - May implement a 'Pre-screening' button in DMPL Tool
        - Long term want to use machine learning to improve quality of pre-screening

- Provides independent review of manufacturing process
  - Coordination of RfAs
  - Review and Approve test programmes
  - Review and approve lists
  - Identify and mitigate obsolescence
- Collaborative process
- Identifies issues
- Attempts resolution
- Escalate if required



MPCB Objectives

- Ensure the materials, mechanical parts and processes used to manufacture the system :
  - will be **fit for purpose** over the life of the mission;
  - will not block the MRR;
  - mitigate the risk of foreseeable NCRs occurring during MAIT and flight.
- Carried out on a **best effort** basis.

NB1: **Fit for purpose** is good enough to do the job it was designed to do.

NB2: **Best effort** basis means that the best efforts will be made to complete a review but does not guarantee success of the review or that all discrepancies can be identified

MPCB Preparation of the lists

- Responsibility of designated M&P Engineer
    - Does not mean they must personally complete the lists
- 4.2.2 Management of the lists
    - *The MMP lists shall be provided in a form that is exchangeable, searchable and sort-able, and suitable for storage and retrieval in accordance with business agreement.*
    - *Each customer shall process the lists from his suppliers as necessary to achieve the objectives of exchangeability, searchability, sortability, storability and retrivability for that set of lists before releasing it for use by the higher-level customer.*

MPCB Input

- At least 10 days prior to an MPCB the Prime shall supply, as a minimum, a data pack containing:
    - Design description;
    - Electronic assembly compliance matrix and documents identified in the ESA Memo ESA-TECMSP-MO-1931
    - Declared material list, DML;
    - Declared mechanical parts, DMPL, list if applicable;
    - Declared process list, DPL;
    - Unsigned RfAs, RfDs, RfWs or NCRs relied upon for approval of any specific line items.

MPCB Review Strategy

- Consider:
    - Experience of the manufacturer with this type of system;
    - Heritage of the system
        - Don’t forget modifications or improvements made that deviate from the known heritage;
    - Qualifications or RFAs, RFDs, RFWs and NCRs relied upon for acceptance of the system;
    - Past experience and good engineering practice;
    - Risk level accepted by the programme;
    - Consequences of system failure to the objectives of the mission and other hazards.
- **NB Status of these considerations change over the project so need regular review**

MPCB Review

A	Approved	All materials classified "A" may be used without restriction
X	Approved with a RFA	Materials shall be subjected to an evaluation or validation programme. *NB Shall become A once qualification complete*
W	Approved with a waiver	Materials do not meet the requirements but are used for functional reasons. *NB Reference to waiver (RfW RfD) shall be provided in Justification*
Y	Approved with restriction	Materials do not meet the requirements but may be used in the specified project(s). *Use in the specified project(s)* ***shall not*** *provide justification for use in another project.* *Not a formal designation but has some project use*
P	Pending decision	Materials for which an evaluation report or a waiver is waiting for the contractor's provisional or definitive approval.
O	Open	New materials or materials for which investigations and validations are in progress
R	Rejected	
D	Deleted	Material is no longer used.

MPCB Review Tools

- DMPL Tool
  - Organisation and consolidation (https://dmpl-web.esa.int/)
- ECSS Doors database
  - Up to date list of ESA requirements (https://ecss.nl/standards/downloads/doors-download/)
- Materials databases
  - ESMDB, does not exist yet
  - ESMAT preferred materials (http://esmat.esa.int/Services/Preferred_Lists/preferred_lists.html)
  - MATREX CNES Materials database (https://matrex.cnes.fr/)
  - MAPTIS US data set (https://maptis.nasa.gov/)
  - MODESA Outgassing data (https://modesa.esa.int/)

esa

- Critical Design Review
- Answer the questions:
  - *Is this a sensible way to build the equipment ?*
  - *Are we ready to build the equipment?*
    - Really an MRR question
- Not:
  - *Is this the best way to build the equipment?*
  - *Is this how I would build the equipment?*
- Expect 90%-95% of line items to be approved by CDR
- Clear path visible for approval of outstanding items

SRR → EQSR → PDR → MPCB → CDR → **MRR** → **QR**

- Manufacturing Readiness Review
  - *Are we ready to build the equipment?*

- Qualification Review
  - Conformation previous reviews & MPCBs closed
  - NCRs closed acceptably
  - All ongoing qualifications closed
  - Should not be a line by line list review

ECSS-Q-ST-70C

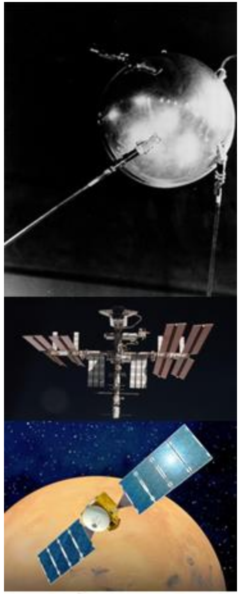
TAILORING

Requirements

Reference to groups of ECSS standards	Absolute number of line items in DOORS	Relative to all ECSS	Relative to ECSS-Q	Relative to ECSS-Q-ST-70
ECSS	27500	100%	-	-
ECSS-Q	9908	36%	100%	-
ECSS-Q-ST-70	6053	22%	61%	100%
PCB	1274	5%	13%	21%
SMT	1197	4%	12%	20%
M&P (General)	3582	13%	36%	59%

Tailoring

- ECSS-Q-ST-70 has 6000+ requirements for Materials, Mechanical Parts and Processes (MMPP).
- Actual requirements for a particular project depend on several factors, e.g.
    - Type of spacecraft (manned or unmanned)
    - Spacecraft orbit (LEO, GEO, polar, etc)
    - Complexity (satellite, payload, etc.)
    - Duration of space exposure (x years, y days, etc.)
- The requirements will therefore be specified as part of the contract either in the statement of work or in the PA plan



Tailoring

Screening	Utilisation				
	Satellites and Probes on expendable launcher		Manned Spacecraft		Ground Packaging
	Not Pressurised	Pressurised	Not Pressurised	Pressurised	
Thermal Vacuum	X	O	X	O	O
Flammability			X	X	
Offgassing and Toxicity				X	
Stress Corrosion	X*	X*	X*	X*	O
Atomic Oxygen	X(LEO)		X(LEO)		
Resistance to Microbial Growth				X	

X = mandatory, O = optional, * = for structure only, LEO = Low Earth Orbit

Tailoring of Requirements

5.1.11 Fluid compatibility

a) Materials within the system exposed to liquid oxygen (LOX), gaseous oxygen (GOX) or other reactive fluids, both directly and as a result of single point failures when failure propagation effects cause hazardous operation of interfacing hardware shall be compatible with that fluid in their application.

b) The possibility of hydrogen embrittlement occurring during component manufacture or use shall be assessed, and an material evaluation be undertaken, including the assessment of adequate protection and control.

5.1.12 Galvanic compatibility

a) When bimetallic contacts are used, the choice of the pair of metallic materials used shall be agreed with the customer.
   a) NOTE This also includes metal-to-conductive fibre-reinforced materials contacts.

b) Galvanic compatibilities shall be selected in conformance with Table 5-1.

c) Materials not listed in Table 5-1 shall be evaluated in a flight-simulated configuration using an accelerated environment to be agreed by the customer.

5.1.11a	Applicable		
5.1.11b	Applicable	The possibility of hydrogen embrittlement occurring during component manufacture or use shall be assessed, and a material evaluation be undertaken, including the assessment of adequate protection and control.	KEY
5.1.11c	New	On steels harder than RC 33, plating shall be applied by a process that is not embrittling to the steel.	KEY
5.1.12a	Applicable		
5.1.12b	Modified	Bimetallic contacts (and metal to conductive-fibre-reinforced materials contacts) shall be selected in conformance with Table 5-1 of ECSS-Q-ST-70C for galvanic compatibilities and submitted to MMPP Control Board approval using the DRD ….	KEY

TRL

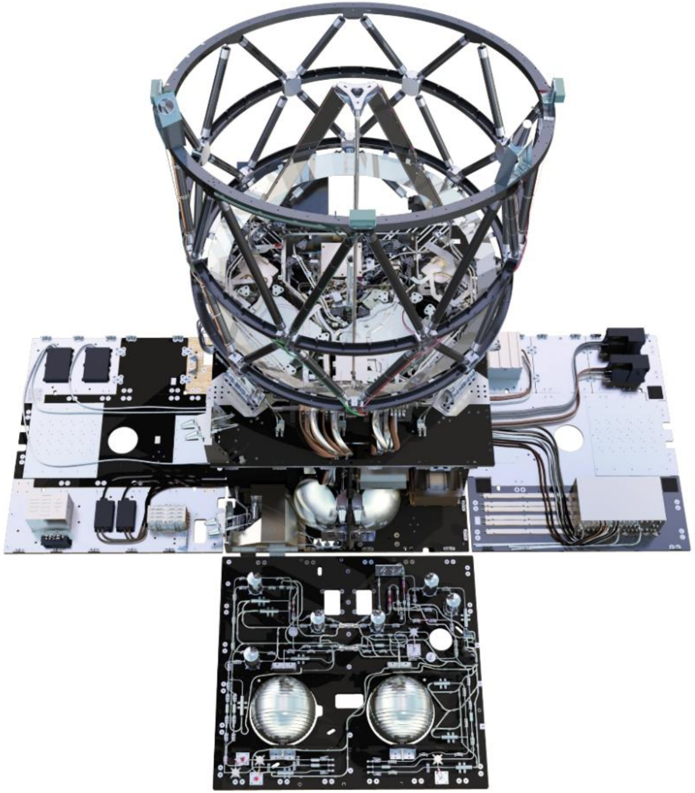
		Testing Requirements	Material&Processes Requirements
TRL 1	Basic principles observed and reported	Test configuration recorded, testing results and environment recorded in a traceable manner	N/A
TRL 2	Technology concept and/or application formulated	Test configuration recorded, testing results and environment recorded in a traceable manner	Material used to be recorded and in process samples maintained.
TRL 3	Analytical & experimental critical function and/or characteristic proof-of-concept	Test procedure defined in advance. Test configuration recorded, testing results and environment recorded in a traceable manner	Materials procured to internationally recognised standards or defined procurement specification. Incoming inspection defined. Processes recorded and traceable.
TRL 4	Component and/or breadboard validation in laboratory environment	Test configuration recorded, testing results and environment recorded in a traceable manner	Function critical materials, processes recorded and followed-up
TRL 5	Component and/or breadboard validation in relevant environment	Test configuration recorded, testing results and environment recorded in a traceable manner	Q-70/Q70-71 applicable, preliminary DMPL exists
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	TRR, TRB+above	All Q-70 applicability for critical functions, Q-70-71 for the whole system
TRL 7	System prototype demonstration in a space environment	TRR, TRB+above	Full Level 2 requirements applicable
TRL 8	Actual system completed and "Flight qualified" through test and demonstration (ground or space)	TRR, TRB+above	Full Level 2 requirements applicable
TRL 9	Actual system "Flight proven" through successful mission operations		

ECSS-Q-ST-70C

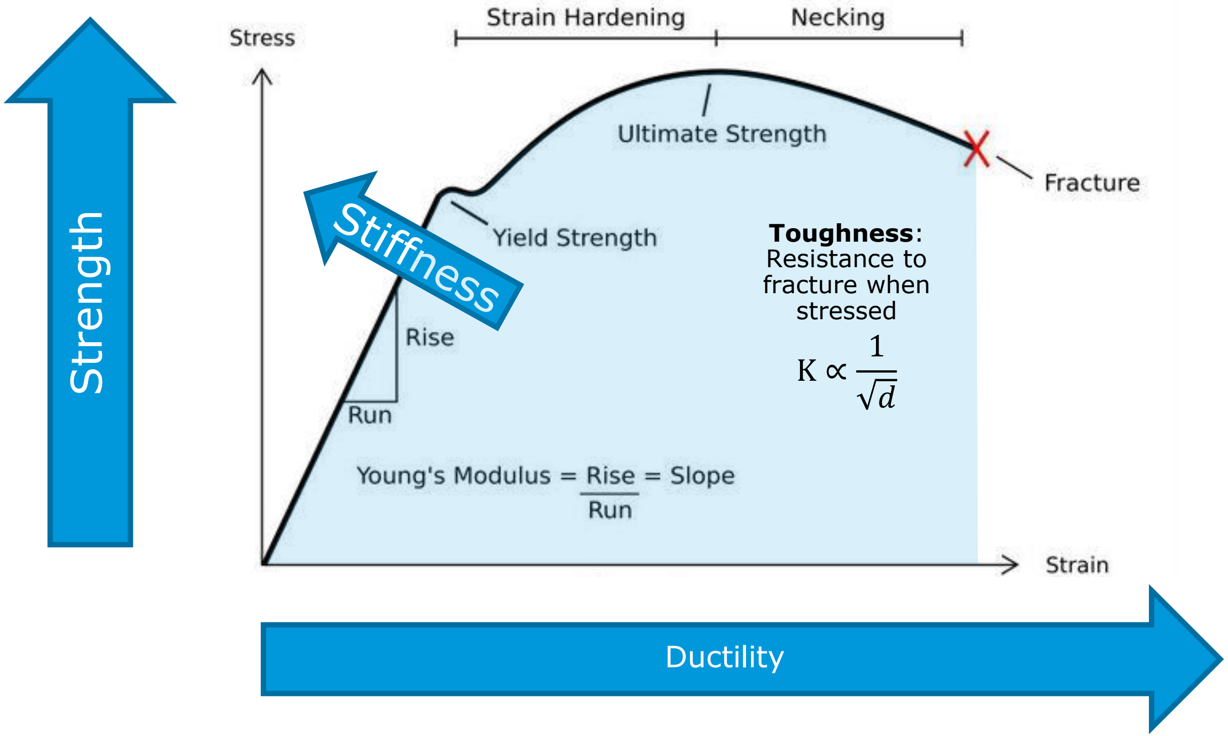
MATERIALS

Materials for Spacecraft

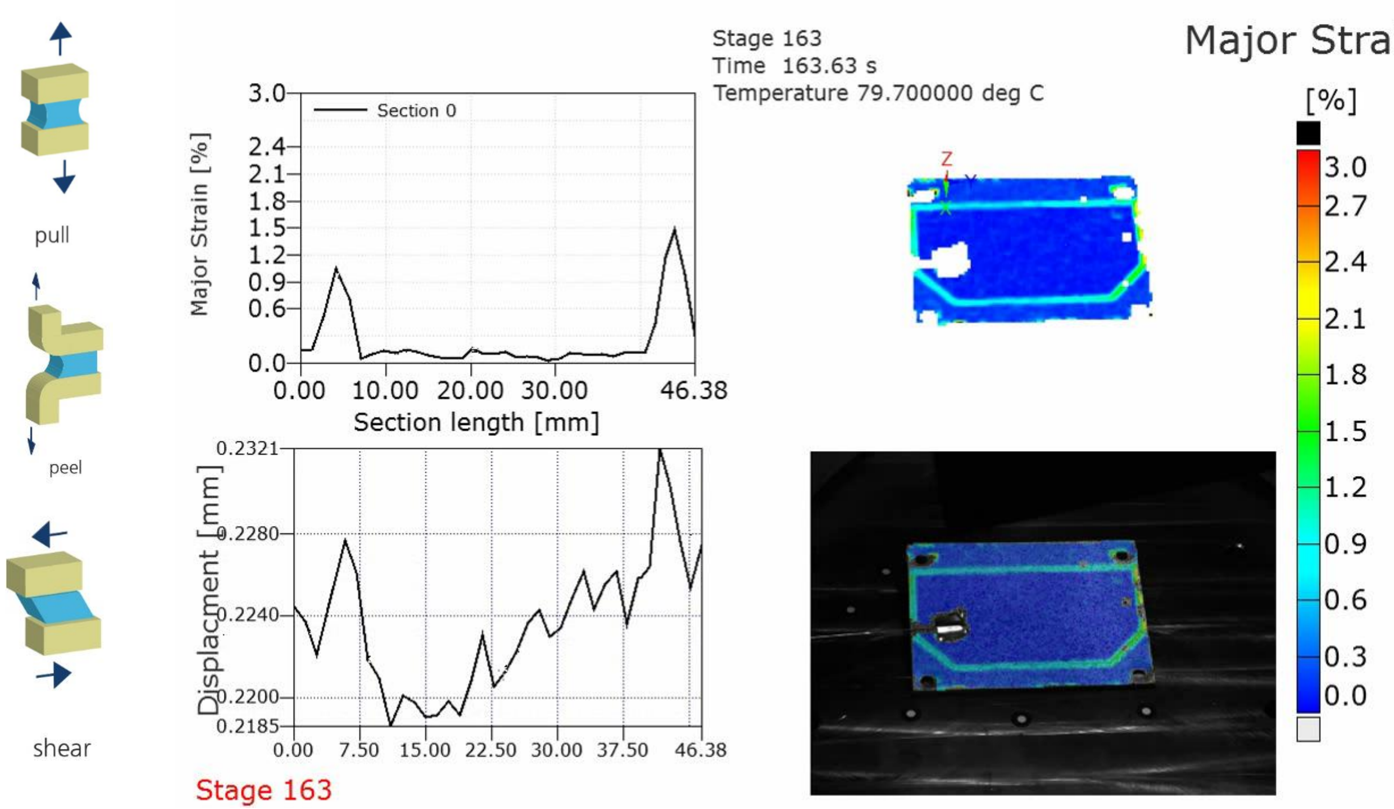
- Metals
  - Structure, cables, pipework, …
- Polymers
  - Bonding, insulation, protection, …
- Ceramics
  - Optics, mirrors, insulation, …
- Glasses
  - Optics, mirrors, windows, …
- Composites
  - Structure, antenna, …



Mechanical Properties

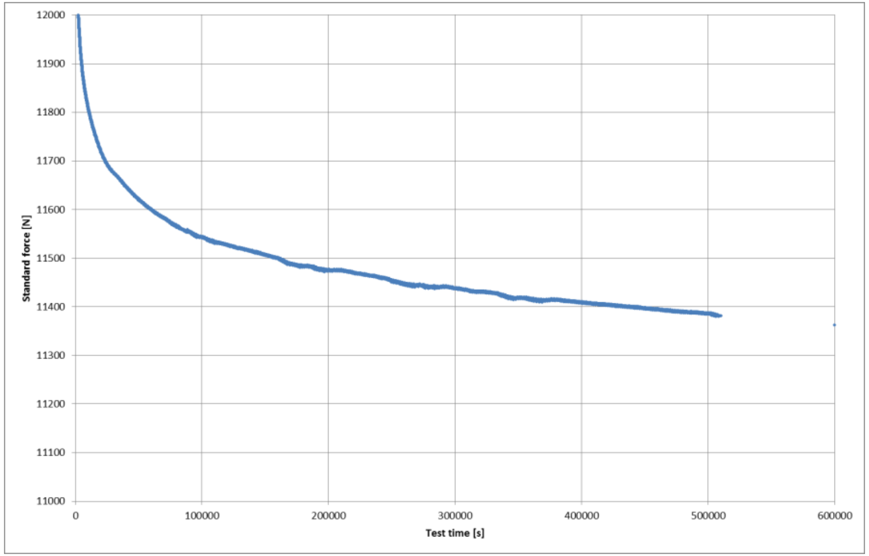


Peeling of Solar Cells



Viscoelasticity

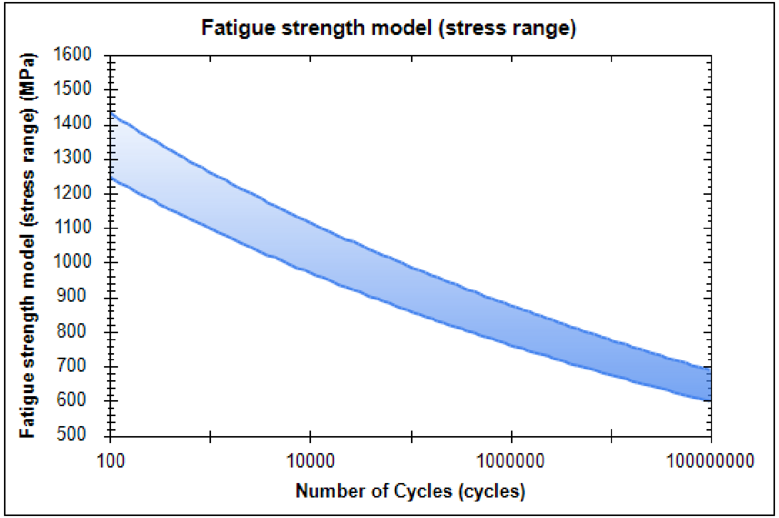
- Both Viscose and Elastic behaviour
- Very common in polymerics
- All materials show some Viscoelasticity
    - Elastic: high strain rate, low temperature
    - Viscose: low strain rate, high temperature
    - Time-Temperature Superposition
- Usually to be considered at >70%T_m/Kelvin
    - Many materials break this rule: Pure metals, stainless steels, titanium alloys
- Produces creep and stress relaxation effects as well as superplasticity



Room temperature stress relaxation of Ti6Al4V

Fatigue

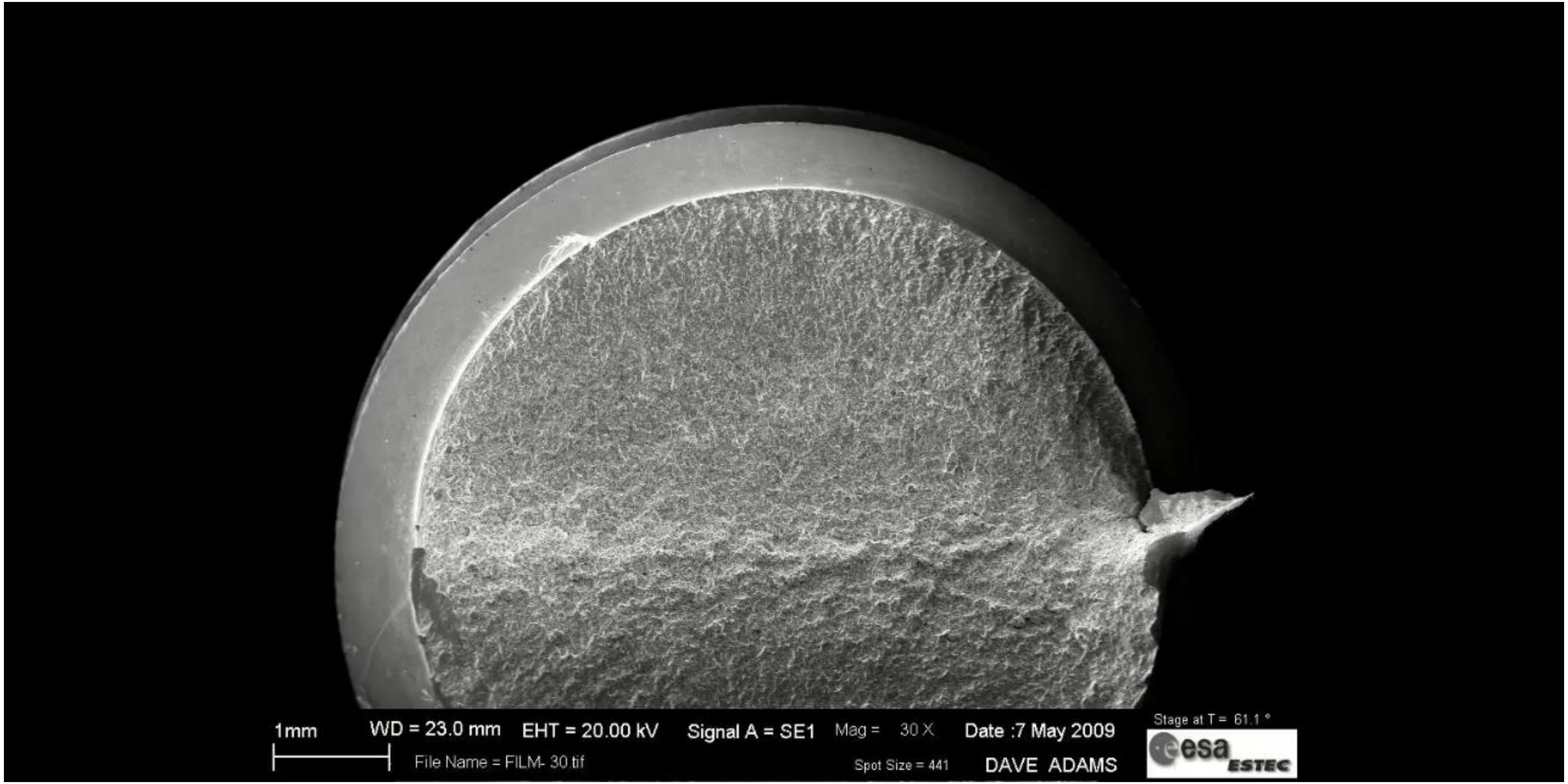
- Weakening of a material caused by cyclic loading that results in progressive and localized structural damage
- High-Cycle Fatigue
  - Loading in the elastic region
  - Many cycles to failure
  - Wöhler curve
- Low-Cycle Fatigue
  - Loading into plastic region
  - Coffin-Manson (Norris-Landzberg) models *damage capacity*



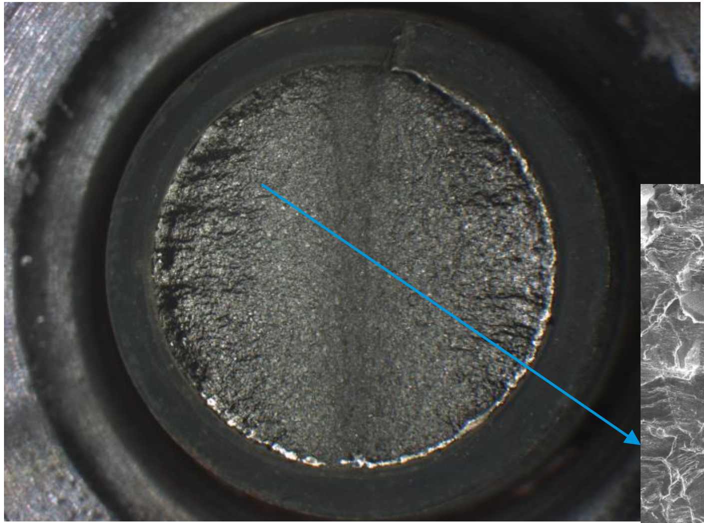
Fatigue strength of Custom 465 H1000

$$AF = \frac{N_{Life}}{N_{Test}} = \left(\frac{Freq_{Life}}{Freq_{Test}}\right)^{-m} \left(\frac{\Delta T_{Life}}{\Delta T_{Test}}\right)^{-n} \left(e^{\frac{E_a}{k}\left(\frac{1}{T_{Max,Life}} - \frac{1}{T_{Max,Test}}\right)}\right)$$

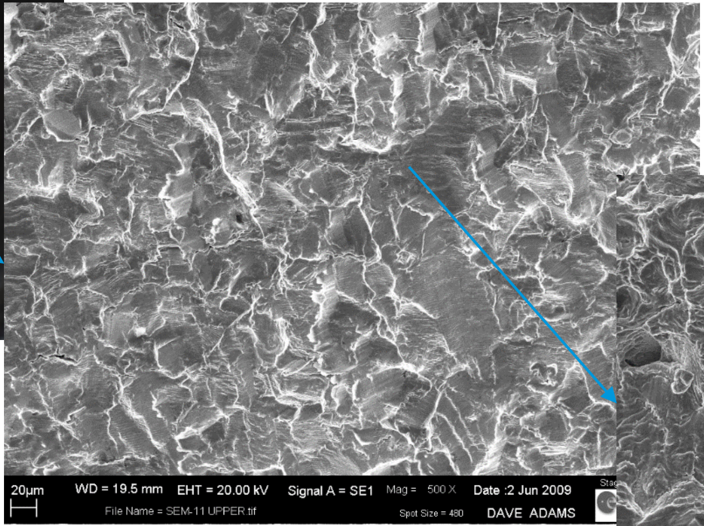
Fatigue


1mm
WD = 23.0 mm
EHT = 20.00 kV
Signal A = SE1
Mag = 30 X
Date :7 May 2009
Stage at T = 61.1 °
File Name = FILM- 30 tif
Spot Size = 441
DAVE ADAMS
esa ESTEC

Fatigue of Screws

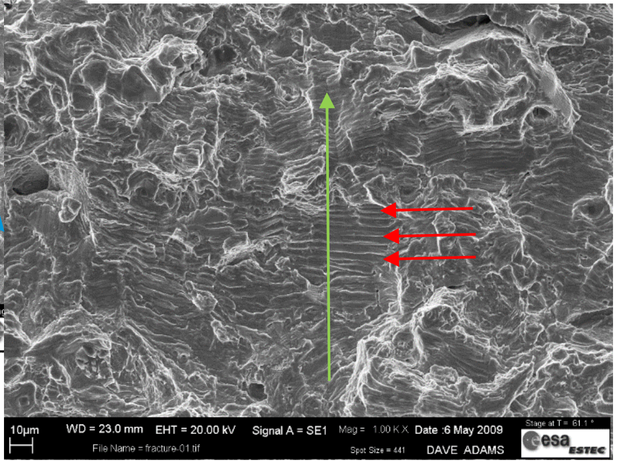


10x



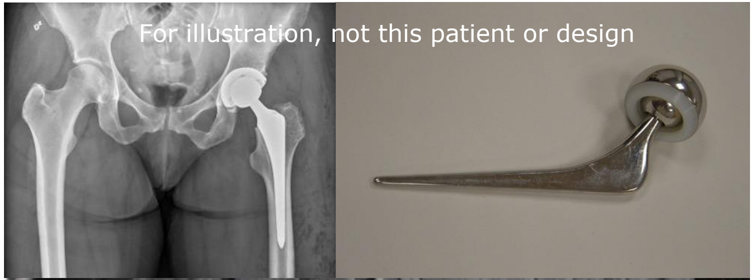
500x

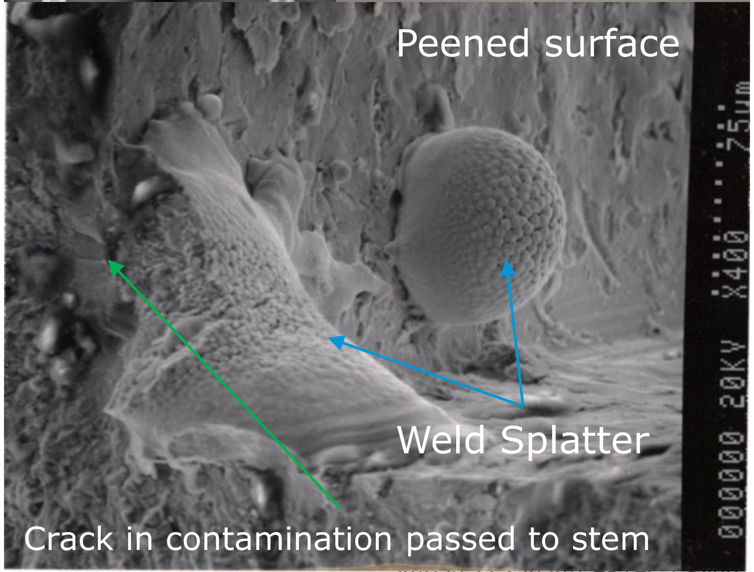
1000x



Fatigue Crack Initiation

- Fatigue failure has two phases, initiation and propagation
    - About half time to failure initiation, half propagation
        - Not true but a good approximation
- Titanium Hip Implant
    - Surface peened to prevent crack initiation
    - Contaminated with weld splatter during manufacture
    - Weld splatter cracked during cyclic loading
    - Crack passed from the contamination to stem of the implant
    - Failed in fatigue
- **Welding bay located next to manufacturing facility**

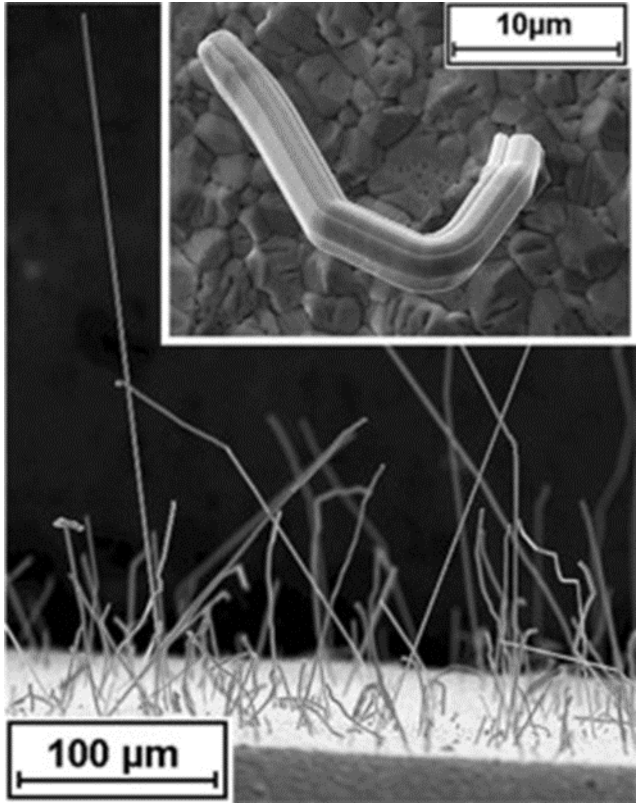




Restricted Materials

Cadmium and Zinc	Evaporate and contaminate, SME, Solid Metal Embrittlement of titanium
Pure tin	Whiskers and tin pest
Mercury	Evaporates and causes LME, Liquid Metal Embrittlement
Beryllium and beryllium oxide	Beryllium oxide toxic, carcinogenic and sensitising
PVC (Polyvinyl-chloride), cellulose, acetates, polyvinylacetate and butyrate	Breakdown in the space environment and can generate contamination such as HCl
Tape with silicone adhesive (prohibition extended also to consumables)	Silicones leave contamination that can creep over surfaces
Any material generating particles	Shedding or flaking coatings, materials producing debris used in mechanisms for the lubrication of moving parts, surface finishes producing particles as a result of cleaning).

- Also applies to GSE used in vacuum.
- Restrictions can be waived but needs to be formally requested (RfW) with Technical justification

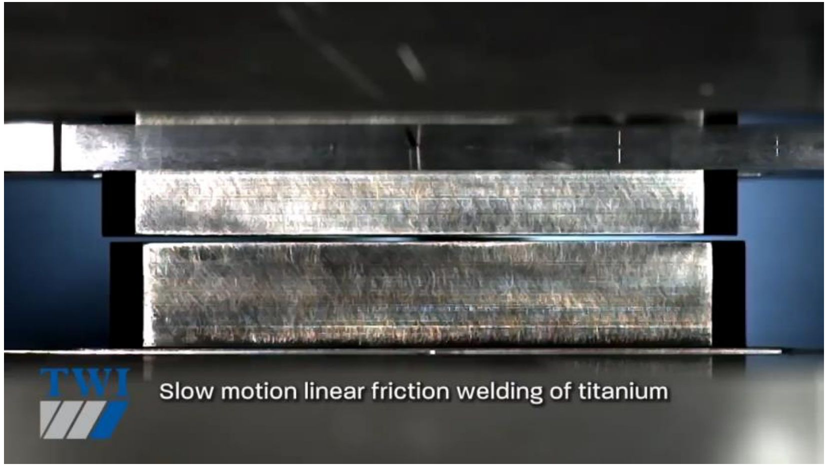


Pure Tin

- Whisker Growth
  - Compressive stress
    - Some evidence for threshold at 37MPa
  - Loss of Galaxy IV by PanAmSat
- Tin Pest
  - Metallic β white tin (tetragonal) to α grey tin (cubic) semiconductor
  - 27% Volume increase
  - Transformation below 13.2°C
    - fastest between -30°C and -40°C
  - Alloying depresses transformation temperature
- **Tin needs a minimum of 4% alloying addition**

Processes

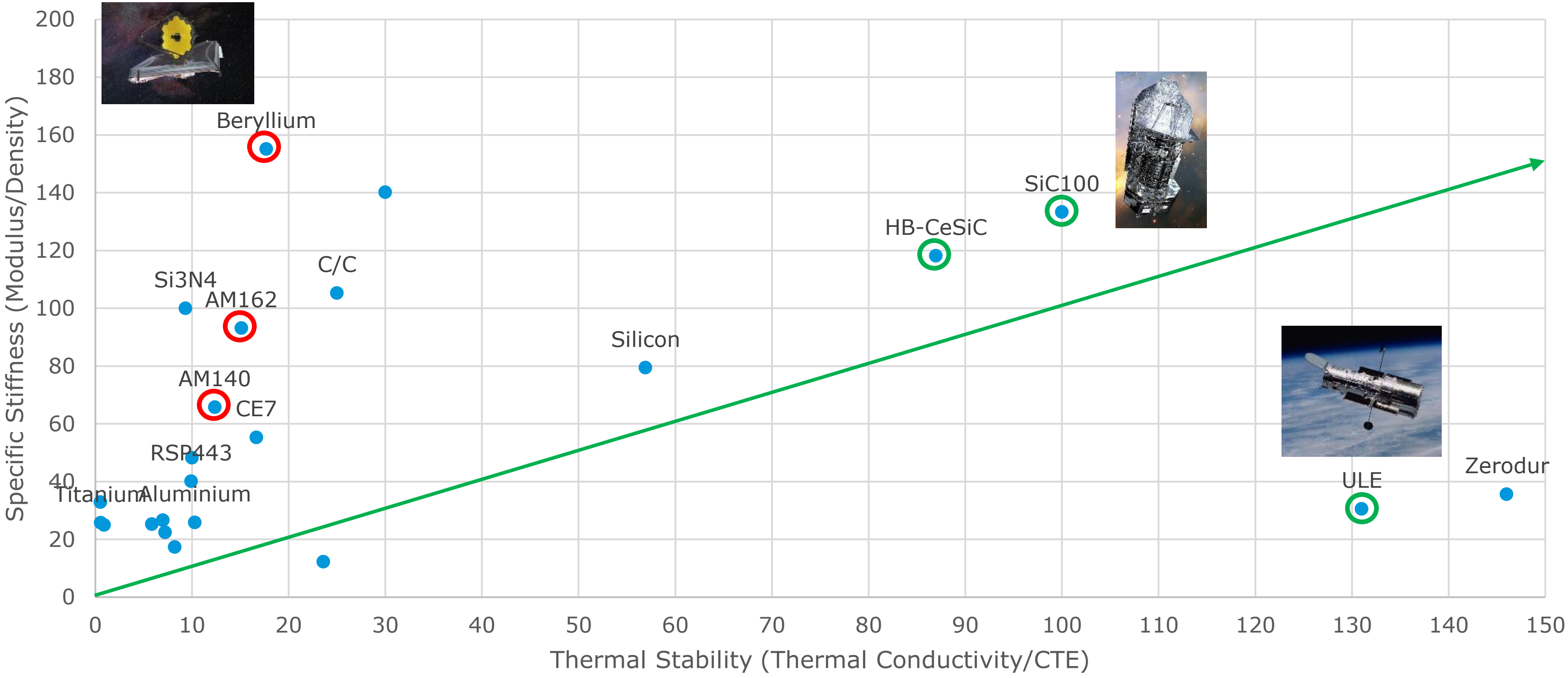
- Any combinations used to transform a material or mechanical part
  - Eg welding, machining, bake out, coating, etc.
- All processes shall be documented and traceable
- Process executors shall be trained and approved
- **If required in process specimens shall be taken and stored**



Specific Stiffness and Weight

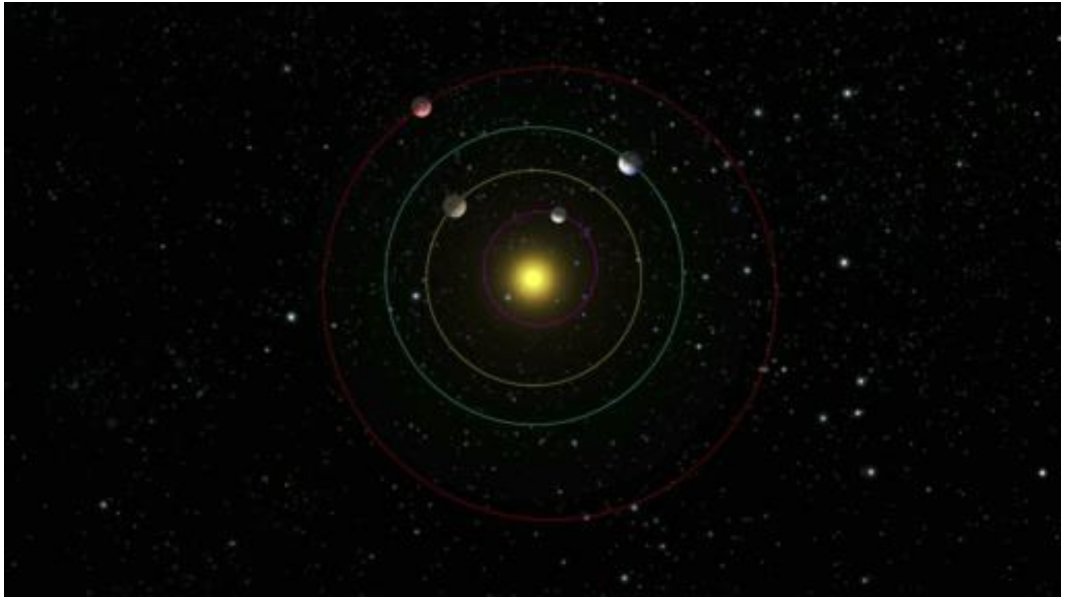
Material	Modulus	Density	Specific stiffness			2 dimensions free			1 dimension free		
	GPa	kg/m³	1000 m²s⁻²		Rank	1E+06		Rank	1E+12		Rank
Steel	210	7870	26.7	97%	23	3.4	281%	27	431	816%	27
300 series	200	8000	25.0	103%	28	3.1	305%	28	391	900%	28
Aluminium	70	2710	25.8	100%	25	9.5	100%	25	3517	100%	24
Copper	110	8930	12.3	210%	31	1.4	691%	31	154	2277%	31
Magnesium	44	1740	25.3	102%	27	14.5	66%	19	8352	42%	15
Invar	140	8050	17.4	149%	30	2.2	441%	30	268	1311%	30
Titanium	116	4500	25.8	100%	26	5.7	166%	26	1273	276%	26
Nickel	200	8908	22.5	115%	29	2.5	378%	29	283	1243%	29
RSP 443	102	2540	40.2	64%	18	15.8	60%	18	6224	57%	18
TISIC	210	4200	50.0	52%	14	11.9	80%	23	2834	124%	25
Beryllium	287	1850	155.1	17%	2	83.9	11%	2	45328	8%	2
AlBeMet 162	193	2071	93.2	28%	9	45.0	21%	3	21728	16%	3
AlBeMet 140	150	2280	65.8	39%	12	28.9	33%	12	12656	28%	11
Silicon Carbide	450	3210	140.2	18%	3	43.7	22%	4	13605	26%	7
Zerodur	90.3	2530	35.7	72%	19	14.1	68%	20	5576	63%	21
Silicon	185	2329	79.4	33%	10	34.1	28%	9	14644	24%	6
CE7	130	2350	55.3	47%	13	23.5	40%	14	10017	35%	12
Pitch C Fibre	896	2150	416.7	6%	1	193.8	5%	1	90156	4%	1
Basalt	89	2700	33.0	78%	21	12.2	78%	22	4522	78%	22
Flax	45	1350	33.3	77%	20	24.7	39%	13	18290	19%	4
Si3N4	320	3200	100.0	26%	8	31.3	31%	11	9766	36%	13
BN (cubic)	400	3450	115.9	22%	6	33.6	28%	10	9741	36%	14

Trade Off: Thermal Behaviour



Degradation through Life cycle of a Spacecraft

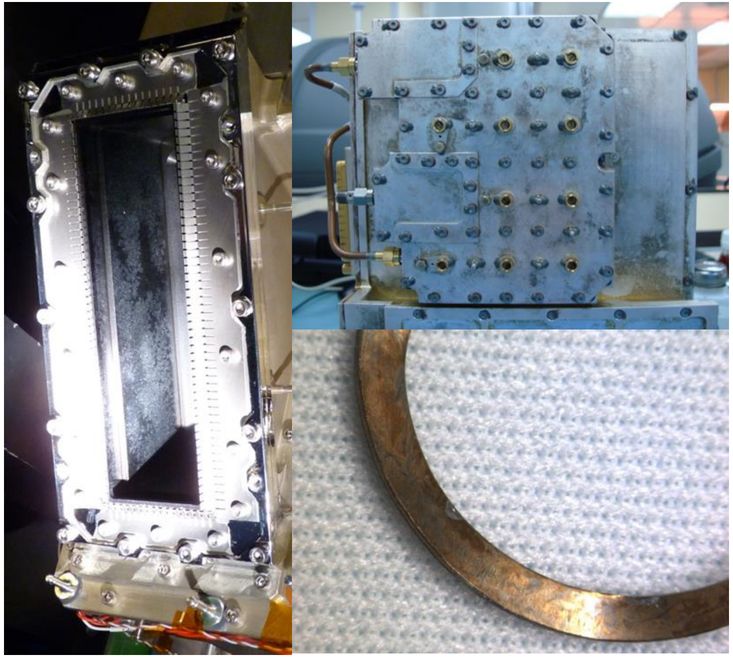
- **Temperature, Strain, Corrosion**
  - **All interdependent**
- MAIT (Manufacturing, Assembly, Integration and Test)
  - Corrosion, Contamination, Handling
- LTS (Long term storage)
  - As MAIT
- Launch
  - Vibration
- Service
  - Vacuum, Radiation, Impact, Thermal cycling, Contamination
- Decommissioning



JUICE flybys of Earth, Venus, Earth, Mars and Earth

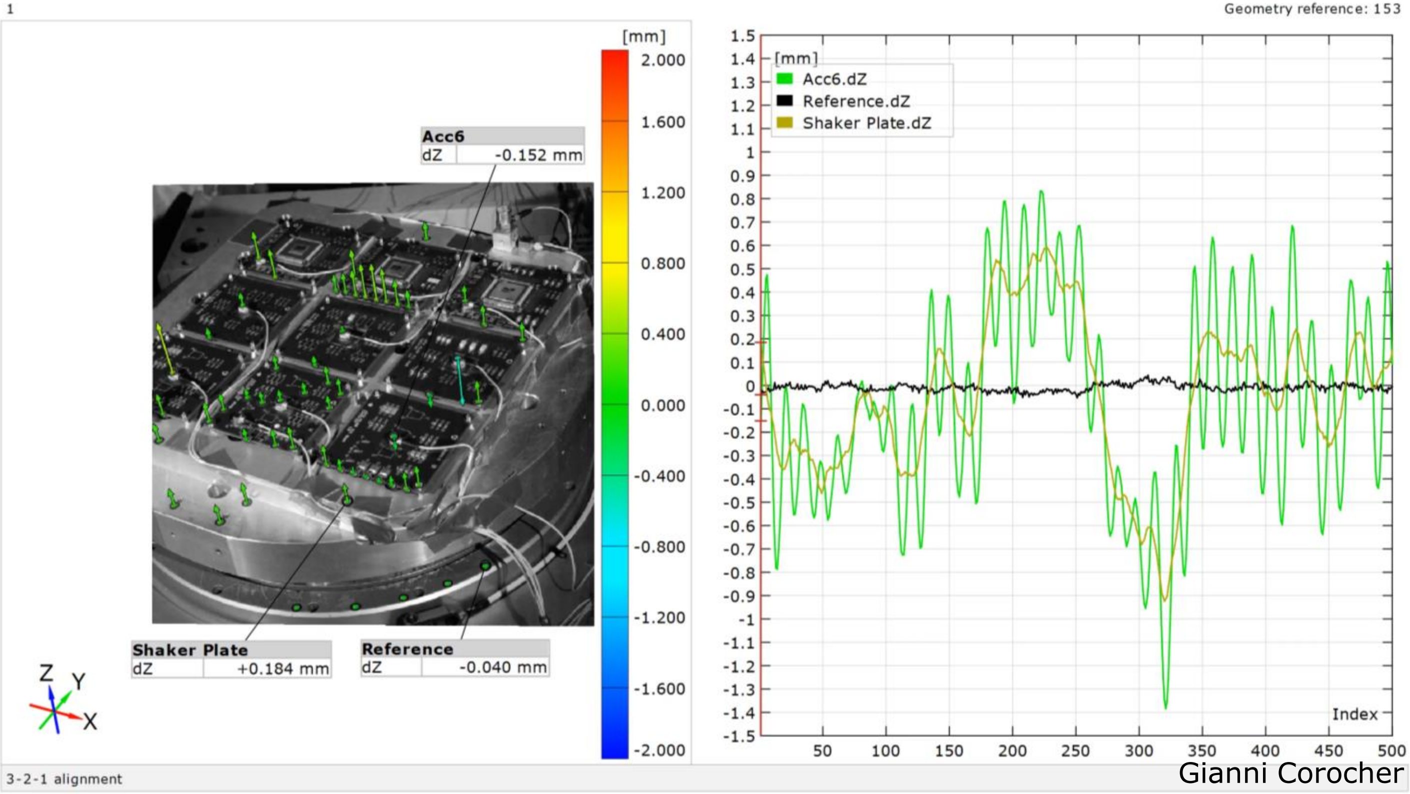
Corrosion

- Corrosion in clean rooms is uncommon but not unknown
- Corrosion products hydroscopic
    - absorb water
    - lowers humidity needed to propagate corrosion
- Typical causes:
    - Restricting airflow allows microclimates
    - Contamination
    - Inadequate cleaning procedures
    - Introduction of cold materials into the clean room
- Galvanic effects can make the situation worse
- Corrosion rating 'A' or 'B'
    - B needs additional protection



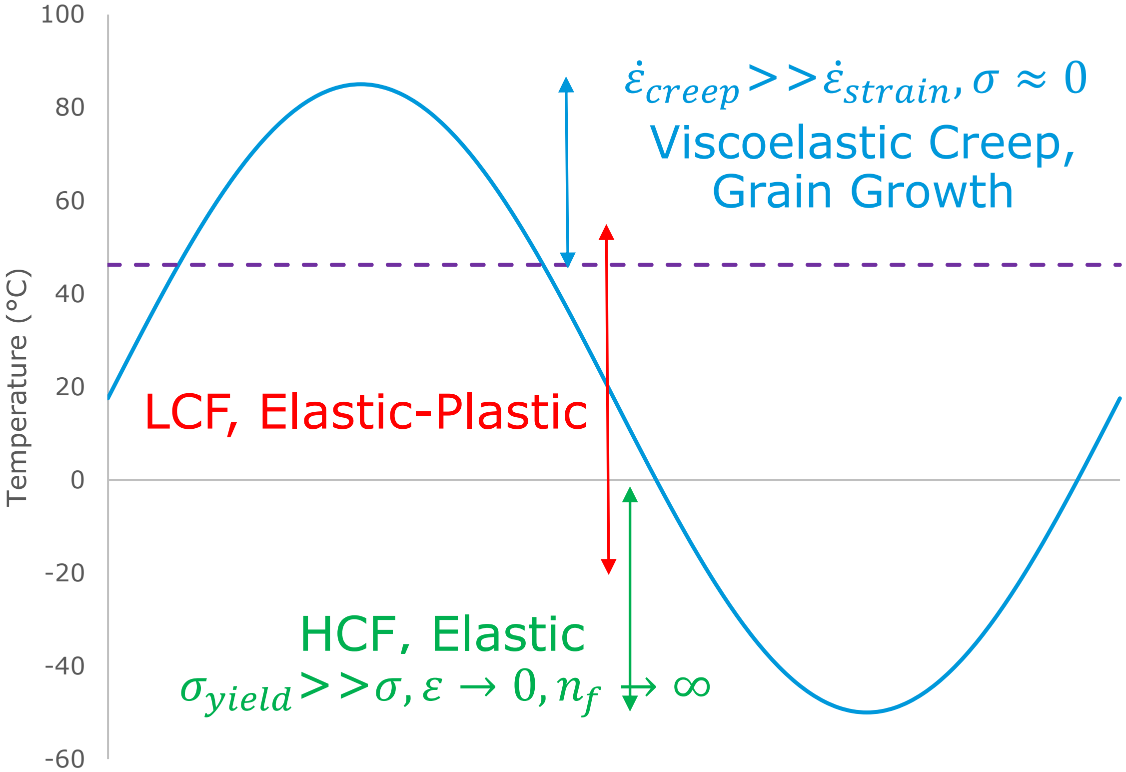
Vibration of PCBs

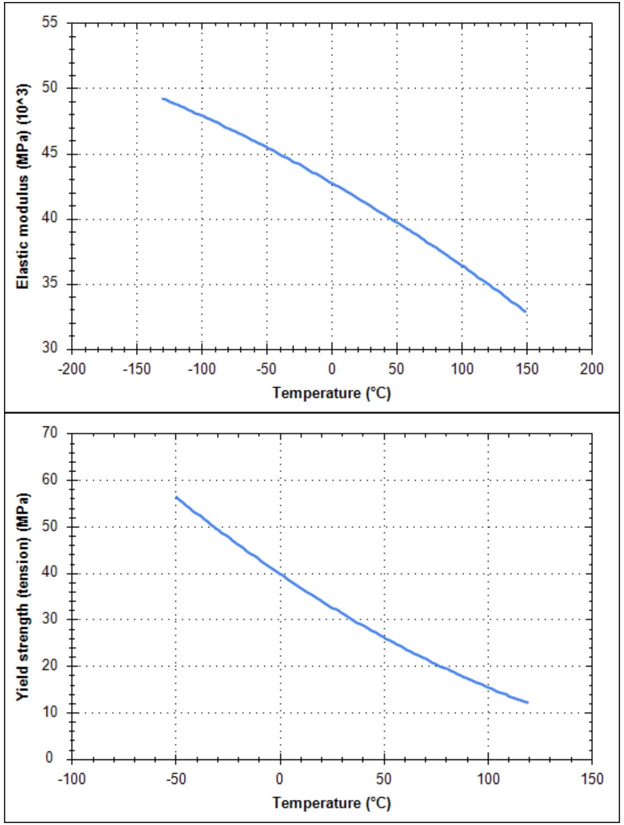
17.5 g acceleration, 0.1 second clip



Gianni Corocher

Thermal Cycle Solder





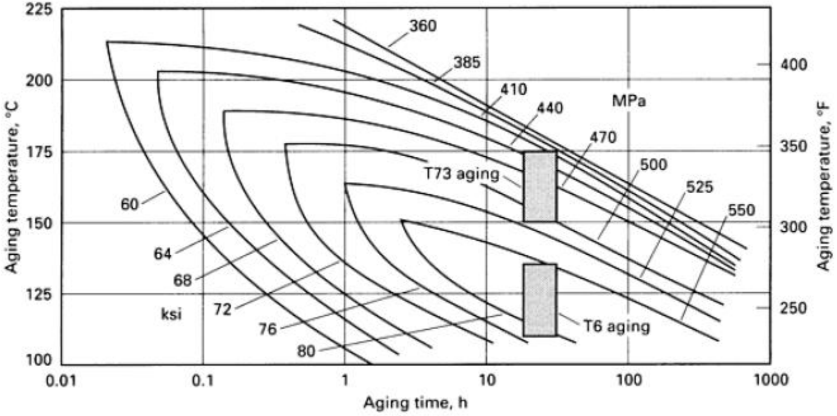
Metals

- Elastic
- Strong
- Malleable
- Crystalline (Usually)
- Conductive (Electrical and Thermal)
- Usually shiny grey
    - Except Gold, Copper, Caesium
- Can be mixed to form stronger alloys or intermetallics
- Properties and Composition usually standardised
- Properties usually depend on heat treatment, not just composition

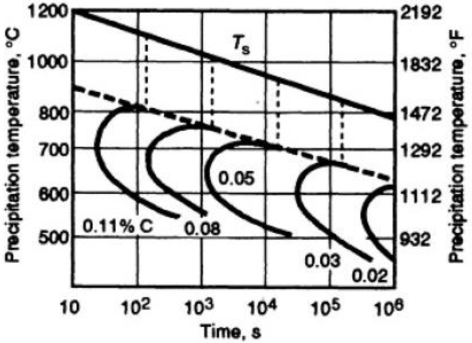
Heat Treatment

- **Annealing:** heating to a specific temperature and then slow cooling to produce a refined microstructure.
- **Stress relieving:** used to remove or reduce the internal stresses created in a metal.
- **Precipitation hardening:** precipitate a fine dispersion of particles in a structure. Increases strength by increasing the resistance to plastic flow.
- **Quenching:** rapid cooling, freezing a thermodynamically unfavourable structure which is often very hard and brittle.
- **Tempering:** after quenching allows a partial relieving of the hard quenched structure to improve toughness and ductility.

ISO-strength curve for AA7075

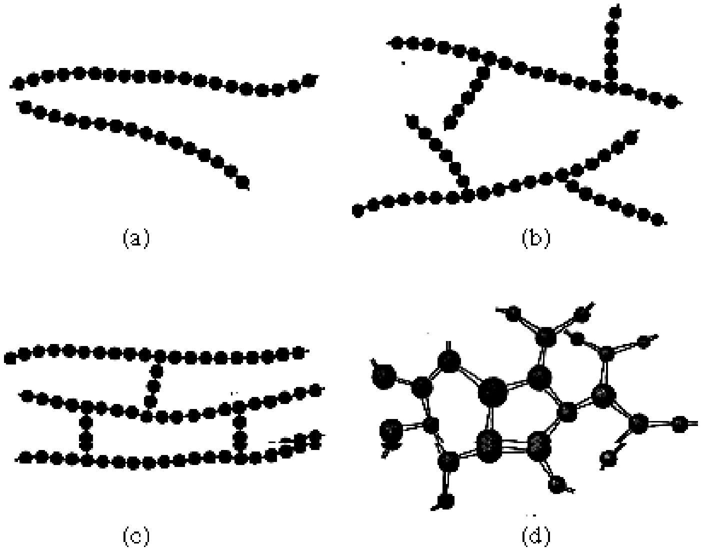


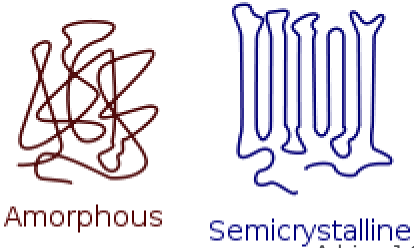
Sensitisation curve for 304



Polymers

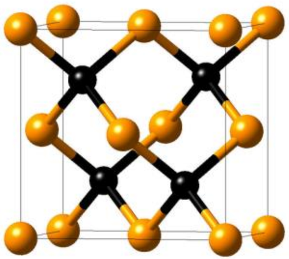
- Chains of Carbon atoms
- Properties from tangles and cross links
- Often show strong viscoelastic behaviour
- Behavior often depends on groups attached to the chain
- Can be amorphous but usually show some semi crystalline behavior

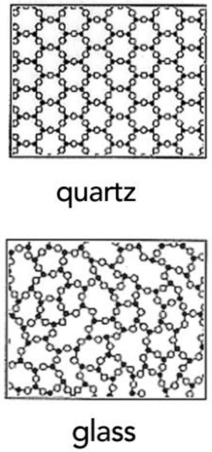


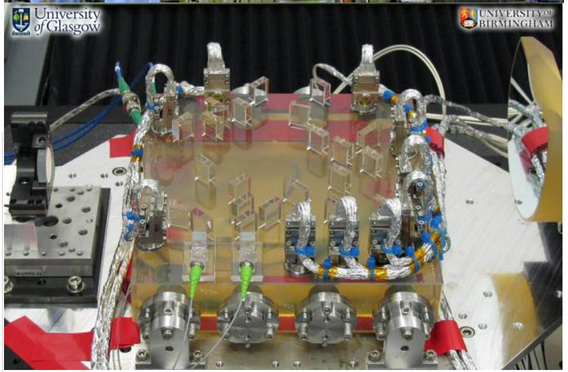


Ceramics and Glasses

- Atoms held together with strong bonds
  - Makes them difficult to move
  - Stiff but brittle
- Often light elements
  - Carbon, silicon, nitrogen, aluminium, oxygen
  - Low density
- Ceramics show long term crystalline order
- Glasses show short term order but over long scales become amorphous







Composites

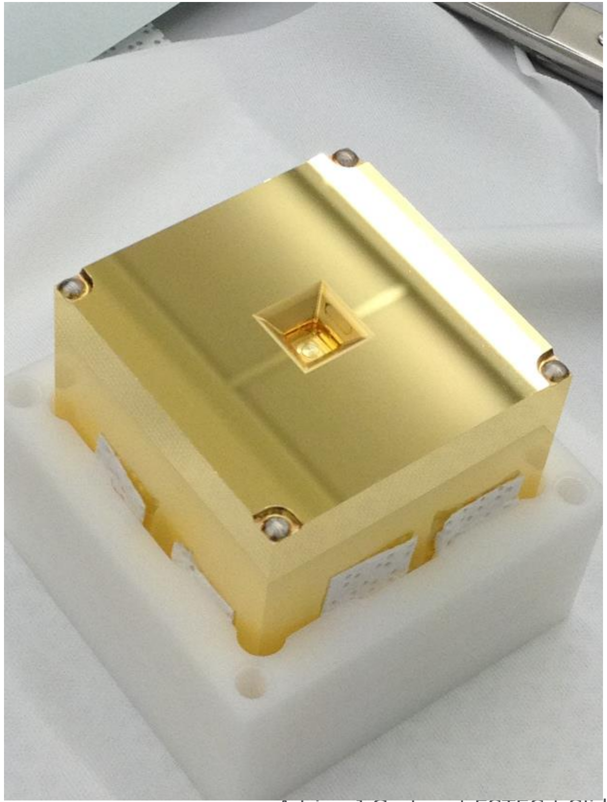
- Combine multiple material systems to get the best from all of them
  - Often strong flexible fibres in a stiff matrix
    - CFRP, GRP, …
  - Allows fibres to be aligned with principle stress
- Not only polymers
  - CMC
    - Ceramic Matrix Composite
  - MMC
    - Metal Matrix Composite
  - Wood

GLARE ULD Unit Load Device

Andreas Tesch

Choice of Materials

- Unusual to depend on mechanical properties
    - Secondary properties
        - Conductivity, Thermo-optical (α/ε), Coating, CTE, etc.
    - Formability
        - Can you make what you need ?
    - Availability
    - Toxicity
    - Ease of Validation
        - How easy is it to tell your material is good enough ?
    - COST and MASS!
        - Think hard if these are your drivers



Considered for material selection

Properties that shall be considered in material selection include, but are not limited to:

- mechanical properties,
- fracture toughness,
- flammability and offgassing characteristics,
- corrosion and stress corrosion,
- thermal and mechanical fatigue properties,
- Glass transition temperature,
- coefficient of thermal expansion mismatch,
- vacuum outgassing,
- fluids compatibility,
- microbial resistance, moisture resistance,
- fretting, galling,
- susceptibility to electrostatic discharge
- Contamination
- ...

Operational requirements shall include, but shall not be limited to:

- operational temperature limits,
- loads,
- contamination,
- life expectancy,
- moisture or other fluid media exposure,
- vehicle-related induced and natural space environments.
- …

Materials Selection

- Supplier is responsible for selection
    - Not “You need to tell me what to use!”
    - Selection is a compromise, rare to be a single solution
- Use based on:
    1. Heritage, same material in a similar application, equivalent environment and duration.
    2. Verification, tests of representative samples in representative environments
        - NB Do not forget the margins, eg 4x life for fatigue
    3. Approved data sources
        - Eg ESMDB, MAPTIS, or other recognised datasets
- New materials must be validated for a specific application

Metallic Materials used in space

- Light metals
  - **Aluminium and Titanium and their alloys**, Beryllium, Magnesium
- Steels
  - **Stainless Steels, precipitation hardenable**, maraging, low-alloy, tool steels,
- Nickel and nickel base alloys
  - **Pure nickel**, NiCu (Monels), NiCr (Inconels), other nickel- and cobalt-base superalloys
- Refractory metals
  - Niobium, Molybdenum, Tungsten
- Copper-base alloys
  - **Pure coppers**, beryllium coppers, Bronzes, Brasses
- Precious metals and their alloys
- Welding, brazing and soldering alloys
- Various plating alloys

Polymer Materials used in space/1

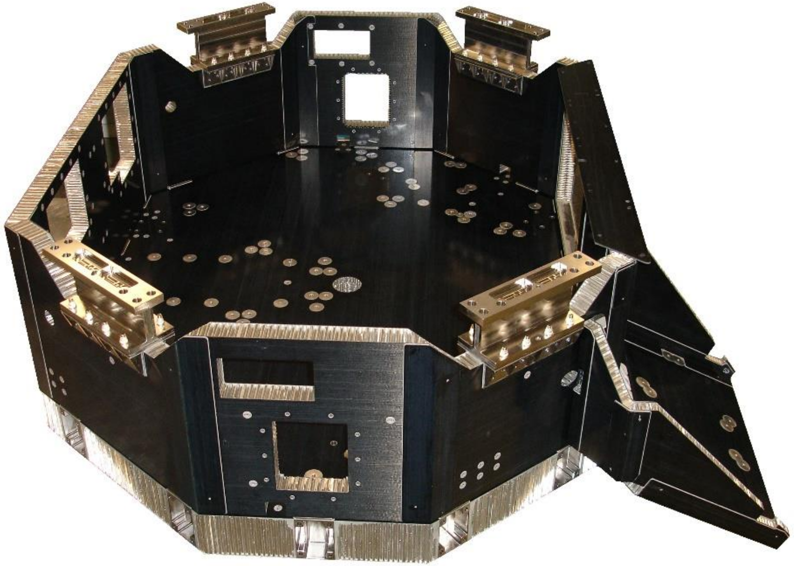
- Structural
  - polyacetal (DELRIN®), PEEK
  - fibre reinforced
    - GFRP, CFRP
- Films
  - thin films such as polyimide, polyethylterephtalate…
  - fluorinated polymers
    - PTFE, FEP…
- Fibres/Cloths/Tissues
  - polyethylene, polyaramid
- Acoustic, Vibration Absorbers
  - Foams
    - polyurethane, polyimide, PEEK…

Polymer Materials used in space/2

- Paints
  - Binder
    - Organic: siloxanes, polyurethanes, polyvinylfluoride
    - Inorganic: silicates…
  - Pigment: metal oxides, graphite

- Electrical
  - Insulation: PI, PTFE, FEP, ETFE
  - Connectors: PET, Siloxanes
  - PCB: flexible: PI, rigid: FRP
  - Shrink sleeves: fluoropolymers, polyolefines
  - Conformal coatings: polyxylene, polyurethane, siloxanes

- Potting materials: polyurethanes, siloxanes



Procurement

- Metals usually defined by standards
  - Need to define composition and heat treatment
    - AA7075 T7351 has extensive heritage
    - AA7075 T6 suffers SCC
- Non-metals supplied by data sheets
  - Subject to change without notice
  - Procurement specifications needed to define requirements
  - Incoming inspection ensure compliance
- Mechanical parts may be to:
  - Standards eg fasteners
  - Data sheets

Material Standards

- Not all standards are equal
- DIN 912/ISO 4762
    - Hexagonal socket head cap screws
    - Very little quality control
- Use ECSS or Aerospace Grade
    - DIN EN 2887: *Aerospace series - bolts, normal hexagonal head, threaded to head, in corrosion resisting steel, passivated - Classification: 600 MPa (at ambient temperature)/425°C*
- Requirement states ECSS-Q-ST-70-46 only
    - Primary Structure: ECSS
    - Secondary structure: Aerospace grade
    - Tertiary structure: Any can be acceptable but need additional PA to ensure not mixed

ECSS-Q-ST-70C

END OF PART 1

METALLIC MATERIALS

Material group numbers

1	Aluminium and aluminium alloys	11	Adhesive tapes
2	Copper and copper alloys	12	Paints and inks
3	Nickel and nickel alloys	13	Lubricants
4	Titanium and titanium alloys	14	Potting compounds, sealants, foams
5	Steels	15	Reinforced plastics (including PCBs)
6	Stainless steels	16	Rubbers and elastomers
7	Filler metals: welding, brazing soldering	17	Thermoplastics
8	Miscellaneous metallic materials	18	Thermoset plastics (including PCBs)
9	Optical materials	19	Material aspects of wires and cables
10	Adhesives, coatings, varnishes	20	Miscellaneous non-metallic materials, e.g. ceramics

DML

DECLARED MATERIALS LIST (DML)

Programme name: ABCDEFG | CI no.: 12345676890 | Doc no.: 001 | Date: 01.10.2000

Group (Title): abcdefg | Issue/Revision: 1/4 | Page: 1

1	2	3	4	5	6	7	8	9			10
								9.1	9.2	9.3	
Item no. and user code	Commercial identification or standardized designation	1) Chemical nature 2) Product type	1) Manufacturer/ supplier name 2) Procurement spec. Issue/RevDate	Summary of process parameters	1) Subsystem 2) Equipment 3) Use	1) R 2) A 3) T	1) A 2) V 3) M	Acronym/ rating/ Validation Ref. for applicable properties	1) Justification for approval 2) Prime comments	Prime approval status	Customer approval status/ comments
1.2.1.TXES	AZ5GU	1) ALZn5.6 Mg2.5 Cdu1.6, Cr0.3 eq. AA7075 2) Plate	1) Almet Pechiney 2) CRB 527 01/02/01.02.1996	T7351 and Iridit 14 heat treatment	1) PL 2) E4 package 3) Structure	1) LS 2) V 3) 3	1) 2) 3) M3		1) Used on ETS2 2)	A	Give evidence of ETS2 specific usage
10.1.1.ETCA	DC93500	1) Silicon 2) Two parts	1) Dow Corning 2) E3846MC105 02/02/1984	Mixture: 10/1 in g Curing: 4h/65 °C	1) PCU 2) Experiment tray 3) Part potting	1) G 2) V 3) 3-4	1) 2) 3) M3		1) ECSS-Q-ST-70-01 2)	A	
11.5.1.KOF	ECCOFOAM EPH	1) Polyurethane 2) Resin/Catalyst 1202H	1) Emerson and Cuming 2) SP/FOK/05/684 03/01/25.06.1992	Resin/ Cat: 100/65g 4h/40 °C +48h/100 °C	1) GP 2) Platform 3) Package potting	1) LS 2) M 3) 3-4	1) 2) V3 3)		1) DU-96-352 2) Used at T > 100 °C (Risk of distortion beyond)	A	A

Group 1: Aluminium and aluminium alloys

Wrought	Alloying	Cast	Alloying
1xxx	Commercially Pure	**1xx.x**	Commercially Pure
2xxx	Cu	**2xx.x**	Cu
3xxx	Mn	**3xx.x**	Si + Cu and/or Mg
4xxx	Si	**4xx.x**	Si
5xxx	Mg	**5xx.x**	Mg
6xxx	Mg and Si	**6xx.x**	Unused
7xxx	Zn	**7xx.x**	Zn
8xxx	Other	**8xx.x**	Sn
		9xx.x	Other

Aluminium for Aerospace Applications

1xxx	Commercially pure low strength but excellent electrical conductivity and corrosion resistance.
2xxx	Heat treatable Al-Cu alloys providing good strength over a wide temperature range. Can be difficult to weld. Often used in structural applications.
5xxx	Weldable alloy that has OK strength but cannot be heat treated. Not suitable for elevated temperatures (>65°C). Often used for cores in composite panels.
6xxx	Good cheap base material which can be heat treated. Reasonable strength, good corrosion resistance and easy to coat or plate
7xxx	Highest strength Al alloys but can be difficult to coat, has corrosion issues and can be difficult to weld.

Aluminium Work Hardening

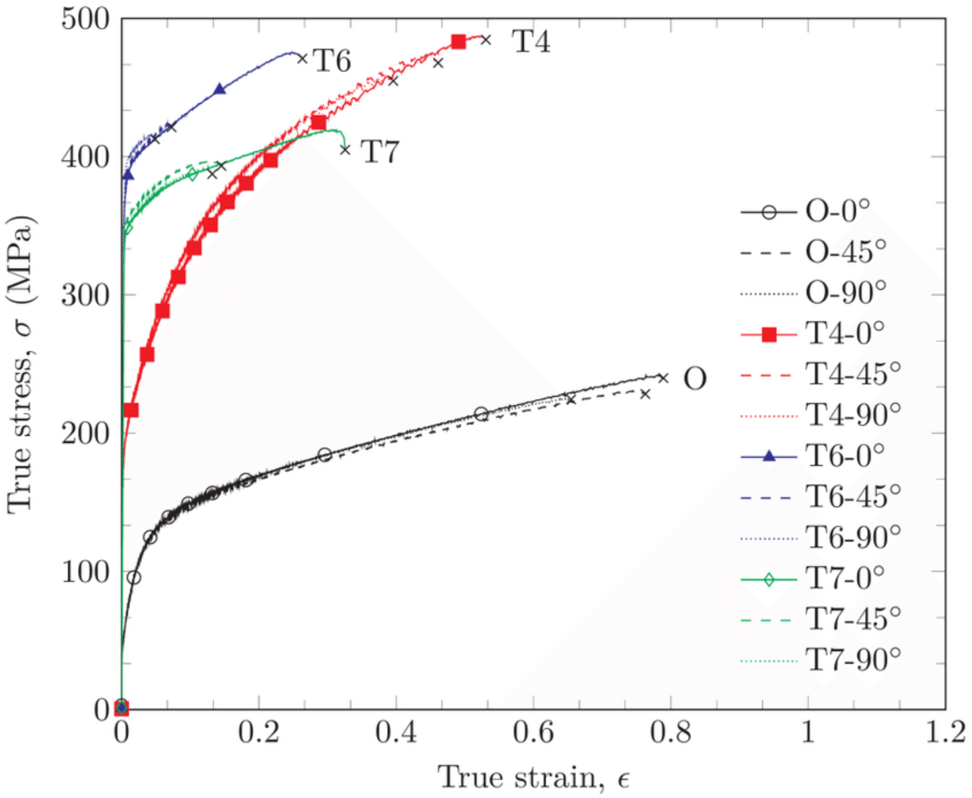
Strain Hardened		Degree of hardening	
H**1**	Strain Hardened Only.	HX**2**	Quarter Hard
H**2**	Strain Hardened and Partially Annealed.	HX**4**	Half Hard
H**3**	Strain Hardened and Stabilized.	HX**6**	Three-Quarters Hard
H**4**	Strain Hardened and Lacquered or Painted.	HX**8**	Full Hard
		HX**9**	Extra Hard

Aluminium Temper

T1	Naturally aged after cooling from an elevated temperature shaping process, such as extruding.
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3	Solution heat-treated, cold worked and naturally aged.
T4	Solution heat-treated and naturally aged.
T5	Artificially aged after cooling from an elevated temperature shaping process.
T6	Solution heat-treated and artificially aged.
T7	Solution heat-treated and stabilized (overaged).
T8	Solution heat-treated, cold worked and artificially aged.
T9	Solution heat treated, artificially aged and cold worked.
T10	Cold worked after cooling from an elevated temperature shaping process and then artificially aged.
Additional digits indicate stress relief. Eg:	
TX**51** or TXX**51**	Stress relieved by stretching.
TX**52** or TXX**52**	Stress relieved by compressing.

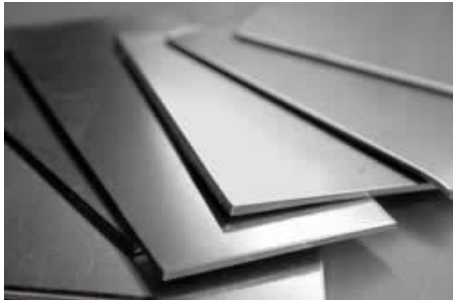
Aluminium Properties

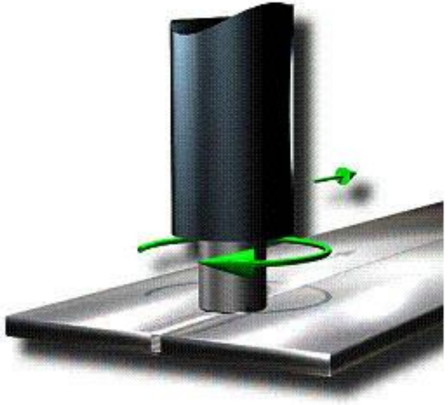
- Properties depend on composition and temper
  - 7075-T6 is strong but can suffer SCC
  - 7075-T7351 is almost as strong but does not suffer SCC
- For Structural applications choose tempers that reduce :
  - General corrosion
  - Pitting
  - Intergranular corrosion
  - Stress-corrosion cracking.



Aluminium Processing

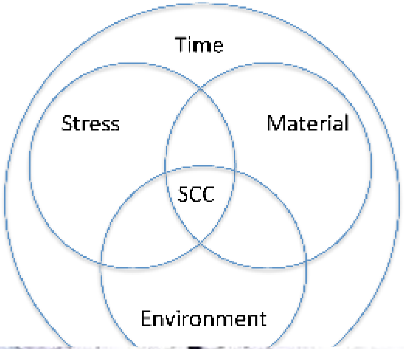
- Forming
    - Extrusion, rolling, forging, casting, etc
- Joining
    - Welding (most alloys), adhesive bonding, brazing, bolting
- No specific space issues
    - Temperature can be a limiting factor
- Residual stresses can induce cumulative effects
    - May lead to a reduction in Fatigue performance
    - Control by stress relieving





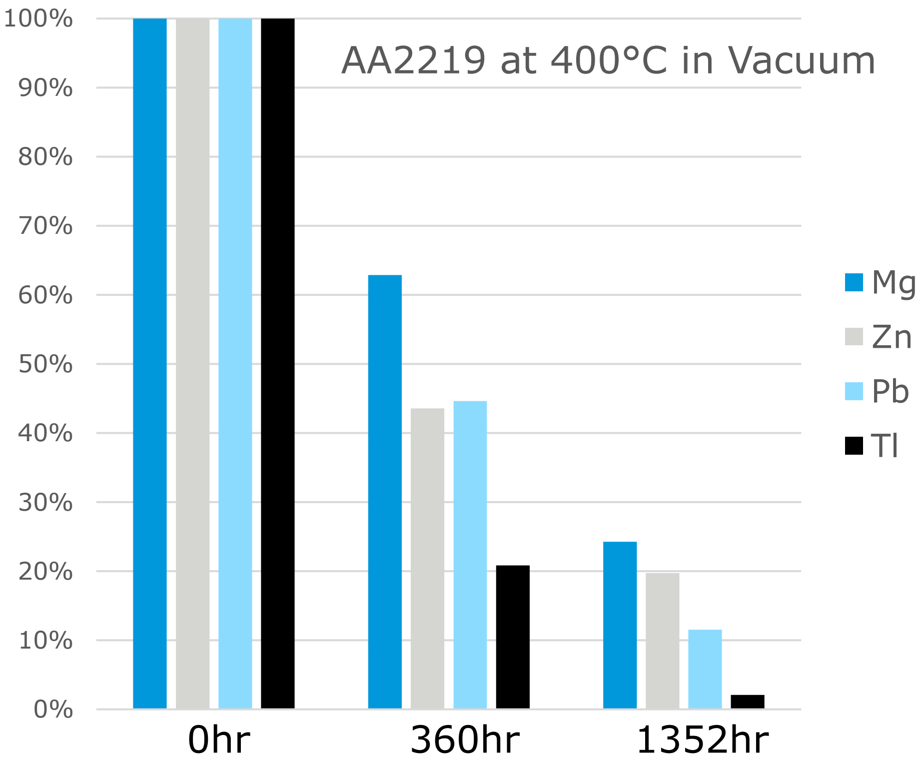
Aluminium Corrosion

- 1xxx, 3xxx, 5xxx and 6xxx series alloys or clad with 1xxx alloys are considered corrosion resistant
- Additional protection is needed for 2xxx and 7xxx series alloys
    - Chemical conversion coating (CCC), Paint, Anodisation, Plating
    - REACH requirements restrict the use of Cr(VI) systems
        - A number of alternatives are available Surtec 650 is popular
        - Application needs validation
        - Colourless so difficult for PA to check
- Coatings **do not** protect against SCC
    - Often increase the risks with localised corrosion

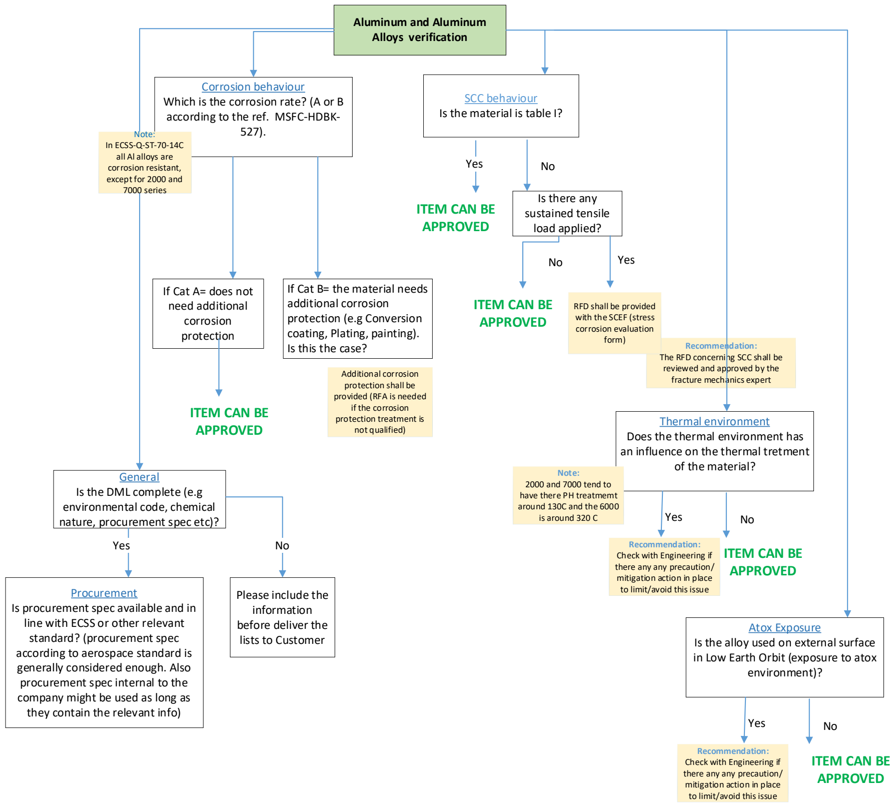


Aluminium in the Space Environment

- In general not affected by Vacuum, Temperature or Radiation
- Temperature can affect heat treatment
    - 5xxx series above 65°C
    - 7075 above 125°C
- Combinations of temperature and vacuum produce dealloying
    - Eg Trace elements in 2219
        - Can discolour coatings



Aluminium Approval



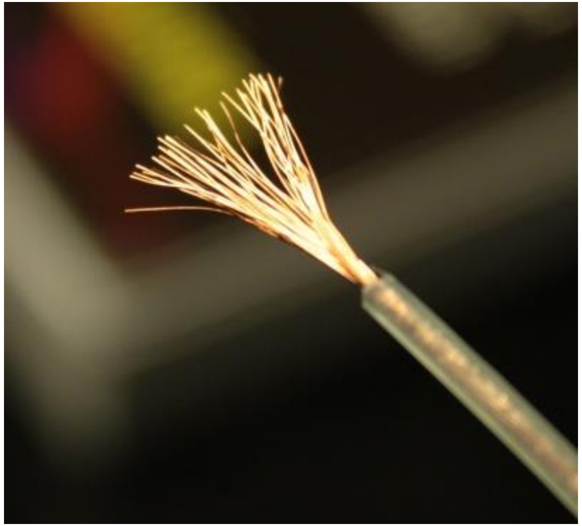
Topic	Questions
Designation	Needs chemical nature and thermal treatment (Eg 6061 T6, 6061 O, 7075 T7351)
Procurement	International and National standards may be used to procure most alloys Some alloys are supplied to datasheet such as: RSA-6061, RSA-443, AlSiC These alloys require procurement specification or appropriate incoming inspection (see ECSS-Q-ST-70C paragraph 5.6)
Use in Spacecraft	Structural parts (primary and secondary structures), antennas, mirrors, etc
Corrosion	ECSS-Q-70-14 Corrosion says additional protection only needed for 2000 (Al-Cu) and 7000 (Al-Zn) alloys Protection can be Anodization, paint, plating, Chemical Conversion coating Chromate based product and Qualification for Cr6 alternatives Suppliers Verified for Surtec 650 Application
Galvanic corrosion	Aluminium alloys are usually the anode in galvanic couples ECSS-Q-ST-70C 5.1.12 Galvanic compatibility
SCC	Avoid alloys with poor Stress Corrosion Cracking behaviour SCC behaviour depends on both composition and heat treatment 7075 T73XX has good SCC resistance 7075 T6 has poor SCC resistance Most Al alloy MMCs have poor SCC performance Usually intergranular cracking along Al/reinforcement boundary
Temperature	Melting point about 660°C Significant drop off in mechanical properties above 300°C Ageing Heat Treatment for 2000 and 7000 series alloys at 120°C so temperatures above this must be avoided or over aging will occur Outgassing of alloying elements can occur at high temperatures e.g. Zn from 7075
Human Space Flight	Long term crewed structures: -shall not use aluminium alloys 2024-T6, 7079-T6 and 7178-T6 in structural applications -shall not use aluminium alloys 5083-H32, 5083-H38,5086-H34, 5086-H38, 5456-H32 and 5456-H38 in applications where the temperature exceeds 66 C. Elevated temperature leads to long term degradation of the stress corrosion resistance (see Table 5-1note 5)

Group 2: Copper and Copper Alloys

Copper	Electrical connections and PCBs, thermal management, helicoils (phosphor bronze)
Copper-Zinc	Brass for terminals, connections, crimps
Copper-Beryllium	Electrical connections, conductive springs, precipitation hardening alloy
Copper-Tin	Bronze for contacts, bushings

Copper and its alloys/1

- General
  - Electrical, electronic equipment
  - Bearing assemblies
- Use in spacecraft
  - Electrical/electronic subsystems
    - wiring, terminals in soldered assemblies
  - Thermal management (copper-tungsten)
  - Plating and Metallizing
    - electronics, thermal control, corrosion protection etc



Copper and its alloys

- Processing/Assembly
  - In electronic assembly operations, copper wires are soldered to terminals (either manually or automatically).
    - Correct selection and use of process materials (approved solders and fluxes for space hardware, solvents, etc) is a controlling factor in making reliable soldered connections
  - Beryllium-copper alloys are heat treated to optimise mechanical performance.
    - Fabrication processes (forming, machining, joining, etc) are generally performed in a softened condition and the material subsequently solution treated and aged.

- Hazardous/precluded
  - Beryllium and beryllium oxide are toxic. Processing methods which may release beryllium from the alloy or produce beryllium oxide (heat treatment, welding, machining, etc) require appropriate safety equipment for operatives and proper facilities for the collection and disposal of dust and debris.
    - `Not usually a problem below 4wt.% Be

Copper Precautions

- Heating brass in an oxidising or corrosive conditions can cause dezincification of the alloy
    - loss of zinc from the exposed surface layer
- Cold worked brass alloys are sensitive to stress-corrosion cracking.
    - `Annealing heat treatments are used to remove the cold work.
- Atmospheres containing sulphur dioxide, oxides of nitrogen and ammonia can cause SCC of some copper alloys.
- In electronic assemblies, terminals fabricated from bronze are preferred.
    - Brass terminals require a barrier layer (plating), to prevent diffusion and surface oxidation of zinc, prior to applying a tin-lead coating.
- Some constituents of potting compounds and sealants (catalysts) are corrosive to copper, and other metals.
- Cupric Oxide is a semiconductor that can affect AC signals

Copper in the space environment

- **Vacuum** presents no special problem for copper-based materials, although copper-zinc alloys are generally plated - see Miscellaneous metals.

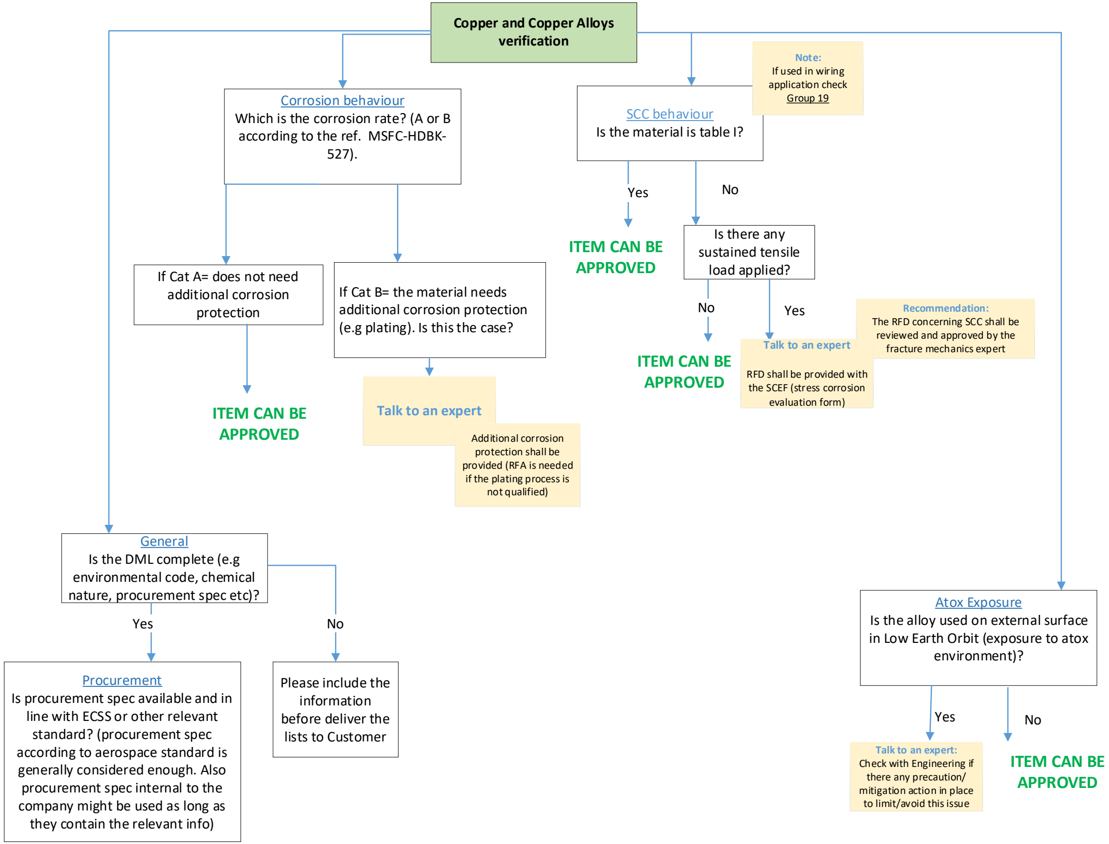
- All metals in contact under vacuum conditions or in inert gas have a tendency to cold weld.
    - Enhanced by mechanical rubbing or any other process which removes or disrupts surface oxide layers.

- **Radiation** at the level existing in space does not modify the properties of copper alloys.

- **Temperature** problems are similar to those encountered in technologies other than space, but are complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling.

- Atomic oxygen in low earth orbit attacks copper.

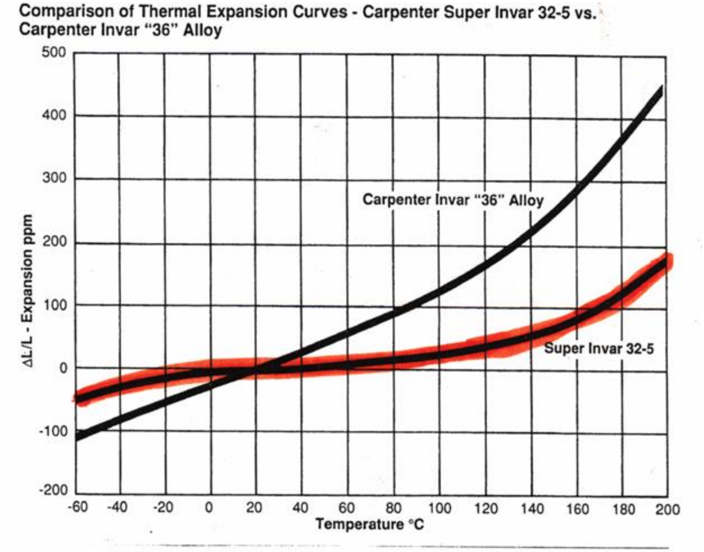
Copper Approval



Topic	Questions
Designation	Needs chemical nature defining Strength increases usually through mechanical work Some alloys, usually copper beryllium, are precipitation hardened
Procurement	International and National standards may be used to procure most alloys Some alloys are supplied to datasheet such as: Copper Tungsten Heat Sinks These alloys require procurement specification or appropriate incoming inspection
Use in spacecraft	The main applications for copper are in electrical and electronic subsystems (wiring, terminals in soldered assemblies) and plating (e.g. electronics, thermal control and corrosion protection). Copper is also used as a metallizing coating and as an additive in other materials). Copper wire are handled under Class 19
Main Categories	Commercially pure grades of which there are many different "named" varieties that indicate the manufacturing method and the level of control of impurities, including oxygen. Alloys in which the alloying additions affect the metallurgical microstructure and consequently their characteristics (mechanical, electrical and thermal properties, environmental resistance). - brass-copper - zinc alloys, often containing other alloying elements, such as lead which acts as a "lubricant" for machining operations - so-called "free-machining"; - bronze-copper - tin alloys, often containing other alloying elements. - beryllium-copper (also known as copper-beryllium) is a copper alloy with small additions of Be.
Corrosion	ECSS-Q-70-14 Corrosion says additional protection only needed for Copper alloys Protection is usually plating, typically nickel phosphorus, often over-plated with gold Without protection Cu alloys typically develop a thin (400 nm) cupric oxide layer. Layer can be unsightly (black) but usually harmless. CuO is a semiconductor so cases of partial rectification of AC signals have been recorded which may lead to issues. if allowed to further oxidize cupric oxide transforms to red cuprous oxide (Cu2O) and more significant corrosion.
Galvanic corrosion	Similar potentials to steels, will be corroded in contact with precious metals (Au, Pt, Rh) etc, will drive the corrosion of tin lead solders ECSS-Q-ST-70C 5.1.12 Galvanic compatibility (table 5-1)
SCC	Natural atmospheres containing the pollutants sulphur dioxide, oxides of nitrogen and ammonia are reported to cause stress corrosion cracking of some copper alloys. Many copper alloys containing over 20 % zinc are susceptible to SCC even in the presence of alloying additions that normally impart resistance to stress corrosion (susceptibility to SCC is reported in the ECSS-Q-ST-70-36C)
Effects of Space Environment	Vacuum presents no special problem for copper-based materials, although copper-zinc alloys are generally plated. All metals in contact under vacuum conditions or in inert gas have a tendency to cold weld. Radiation at the level existing in space does not modify the properties of copper alloys. Temperature problems are similar to those encountered in technologies other than space, but are complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling. Atomic oxygen in low Earth orbit attacks copper.

Group 3: Nickel and its alloys

- Used in many engineering fields for their corrosion resistance and high-temperature performance.
- Also used as heating elements and transformer components.
- Often known by trade names, rather than by their specification code numbers.
  - Many based on the old INCO designation (Inconel, Monel, etc)
- Controlled-expansion and constant-modulus properties (bimetals, thermostats, glass sealing, precision equipment).
  - Invar, Kovar, etc
- Shape-memory effect
  - Nitinol
- There are also a number of alloys used as welding and brazing filler materials. Some Ni-based materials are applied as coatings or hard facings to other materials to provide wear or corrosion resistance.



Nickel in Spacecraft

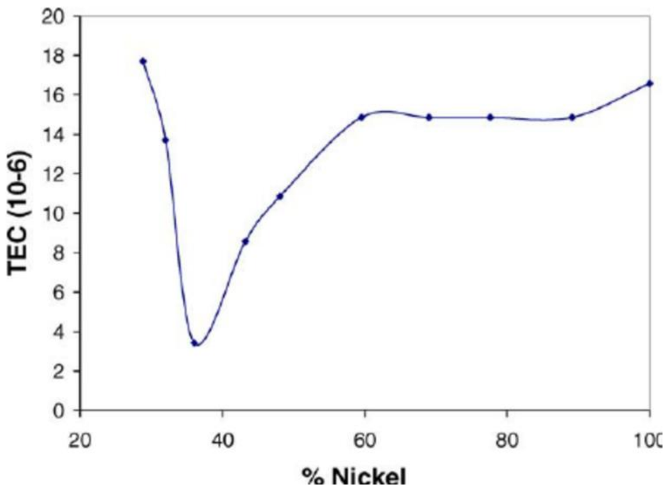
- Nickel plating appears in many applications (electronics, thermal control, corrosion protection etc).
- Corrosion resistance (storage and delivery systems);
- High-temperature performance, often combined with oxidation resistance (propulsion units - gas turbines and rocket motors, power generation, heat-exchangers and turbines);
- High-reliability, high-strength fasteners.
- Magnetic alloys find a limited but important role.
- Memory alloys may find use as actuators.

Invar

- Exploits the "Invar" effect to produce a family of low expansion alloys. Invar short for invariable
- Not really a nickel alloy with 64% iron but usually associated with Group 3
- Advantages
  - Low CTE, 1.3-1.7 ppm/K with correct heat treatment
  - CTE closely matches Silicon Carbide down to 100K
  - Mechanical behaviour and processing as for a metal
- Disadvantages
  - High density, ≈8100 kg/m^3, often results in heavy components
  - Temporally unstable, dimensions change over time, particularly in first 100 days after manufacture
  - Multi stage heat treatment required for stable CTE
- Difficult to machine with heavy tool wear and slower cutting speeds
- Heavy machining or other plastic work can change the absolute CTE of the material, lead to a change in CTE with time and dimensional changes with time

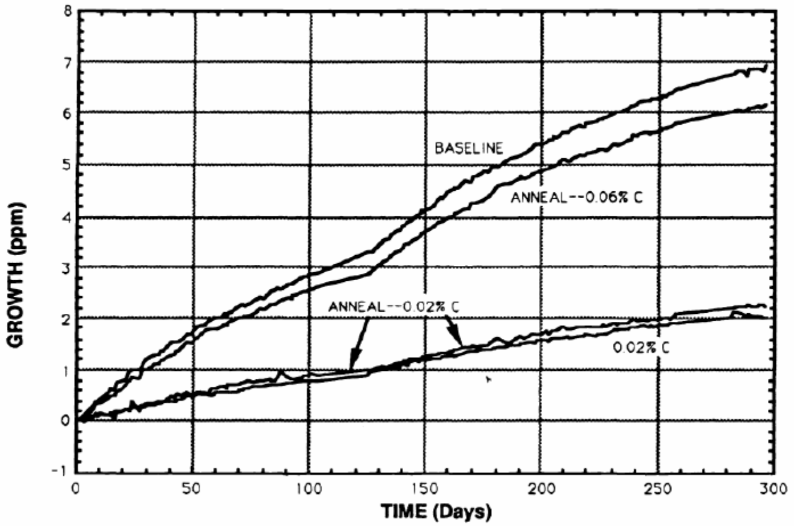
Invar effect

- CTE varies with Nickel content
  - Minima at 36 wt% nickel
- Low CTE depends on two effects:
  - Electron structure of random distribution of Fe and Ni atoms produces adharminic thermal vibration
    - As temperature increases secondary vibrations damp the main thermal vibration
  - Electron spin from Fe and Ni atoms dictates magnetic behaviour
    - Pauli exclusion effect
- Overall CTE is combination of adhamonic thermal vibration and magnetic temperature dependence



Invar Heat Treatment

- Annealing
  - 830°C allowing 30 minutes per 25mm of thickness, water or glycol quench
  - Quench method affects CTE
- Stress Relief
  - 313°C for 1 hour, air cool
- Magnetic stabilisation
  - 92°C hold for 24 to 48 hours
- Stress relief and magnetic stabilisation can be combined
- Mechanical work and machining (>100µm)
  - Temporal instability in both CTE and absolute dimensions
  - Allow 100 days after machining before final metrology to ensure best stability.

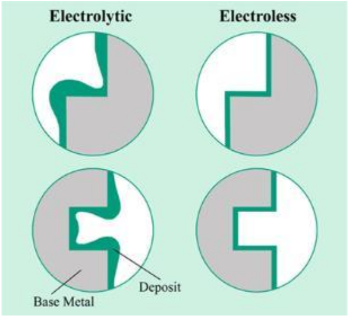


Invar type alloys

Invar 36	Iron 36% Nickel alloy "Invar" is a trade name of Imphy Alloys, now owned by Apream. CTE stable in the range 1.3 to 1.7 ppm/K between room temperature and 200°C. Standards: 1.3912, K93600, K93601, K93603, DIN1715, SEW385, ASTM A658, ASTM F1684 Also known as: FeNi36, 64FeNi, Alloy 36, Nilo 36, Pernifer 36
Invar M93	High purity Iron 36% Nickel alloy from Imphy alloys CTE stable in the range 1.3 to 1.7 ppm/K between -100°C and 200°C.
Super Invar	Fe 32Ni 5Co alloy with CTE < 1ppm/K between -55°C and 95°C
Elinvar	Fe 32Ni 12Cr alloy with an elastic modulus almost constant between 20°C and 150°C Also Ni-Span from Inco Alloys

Nickel Plating

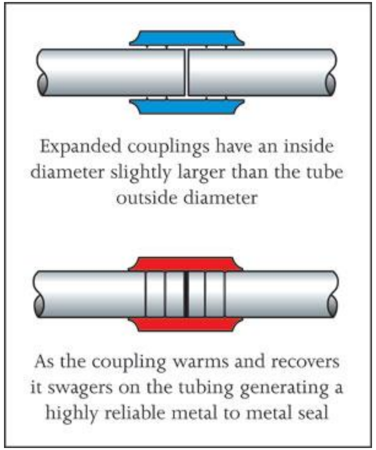
- Versatile plating system
- Electroless or Electrolytic
- Hardness and magnetic properties often controlled by phosphorous content
- Structural applications by electroforming
  - Thick plating over a disposable mandrel
- Often used as intermediate layer
  - Acts as both adhesion and anti-diffusion layer
- Good corrosion protection but always assume it is cracked
  - Particularly hard coatings
  - Cracks can be used to aid lubrication
- May need a protective layer to ensure solderability

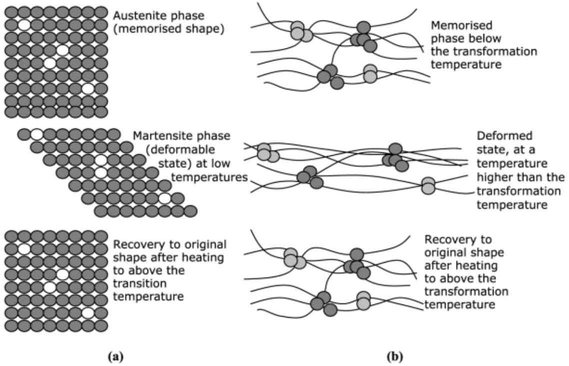


	LOW PHOSPHORUS	MEDIUM PHOSPHORUS	HIGH PHOSPHORUS
Nickel content	95-99%	92-95%	88-91%
Phosphorus content	1-5%	5-8%	9-12%
Hardness (Rc)			
as plated	58-62	46-50	44-48
heat treated	68-70	65-68	65-67
Abrasion Resistance	Very Good	Very Good	Very Good
Wear/Galling	Superior	Excellent	Excellent
Corrosion	+ Alkaline, - Acidic	Mild environments	+ Acid, fair in Alkaline
Stress	Compressive in some cases	Tensile	Compressive in most cases
Magnetic properties	Magnetic	Slightly Magnetic	Non-Magnetic

Nitinol

- Ni-Ti shape memory alloys
- Based around the 50/50 composition.
- Can be deformed below a specific temperature
  - 30°C to 130°C depending on exact composition
- Returns to original shape on heating above specific temperature (≈500°C)
  - Temperature sensitive actuators,
  - fixing and gripping devices
    - often in inaccessible locations



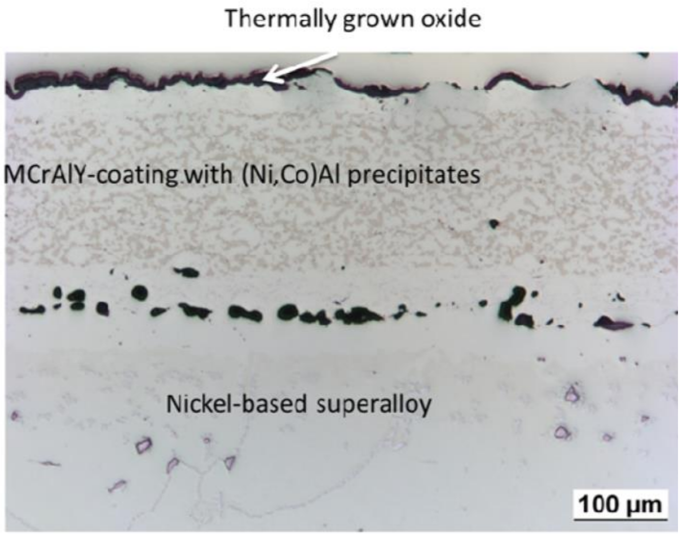


Nickel Processing

- The chemical composition largely dictates the processing methods applicable to a particular alloy.
- In addition to casting, normally under vacuum, and forging, powder metallurgy techniques are used to produce highly-alloyed or dispersion-strengthened materials from metal powders.
- Similar processes, i.e. hot isostatic pressing, can be used for the consolidation (porosity elimination) of cast components.
- All processes require strict control and the specifications applied to aircraft and other critical industry applications (power generation) are used.

Nickel Coating

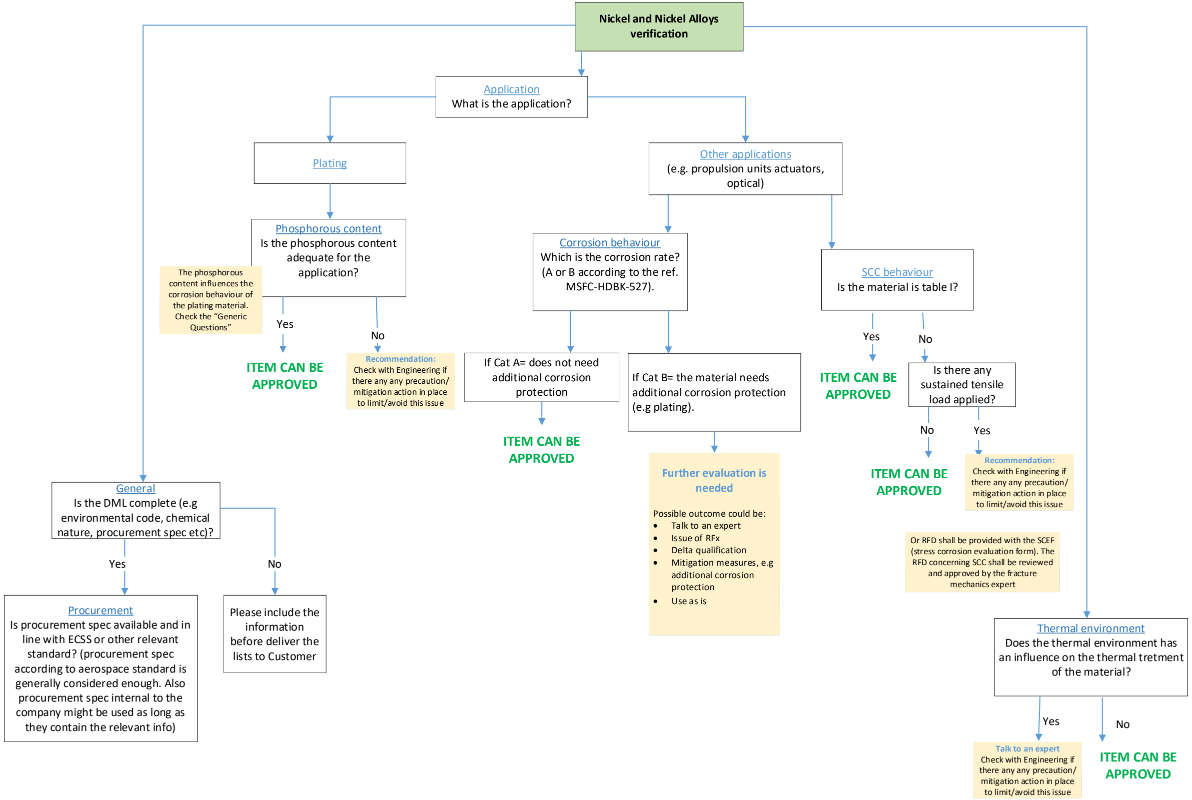
- Corrosion resistance depends on surface passivation (Oxidation)
- Thermal cycling may induce spalling
    - Cracking of coating due to CTE mismatch with substrate
- Alloys often doped with Chromium, Aluminium, Yttrium to help stabilise coating
- Selection and use of coatings for oxidation/corrosion resistance requires evaluation of service conditions and interfacial effects
    - thermal mismatch, diffusion, etc
- Barrier, ceramic-type coatings can crack and spall during thermal cycling
- Elements of metal coatings may diffuse into the substrate at prolonged elevated temperatures.



Nickel in the Space Environment

- Vacuum:
  - No significant effects in typical spacecraft environments
  - Cold welding must always be considered especially if the oxide layer may be disrupted
- Temperature:
  - No significant effects in typical spacecraft environments
- Radiation:
  - No significant effects in typical spacecraft environments
  - Neutron activation of the chromium alloying additions can occur
    - Produces slightly radioactive materials

Nickel Approval

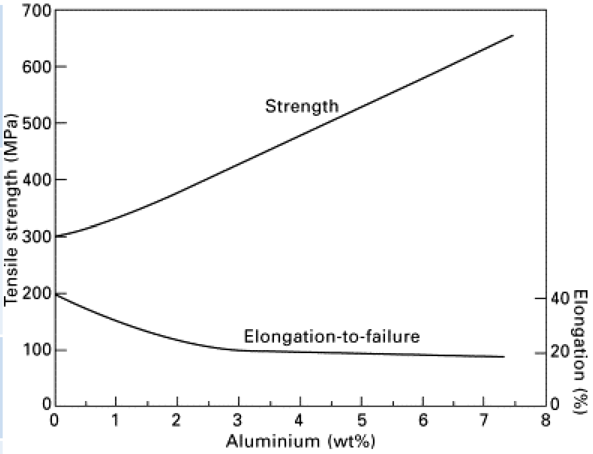


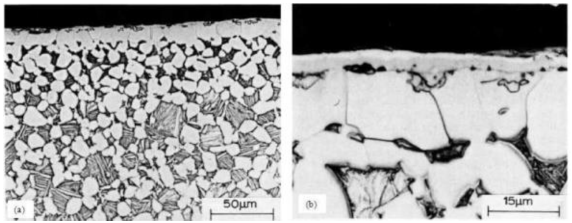
Nickel Approval 2

Topic	Major Aspects
Designation	- Corrosion resistant alloys: Monel, Inconel, Hastelloy - High-temperature alloys: Nimonic, Inconel. - Electrical conductive alloys: Monel, Brightray, Nichrome, Tophet, Chromel, Alumel - Magnetic alloys: Mumetal, Radiometal, Permalloy, Nilomag - Controlled-expansion alloys: Invar - Shape-memory alloy: Nitinol There are also a number of alloys used as welding and brazing filler materials. Some Ni-based materials are applied as coatings or hard facings to other materials to provide wear or corrosion resistance.
Heat Treatment	Mechanical behaviour of most Nickel alloys depend on correct heat treatment. For structural applications, confirm with structural engineer that heat treatment meets mechanical property requirements.
Procurement	International and National standards may be used to procure most alloys These alloys require procurement specification or appropriate incoming inspection (see ECSS-Q-ST-70C paragraph 5.6)
Processing	• The chemical composition largely dictates the processing methods applicable to a particular alloy. • In addition to casting, normally under vacuum, and forging, powder metallurgy techniques are used to produce highly-alloyed or dispersion-strengthened materials from metal powders. • Similar processes, i.e. hot isostatic pressing, can be used for the consolidation (porosity elimination) of cast components. • All processes require strict control and the specifications applied to aircraft and other critical industry applications (power generation) are used.
Use in Spacecraft	Ni-alloys are used for: •Nickel plating (electronics, thermal control and corrosion protection) •corrosion resistance application (storage and delivery systems); •high-temperature performance applications (propulsion units - gas turbines and rocket motors, power generation, heat-exchangers and turbines); •Memory-shape alloys (e.g. actuators); •Optical applications (low CTE mismatch)
Corrosion	The corrosion resistance of electroless nickel is one of the major reasons for its widespread use as a protective coating. However, this beahavour is dependent of the phosphorous content. •high (>8%) phosphorus deposits have superior corrosion behaviour in neutral or acidic media. •low (<8 %) phosphorus deposits have superior corrosion behaviour in elevated temperature, strongly alkaline media The content of phosphorus shall be tailored to the intended application (see here more information)
Galvanic corrosion	ECSS-Q-ST-70C 5.1.12 Galvanic compatibility
SCC	Nickel alloys that were evaluated and shown to have a high resistance to stress corrosion cracking are listed in Table 5 from ECSS-Q-ST-70-36C. For non-listed alloys a SCC evaluation shall be obtained prior to use.
Temperature	Thermal cycling may induce spalling, cracking of coating due to CTE mismatch with substrate (Alloys often doped with Chromium, Aluminium, Yttrium to help stabilise coating) Selection and use of coatings for oxidation/corrosion resistance requires evaluation of service conditions and interfacial effects, thermal mismatch, diffusion, etc Barrier, ceramic-type coatings can crack and spall during thermal cycling Elements of metal coatings may diffuse into the substrate at prolonged elevated temperatures.
Space environment	No significant effects in typical spacecraft environments.

Group 4: Titanium and titanium alloys

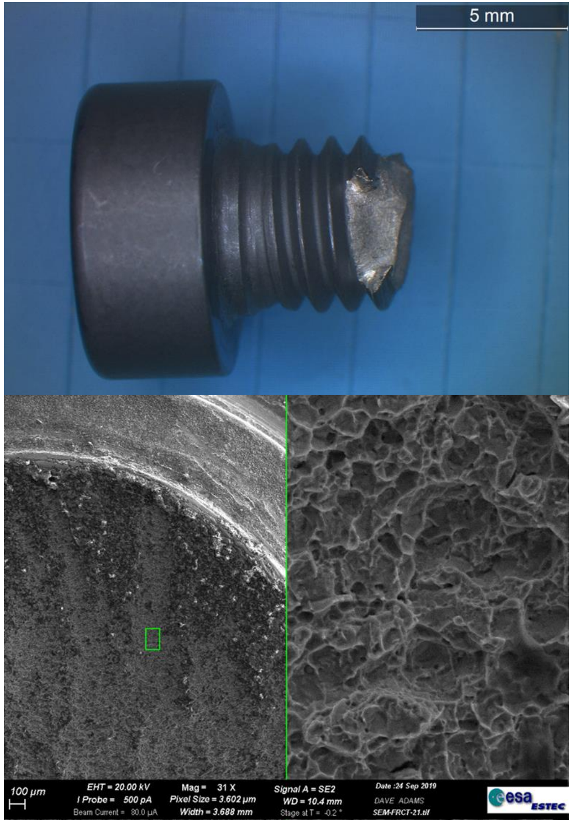
Pure Titanium	Commercially pure system of α (hexagonal phase) Cannot be heat treated Soft, ductile, excellent corrosion resistance
α-alloys	Additions of neutral or alpha stabilising elements Al, Sn, Zr, O Improved creep and high temperature resistance Can be heat treated and precipitation hardened
Near α-alloys	Small quantity of β (<2%) improving strength and high temperature properties up to 600°C
α/β-alloys	β phase increases toughness and allows a wider range of heat treatments Most widely used alloys particularly Ti6Al4V
β-alloys	Addition of V, Mo, Nb, Fe and Cr to stabilise β Excellent strength and fatigue performance but poor in creep Low volume use





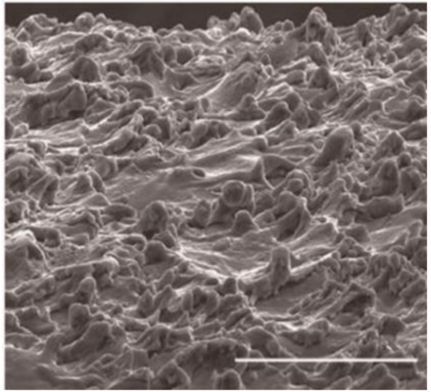
Titanium and its alloys uses

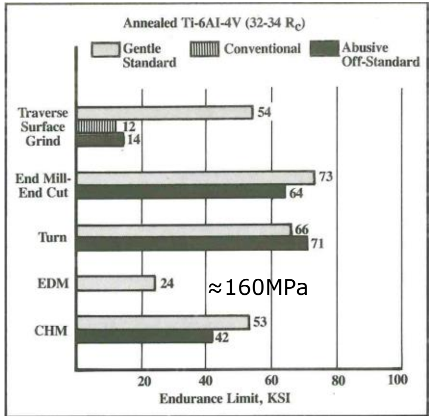
- Advantages
  - Wide range of properties depending on alloy and heat treatment
  - Tailor strength, toughness, ductility etc
  - CTE matches 440C bearings simplifying mechanism design
- Disadvantages
  - Expensive
  - Poor wear resistance
    - Needs additional protection to avoid fretting
  - Poor fracture toughness
    - Can be improved using ELI
      - Extra Low Interstitial alloys



Titanium Processing

- Processes using usual shaping, forming and machining techniques
  - Forging can produce anisotropy
- Electro-discharge machining (EDM) embrittles the surface
  - Surface layer ≈50µm must be removed
- Titanium adsorbs oxygen and nitrogen above ≈500°C
  - Generates a brittle alpha-case layer
  - Process in vacuum or post machine to remove alpha-case
  - Generally easier to remove layer
    - Can be difficult to generate a clean enough vacuum to guarantee no contamination
  - Fusion welding must be done under a protective atmosphere
    - Reject any surface coloured more than a pale yellow ‘straw’





Titanium Embrittlement

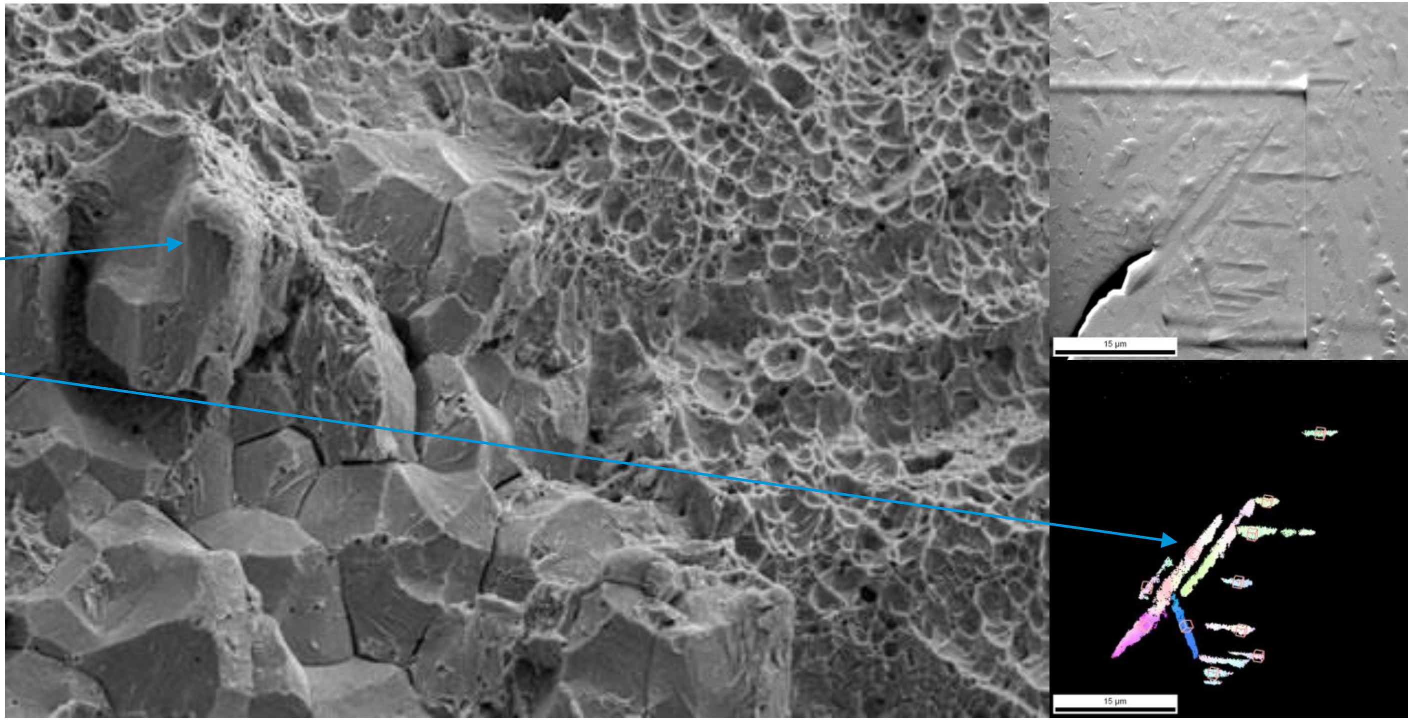
- EDM
- Hydrogen, Oxygen and Nitrogen contamination
- SCC
    - Generally very good in our environments
    - SCC when oxygen, or oxygen containing chemicals are excluded
        - hydrochloric acid, chlorinated cutting oils and solvents, methyl alcohol, fluorinated hydrocarbons, mercury and compounds containing mercury
- Solid Metal Embrittlement (SME)
    - Elevated temperatures
    - Cadmium >260°C, Silver >220°C, Gold >250°C

Titanium and Hydrogen

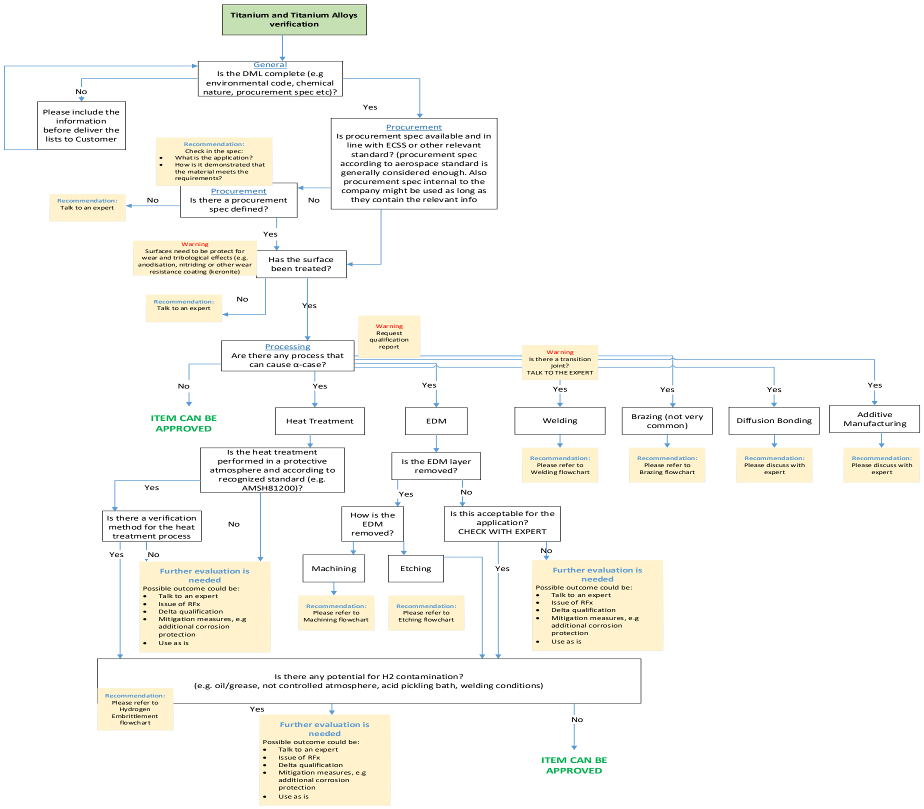
Produces:

embrittlement

hydride formation



Titanium Approval

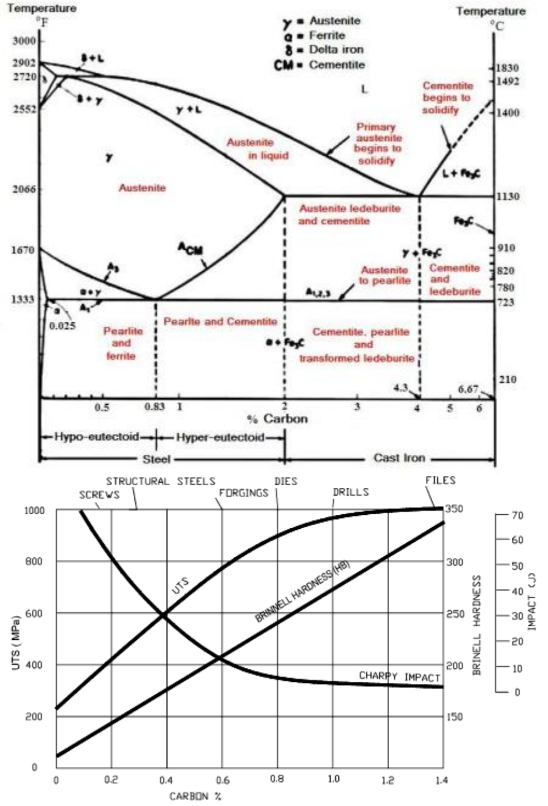


Titanium in Space Environment

Vacuum	Poses no special problems. All metals in contact under vacuum conditions or in inert gas have a tendency to cold weld. Enhanced by mechanical rubbing or any other process which can remove or disrupt oxide layers. Fretting is a particular concern for titanium alloys. Anodised finish required to mitigate fretting
Radiation	At the level existing in space does not modify the properties of metals. Proton radiation can embrittle titanium alloys, particularly Ti6Al4V Not usual at the radiation levels seen in typical flights
Temperature	Problems are similar to those encountered in technologies other than space Complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling.
Atomic oxygen	No significant effect on titanium

Group 5: Steels

- Iron carbon alloys
- “The world turns round on steel” Trevor Gouch
- General corrosion tends to mean limited application in Space business
- Stainless steels (>12%) Chromium typical solution
- 52100 bearing systems now replaced by 440C
    - Not as good a bearing but better corrosion resistance



Steel Precautions

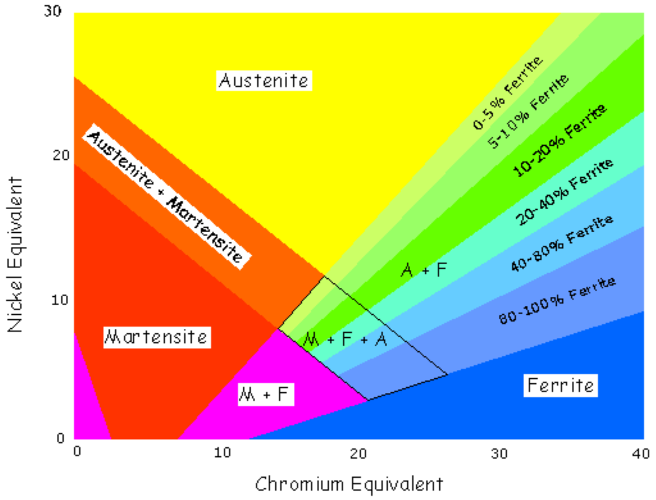
- Carbon and low-alloy steels with ultimate tensile strengths below 1225 MPa (180ksi) are generally resistant to stress-corrosion cracking.
- Some steels have a ductile-brittle transformation which, depending on the alloy composition, can occur within the normal service conditions for some space components.
- Depending on the alloy, some steels exhibit poor weldability. This is linked to the carbon content (or carbon-equivalent value) and can produce brittleness in the weld affected zone.
- Steels are prone to corrosion in atmospheric and acidic aqueous solutions.
    - Protection from direct expose to the environment can significantly reduce corrosion
- Low-alloy steels, depending on the composition, tend to have better resistance to atmospheric corrosion.
    - Addition of alloying elements can stabilize oxide formation, eg copper
- High-alloy steels with nickel contents >3% show improved resistance to atmospheric and marine environments.
- Higher strength steels are also prone to SCC in seawater and other chloride solutions.

Steel in Space Environment

Vacuum	Poses no special problems. All metals in contact under vacuum conditions or in inert gas have a tendency to cold weld. This phenomenon is enhanced by mechanical rubbing or any other process which can remove or disrupt oxide layers.
Radiation	At the level existing in space does not modify the properties of metals.
Temperature	Problems are similar to those encountered in technologies other than space, but are complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling.
Atomic oxygen	No significant effect

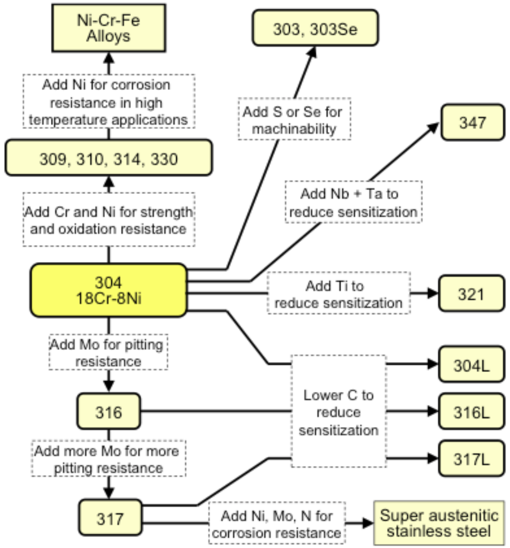
Group 6 Stainless Steels

Austenitic	Derived from the basic 18Cr/10Ni compositions (300 series), or higher strength versions in which some of the Ni-content has been replaced by nitrogen and manganese (200-series). Strength is increased by cold-working and properties are retained at low temperatures.
Ferritic	400-series materials contain between 11-30%Cr and a maximum of 0.1%C. Often used in the annealed or cold-worked condition, increased strength can be obtained by heat-treatment.
Martensitic	Also within the 400-series, normally have chromium contents between 11 and 18%. Some can be heat-treated to give high tensile strengths (>1400MPa).
Precipitation Hardening	Based on martensitic or duplex grades with additions of copper and aluminium for precipitation hardening. They can be heat-treated to give high strengths combined with high corrosion resistance.
Duplex	Mixed ferritic/austenitic microstructures. High Cr and Mo contents provide pitting corrosion resistance and reasonable resistance to SCC in chloride environments, (i.e. better than some austenitic grades).



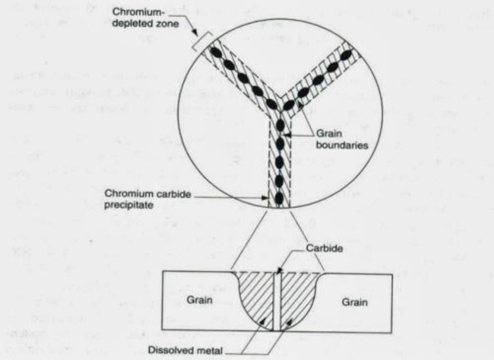
Stainless Steels Processing

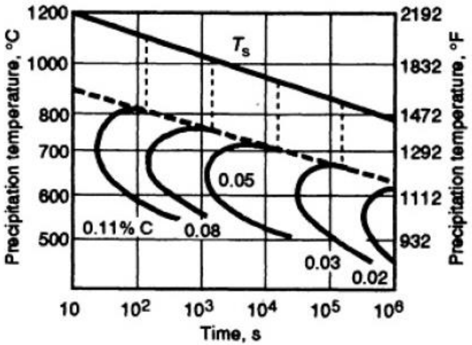
- Use of stainless steels in spacecraft centre on applications requiring corrosion resistance, components within some thermal protection systems and fasteners.
- Most conventional processing techniques are applied to steels
  - machining, welding, fastening, etc
- Care is required with some alloys that the processing does not degrade the microstructure, hence properties.
- Welding can affect the corrosion resistance of the weld and heat-affected zone (localised reduction of Cr-content) and produce heat distortion of the assembly.
  - Correct choice of filler rod is important.
- Aircraft specifications for heat-treatments and processing are used.



Sensitisation

- Chromium within the alloy may react with carbon and form localised Cr-depleted areas and brittle compounds, normally at grain boundaries.
- Effect is known as 'sensitisation' and can have serious consequences for corrosion resistance, especially stress-corrosion cracking.
- 'Stabilised' stainless steels have alloying additions (Ti, Mo, Nb) specifically to 'tie-up' carbon as carbides and so prevent sensitisation (also known as weld decay).
- Unstabilised, austenitic steels have a service temperature limit of 370°C.
- With the exception of stabilised or low-carbon grades (such as 321, 347, 316L, 304L), welded assemblies require solution treating and quenching after welding.

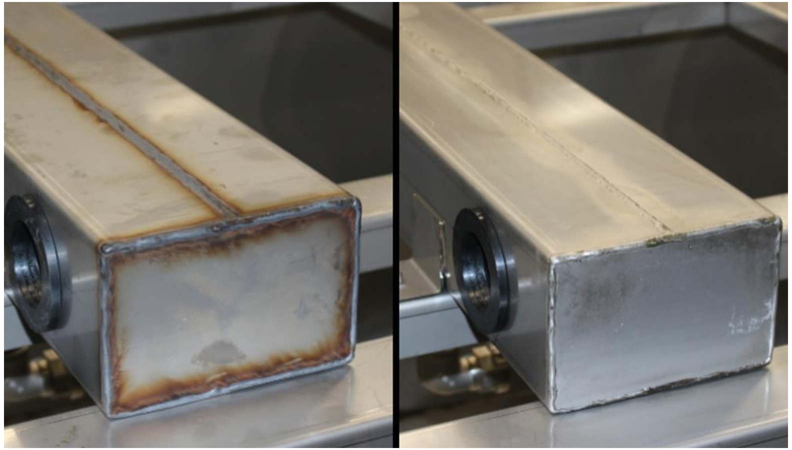




Sensitisation curve for 304

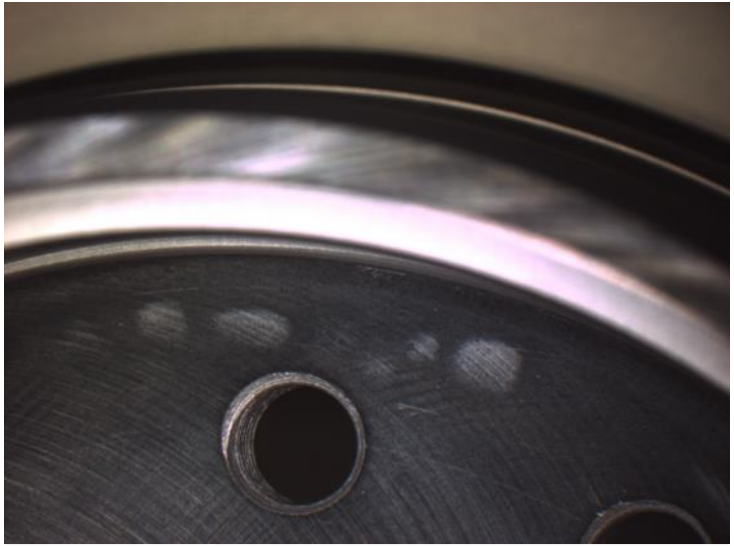
Passivation of Stainless steels

- Most stainless steels are relatively soft
- During processing they often pick up small amounts of ferritic debris
- Ferrite is anodic to the stainless steel and corrodes
- The corrosion polarises the surface attracting ions and lowering the pH whilst limiting oxygen access
- Limited oxygen allows the corrosion to propagate into the stainless steel
- Good practice is to passivate stainless steels by treating with a weak acid to remove any embedded ferrite
- Standards or PARD often contain the requirement:
    - *Stainless steels shall be passivated*



Passivation Recommendations

- Austenitic stainless steels that have been handled, welded or machined
  - Passivate
- Ferritic steels
  - Tend to be harder than austenitic grades
  - Risks of particle pickup are reduced.
  - Chromium rich ferrite will be cathodic to a ferritic carbon steel
  - Passivate
- Martensitic stainless steels
  - Usually very hard
    - do not tend to collect embedded particles
  - Sensitive to adsorbed hydrogen
    - by-product of the acid passivation process
      - particularly if the passivation solution becomes contaminated
    - diffuses to areas under tensile strain and can produce delayed fracture.
  - Passivation not recommended



Recommendation	Alloy
Passivate	301, 303, 304, 316, 321, 347, 410L, 430, 430Ti, 434, 660
Do not passivate	410, 420, 430F, 431, 440C, 630

Stainless Steel Precautions

- Austenitic stainless of the 300-series and the and ferritic steels of the 400 series are generally resistant to stress-corrosion cracking below 60°C.
- Martensitic stainless steels of the 400-series are more or less susceptible, depending on composition and heat treatment.
- Precipitation hardening stainless steels vary in SCC susceptibility from extremely high to extremely low, depending on composition and heat treatment.
  - Susceptibility of these materials is particularly sensitive to heat treatment, and special vigilance is required to avoid problems due to SCC.
- Stainless steel parts and fabrications normally require careful cleaning prior to operation in service.
  - Cleaning processes are normally chemical pickling using various combinations of acids, the residues of which also have to be removed thoroughly.
  - Some grades may be susceptible to hydrogen embrittlement resulting from hydrogen pick-up during pickling processes.

Stainless Steels in Space Environment

Vacuum	Poses no special problems. All metals in contact under vacuum conditions or in inert gas have a tendency to cold weld. This phenomenon is enhanced by mechanical rubbing or any other process which can remove or disrupt oxide layers.
Radiation	At the level existing in space does not modify the properties of metals. Neutron activation of the chromium alloying additions can occur Produces slightly radioactive materials
Temperature	Problems are similar to those encountered in technologies other than space Complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling.
Atomic oxygen	No significant effect on stainless steels

Group 7: Filler metals: welding, brazing soldering

- General
  - Fusion joining techniques produce permanent joints. Soldered joints and some brazed joints can be disassembled with care.
- Use in spacecraft
  - Welding is a common fabrication method for metals used in spacecraft.
  - Brazing usually refers to joining with alloys of copper, silver and zinc and is preferred to soldering when stronger joints and an increase in temperature resistance is required.
  - Soldered joints are used for electrical and thermal conducting paths and for low mechanical strength joints. Soldering is commonly referred to as 'soft-soldering' in which low-melting point alloys, such as tin-lead or indium-based materials are used.
  - Brazing and soldering not permitted for structural joints in manned applications

Filler metals: welding, brazing soldering

- Detailed in aerospace standards and specifications
- Comments on weld filler materials also apply to braze metals and processes.
- Braze fillers different from the parent weld materials
    - Galvanic couples and other corrosion needs consideration.
- Solder alloys that are acceptable for use in electronic assemblies in space, and their associated fluxes and process chemicals (solvents; cleaning baths, etc), have been subject to intense evaluation, see the tables 'Guide to choice of solder-types for space use' and 'Representative products' table (from ECSS-Q-ST-70-08C).
- Solder alloys consist of the tin-lead and indium-lead alloys defined in ECSS-Q-ST-70-08C and ECSS-Q-ST-70-38C.
    - Must be procured according to these specifications
        - Define purity levels and, where necessary, fluxes of suitable formulation for the assembly of spacecraft electronics.
- ECSS-Q-70-40C Brazing about to be released

Solder types for space use

Solder Type	Solidus	Liquidus	Use
63 tin solder (eutectic)	183	183	Soldering PCBs where temperature limitations are critical and in applications where an extremely short melting range is required.
62 tin silver loaded	175	189	Soldering of components having silver-plated or 'paint' finish, i.e. ceramic capacitor. This solder composition is saturated with silver and prevents the scavenging of silver surfaces.
60 tin solder	183	188	Soldering electrical wire/cable harnesses or terminal connections and for coating or pre-tinning metals.
96 tin silver (eutectic)	221	221	May be used for special applications such as soldering terminal posts.
75 Indium lead	145	162	Special solder used for low temperature soldering process when soldering gold and gold-plated finishes.(smd). Can be used for cryogenic applications
70 indium lead	165	175	For use when soldering gold and gold-plated finishes when impractical to degold.(smd)
10 tin lead	268	290	May be used for special applications such as soldering terminal posts.

Approved solder compositions for space use

Composition		63 tin solder (eutectic)	62 tin silver-loaded solder	60 tin solder	96 tin silver solder (eutectic)	10 tin lead solder (10/90)
	Min%	62.5	61.5	59.5		9
Tin (Sn)	Max%	63.5	62.5	61.5	remainder	10.5
Lead (Pb)	Max%	remainder	remainder	remainder	0.10	remainder
Antimony (Sb)	Max%	0.05	0.05	0.05	0.12	0.05
	Min%	-	1.8	-	3.5	-
Silver (Ag)	Max%	-	2.2	-	4.0	-
Bismuth (Bi)	Max%	0.10	0.10	0.10	0.10	0.10
Copper (Cu)	Max%	0.05	0.05	0.05	0.05	0.05
Iron (Fe)	Max%	0.02	0.02	0.02	0.02	0.02
Aluminium (Al)	Max%	0.001	0.001	0.001	0.001	0.001
Zinc (Zn)	Max%	0.001	0.001	0.001	0.001	0.001
Arsenic (As)	Max%	0.03	0.03	0.03	0.03	0.03
Cadmium (Cd)	Max%	0.002	0.002	0.002	0.002	0.002
Others	Max%	0.08	0.08	0.08	0.08	0.08

Assembly and Precautions

- Aircraft standards and specifications are normally applied.
    - Other critical industry sectors (nuclear, power-generation, etc) may offer guidance on specialist materials.
- Personnel must have appropriate training and certification to produce reliable joints.
- Not all metals and alloys can be joined by welding or brazing.
- Heat-affected zone (HAZ) and the parent (base) metals must be considered.
- Not all 'industrial' welding techniques can be used on all materials.
- Brazing is normally restricted to joints in structural parts that experience shear loading rather than tensile loading.
- Fluxes may be corrosive and must be removed
    - Residues of chemicals or processes used for flux removal must also be cleaned from components.
- Common soldering fluxes, their application and use are detailed in ECSS-Q-ST-70-08.
    - Rosin based systems may break down at higher temperatures (<315°C, cf High lead solder)

Group 8: Miscellaneous metallic materials

- Metal is classed as miscellaneous if it does not fall within another Declared Materials List (DML) group in ECSS-Q-ST-70C.
- Also included in this section are comments on metal-based materials that are either prohibited or should be approached with caution for space applications.

Miscellaneous metals: Use in spacecraft

- Beryllium and Beryllium alloys
    - High specific stiffness
    - Commercially pure or Al-Be alloys
    - Often coated to limit contamination risks
- Precious metals
    - Gold, silver, Platinum, etc
    - Coatings and specialist sensors
- Germanium
    - Transparent in infrared
    - Optics and coatings
- Refectory Metals
    - Tungsten, molybdenum
    - Wires, filiements, shielding, coatings
- 'Memory alloys' based on titanium and nickel may find uses as actuators
- Superalloys
    - Often cobalt based
    - High temperature and/or specific corrosion issues Similar to the Group 3 Nickel alloys)
- In addition to standard conventional alloys, more recent material developments include:
    - reinforced alloys (metal matrix composites - MMC) consisting of magnesium alloys reinforced with carbon fibres;
    - lithium additions to conventional magnesium alloys;
    - reinforced silver alloys.

Special Metals Assembly

- Magnesium alloys are available as wrought forms or for casting.
    - Care is needed in storing magnesium alloys due to their tendency to corrode.
    - Turnings and swarf can be highly flammable
- Processing of beryllium requires sophisticated techniques and rigorous safety procedures to avoid the formation and release of beryllium oxide, metal particles and compounds which are toxic and carcenogenic.
- Superalloys are processed following recognised aerospace procedures or other appropriate industry standards.
- Specialist methods for processing refractory metals and alloys are applied.

Miscellaneous Metallic Precautions

- Magnesium alloys
  - Dusts of magnesium and its alloys are flammable; requiring special safety measures.
  - Some magnesium alloys (with thorium) may have a slight residual radioactivity.
- Refractory alloys are generally selected for extreme high-temperature applications where other metals cannot be used.
  - Engineering data on refractory alloys are limited, especially under the extreme environments encountered on spacecraft.
  - Recrystallization can result in brittleness

Beryllium Alloys

- Beryllium
  - Commercial Purity, strength modified with oxide additions
    - Oxide additions can affect polishing characteristics
- AlBeMet 162 (AM162H)
  - 62%Be38%Al alloy, sometimes referred to as a composite
  - Direct replacement for aluminium alloys
    - Processing very similar to aluminium
- AlBeMet 140
  - 40%Be58%Al
    - No longer available ?
- N.B. Copper Beryllium
  - Only 2% Be, not considered a Be alloy

Beryllium Health Effects

- Beryllium and its compounds
  - **Toxic, carcinogenic and sensitizing**
  - Main issue with dust and fine particles
- Acute Beryllium Poisoning
  - Chemical pneumonia from the toxic effects
  - Doubles the risk of lung cancer
  - Exposure at levels >100 μg/m^3
- IARC Group 1 carcinogen
  - Carcinogenic to humans
- Berylliosis
  - Allergic lung response and disease
    - Prevalence between 9% and 19% depending on industry
  - Granuloma form in the lung as immune system attempts to seal substance

Beryllium Safety

- No special risk from finished products
- Avoid inhaling dust or particles
- All machining operations to be carried out to control release of dust
  - Fully enclosed hooding
  - Interlocked ventilation
  - Discharged through filters and away from air intakes
  - Grinding very difficult to control
- Avoid contact with skin
- Containerize soiled clothing and towels
- Prohibit use of compressed air cleaning

Permissible Exposure Limit (PEL)	0.2 μg/m^3
8-hour Time Weighted Average (TWA)	0.2 μg/m^3
Short-Term (15min) Exposure Limit (STEL)	2.0 μg/m^3

Be Properties: Manufacturer Data (S-Value)

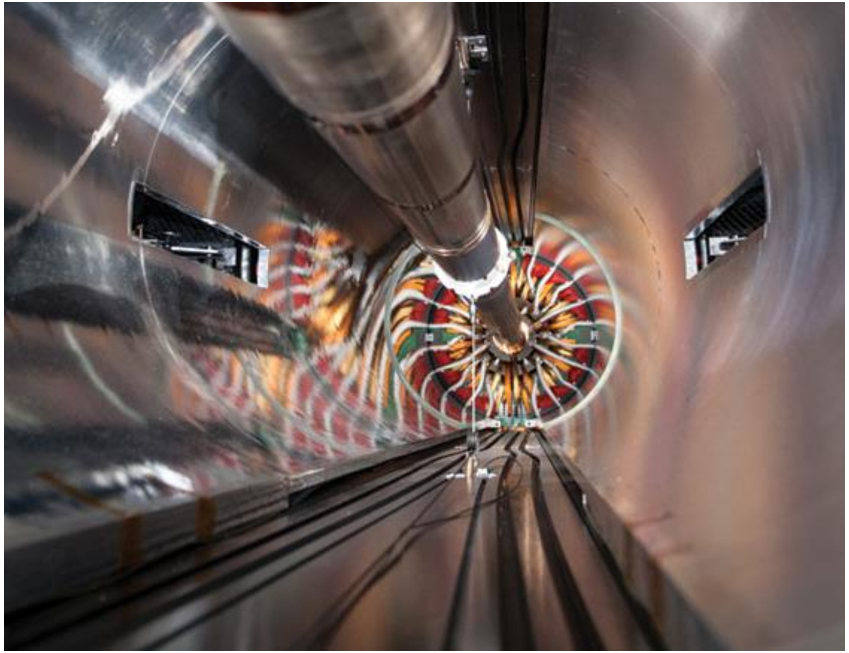
Property	S200F (AMS 7906)	S200FH (AMS 7908)	AlBeMet 162 (AMS 7911)
Density (kg/m^3)	1850	1850	2100
Modulus (GPa)	290	303	193
UTS (MPa)	324	414	288
Yield (MPa)	241	296	221
Elongation (%)	2	3	7
Fatigue Strength (MPa)	262	214	207
Thermal Conductivity (W/m.K)	216	216	210
Heat Capacity (J/g.K)	1.95	1.95	1.56
CTE (ppm/K)	11.3	11.3	13.9
Electrical Conductivity (%IACS)	45	45	49

Beryllium Space Applications

- Mirrors
    - Excellent specific stiffness,
    - Polishable
        - Can be polished bare but often nickel or gold plated for a better finish
    - Thermal stability
    - JWST
- Structure
    - Specific stiffness
    - Thermal conductivity
    - Shuttle window and door frame, Spitzer, Hubble
- Heat shields
    - Mercury Spacecraft

Beryllium Available Forms

- Usually starts as powder
- VHP and HIP blocks
  - Vacuum Hot Pressed and Hot Isostatic Pressed
  - Can be near net shape
- Plate and Sheet (< 6.350 mm, 0.250")
- Extrusions
- Tubes



Beryllium Machining

- Machining behaviour similar to cast iron
- Can result in surface damage (up to 50 µm)
    - Will significantly reduce tensile and fatigue properties
    - Final etching (≈100 µm) or heat treatment required
    - Damage avoided with chemical milling
- Use specialist machine shops
    - ExoTec Precision, Taunton, UK (https://www.exotecprecision.com/)
    - Atmostat, Villejuif, France (https://www.atmostat-alcen.com/en)
    - Rigo, Sersheim, Germany (http://www.rigogmbh.de/)

Beryllium Joining

- Brazing
  - Most reliable method
  - Use silver or aluminium braze,
    - Zinc based possible but only for pressurised applications
- Adhesive bonding
  - Surface preparation critical
  - Usually acid clean and neutralisation
- Fusion welding
  - In general not recommended
  - Be: EB possible but not recommended for high load applications
  - AlBeMet: Can be EB welded
- Diffusion bonding
  - Successful but not common

Beryllium Coating

- Passivation
  - Conversion coatings usually used
    - Alodine or Irridite following procedures for aluminium
    - NOTE: Affected by Cr(VI) REACH regulations
- Anodization
  - For corrosion protection of thermo-optical performance
    - Inorganic black chromic anodization available
- Plating
  - Possible but needs experience
  - Difficult plating cubic material on hexagonal substrate

Miscellaneous metallic Precautions cont.

- Refractory alloys are generally selected for extreme high-temperature applications where other metals cannot be used.
  - Engineering data on refractory alloys are limited, especially under the extreme environments encountered on spacecraft.
  - Recrystallization can result in brittleness
- Nickel-based and Cobalt-based superalloys possess various combinations of high-temperature mechanical properties and oxidation resistance up to approximately 550°C.
  - Many alloys also have excellent cryogenic temperature properties.
- Some metals, such as cadmium and zinc, are rather volatile and should not appear in space hardware.
  - Platings of these metals, as well as tin, are known to grow whiskers both in air and under vacuum.
    - Shall be excluded from all spacecraft and ground-support equipment.
- Porous platings are potential sources of danger and this occurs frequently with gold plate over silver.
- Osmium oxide is toxic; work on this material requires special precautions.

Cadmium plated steel parts

Miscellaneous metallic Precautions cont.2

- Mercury and mercury-containing compounds can cause accelerated cracking of Al and Ti alloys.
    - Prohibited substance

- In electronic assemblies, tin-, silver- and gold-plating on terminals of PCBs is removed in order to achieve an approved tin-lead finish.

- Soldering directly to gold finishes is unacceptable and de-golding processes are used. In unavoidable use of gold-finishes, such as in RF circuitry, selective plating processes are used for soldered connections.

Miscellaneous metals in Space Environment

Vacuum	Affects volatile metals, such as cadmium and zinc. These metals sublime readily at temperatures over 100°C and 150°C respectively, and may form conductive deposits on insulators or opaque deposits on optical components or SME on Ti alloys
Radiation	At the level existing in space does not modify the properties of metals.
Temperature	Temperature problems are similar to those encountered in technologies other than space, but are complicated by the difficulty of achieving good thermal contact in vacuum and the absence of any convective cooling.
Atomic oxygen	Attacks some metals, such as silver (solar-cell interconnectors) and osmium (extreme-UV mirrors).

Group 9 Optical Materials

General

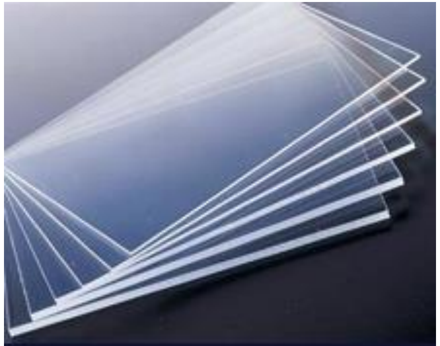
- The meaning of the word “glass” is extended to cover “organic glass” and some crystalline optical materials

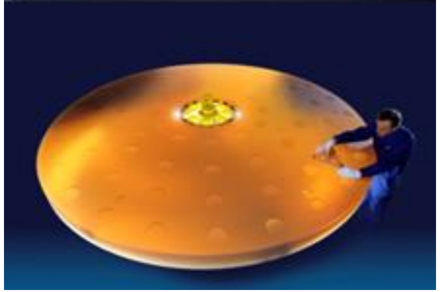
Use in spacecraft

- Glasses, inorganic as well as organic, appear as optical elements: e.g. windows, lenses, prisms, solar-cell covers and filters.

Main categories

- Optical materials can be grouped as:
    - inorganic glasses - such as silicates, alumino-silicates and boro-silicates;
    - organic “glasses” - polymers based on acrylic and methacrylic polymers, polycarbonate and some polystyrene grades;
    - crystalline optical materials - pure silica, sapphire and transparent fluorides.





Optical materials

- Precautions
  - Glasses are transparent only to a certain wavelength range and shall be chosen in accordance with the mission requirements.
  - Inorganic glasses are sensitive to mechanical and thermal shocks.
  - Organic glasses are easily scratched and lose their polish.

- Hazardous or precluded
  - Organic glasses should not appear in high-precision equipment except as plain windows or light-pipes.

Optical materials in Space Environment

Vacuum	Vacuum exposure does not affect inorganic glasses or most organic glasses.
Radiation	Radiation is the most harmful factor to be considered for glasses. Plastics can be damaged by particle and UV radiation. The result is, in general, a “yellowing”, and the damage under sunlight can be auto-accelerated by the increase in temperature due to higher absorption.
Temperature	Thermal shock can lead to fracture in inorganic glasses. Organic glasses soften at quite low temperature (80 ºC to 100 ºC frequently) and have rather high expansion coefficients.
Atomic oxygen	Atomic oxygen can attack organic glasses.

Group 13: Lubricants

Use in spacecraft

- All moving parts under vacuum, either “one shot” or constantly operating items, shall be lubricated.

Main categories

- Basic oils are hydrocarbons, silicones, diesters, polyglycols and fluorinated compounds.
- Laminar inorganic substances, such as MoS_2 and WS_2
    - ‘Dry’ Lubricants
- Lead (Pb)

Processing and assembly

- Application of oil or grease is straightforward.
- Dry lubricants are more difficult to apply and some processes are proprietary. In the case of metals, chemical and electrochemical plating can be used, as well as vacuum deposition.

Lubricants Precautions

- Problem to ensure that the lubricant stays where it is useful
    - Migrates to places where it is not wanted
    - Creep barrier may be needed
- Graphite is not a lubricant in vacuum, but an abrasive (it can be used in combination with other lubricating materials such as silver or MoS_2).
    - DLC can act as a lubricant in vacuum but properties change with water content
        - DLC must be tested in vacuum
- Lead does not have the bearing capacity of laminar substances
    - Can have better longevity

Lubricants in Space Environment

Vacuum	Vacuum effects are mainly the evaporation of oils and “dry-off” of greases. Surface “cleaning” due to vacuum encourages oils to creep out of their location; this is particularly so with silicones.
Radiation	Under radiation, oils have a tendency to evolve gases or corrosive products, to foam or to gel, but this needs rather high doses. Dry lubricants are quite resistant to all types of radiation.
Temperature	Normally, friction generates higher temperatures in space than on the ground for the same part: this is due to the difficulty of eliminating heat under vacuum
Atomic oxygen	Atomic oxygen can degrade MoS_2 and similar solid lubricants which are exposed to it.

Group 20: Miscellaneous non-metallic materials

General

- This covers ceramic-type materials used for space engineering applications.
    - These materials are generally known as advanced technical ceramics (ATCs): a term that encompasses a wide range of material types used in engineering applications for mechanical, electrical or thermal characteristics or some combination thereof.
- Also covers “Functional” ceramics, e.g. piezoelectric.

Use in spacecraft

- Structural uses of ceramics for extreme service temperatures, aggressive environmental and or thermally stable structures;
- Ceramics and glasses are used in electrical and electronic equipment subassemblies (electrical insulators).

Precautions

- The brittle characteristics of ceramics and glasses, along with the scarcity of reliable characterization of their properties and in-service performance mean that they are not among the routine structural materials applied to spacecraft.

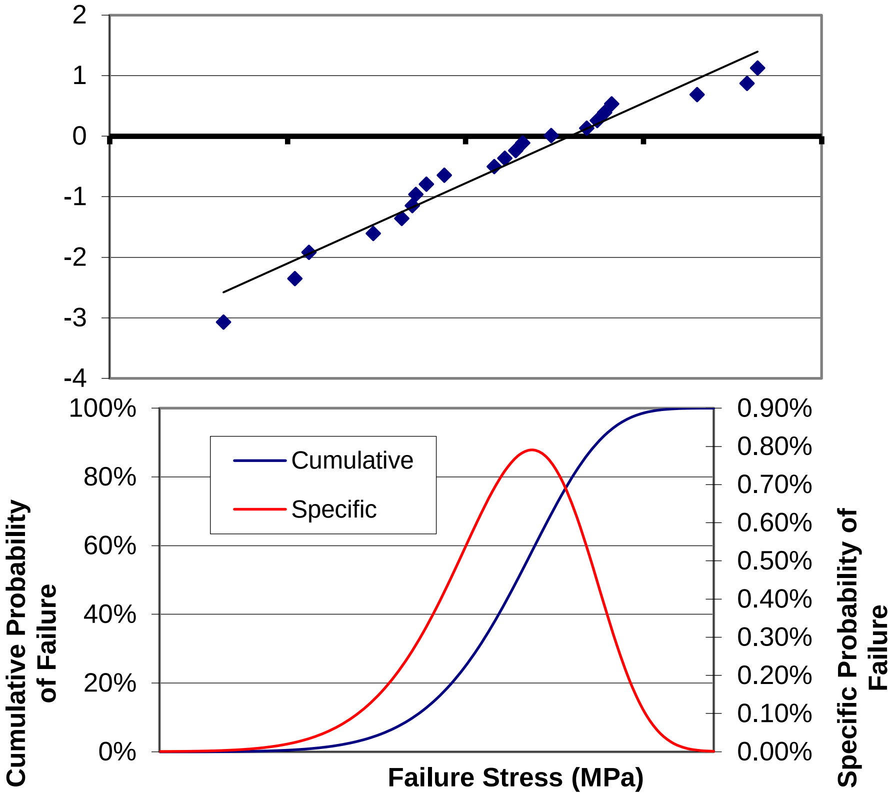
Hazardous or precluded

- Specialist safety equipment and procedures shall be applied when operators are working with ceramic fibres and fine powders or processing methods that produce dust and debris.

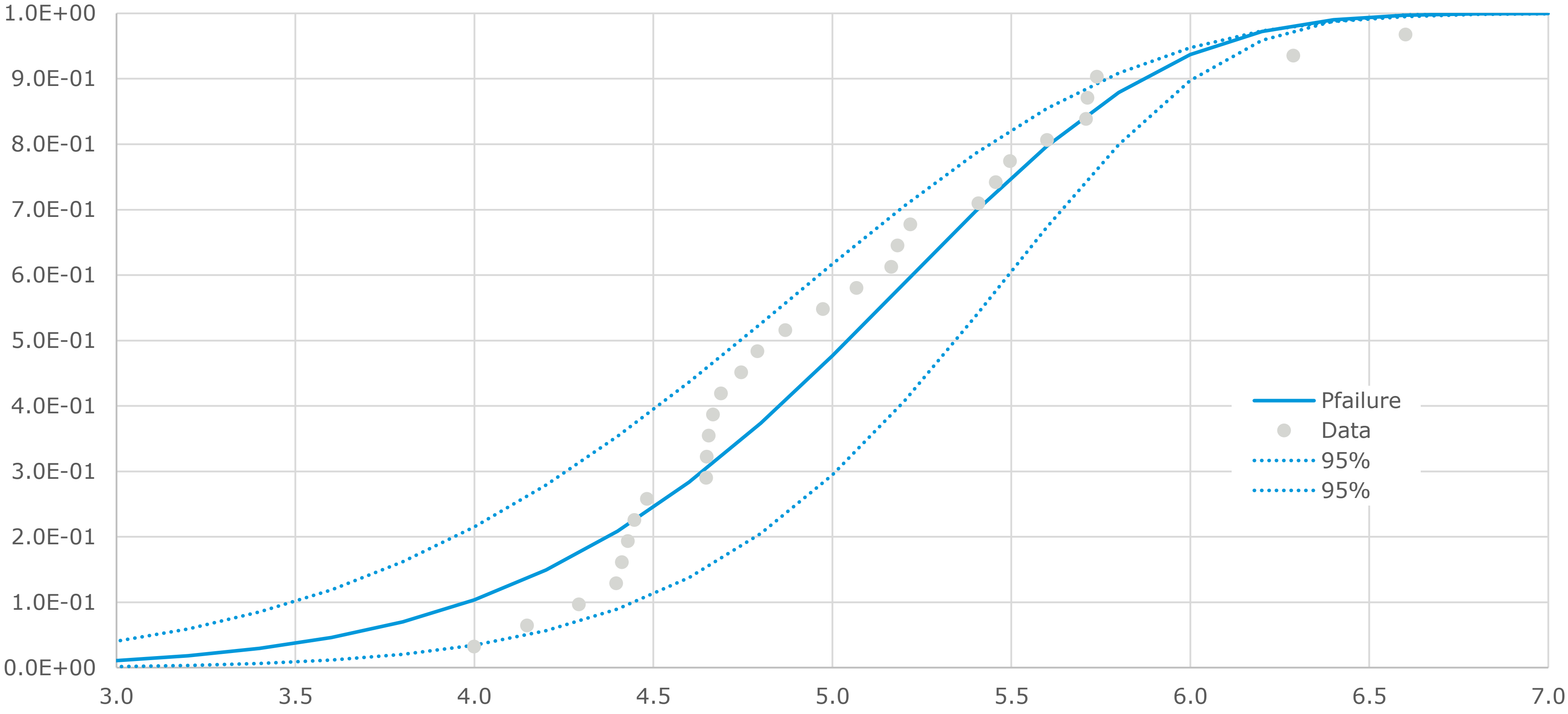
Failure of Ceramics

- Needs probabilistic approach
  - Not deterministic
- Behaviour can be modelled using Weibull distribution
  - Plot Ln(failure load) vs Ln(Ln(P_f))
- Static loads have addition effects
  - Sub-Critical Crack Growth

$$P_S(V) = \exp\left[-\frac{V}{V_0}\left(\frac{\sigma - \sigma_U}{\sigma_0}\right)^m\right]$$



2 Parameter Wiebull

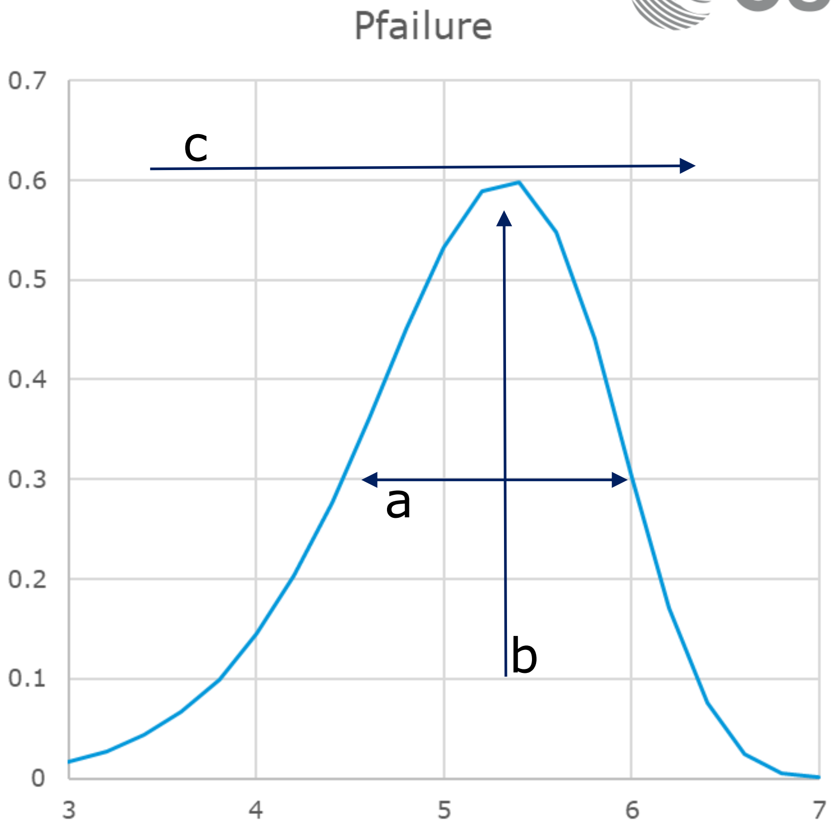


2 vs 3 Parameter Weibull

- 3 Parameter

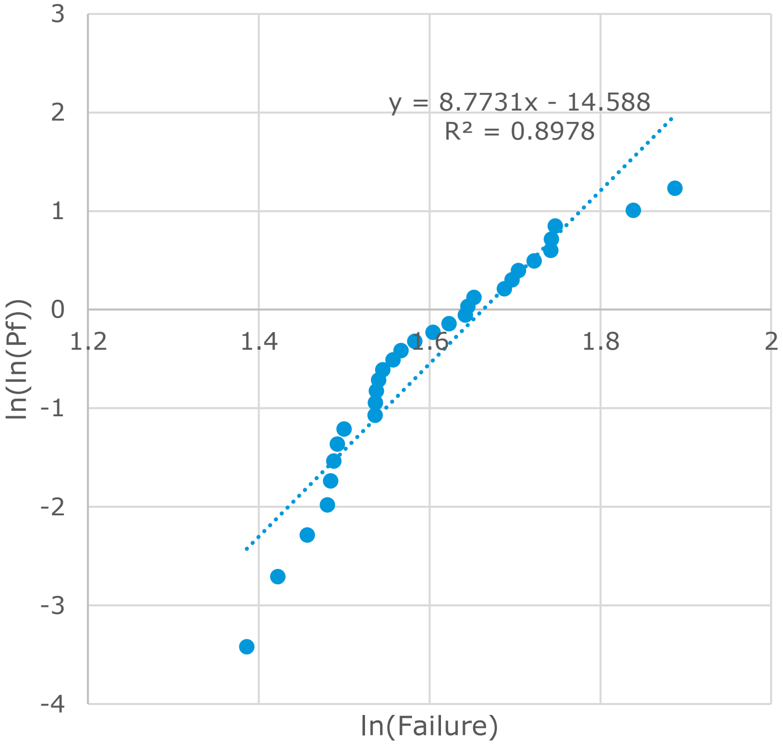
$$P_f = \frac{a}{b}\left[\frac{(x-c)}{b}\right]^{a-1} e^{-\left[\left[\frac{(x-c)}{b}\right]^{a}\right]}$$

  - a: shape parameter,
  - b: scale parameter, and
  - c: location parameter
    - Implies minimum defect size
- 2 parameter, fixes location (c)



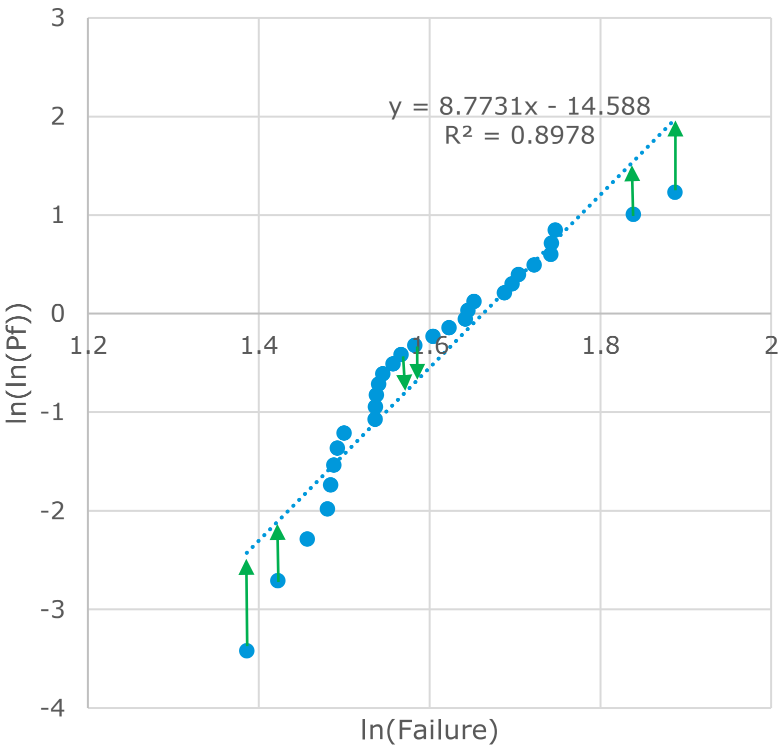
Reasons Plot is not Linear

- In no particular order:
  - Noisy Data
  - Poor assignment of failure probability
  - Sample fracture does not follow Weibull distribution
  - Multiple Fracture Modes
  - Threshold defect size
    - i.e. location parameter greater than zero



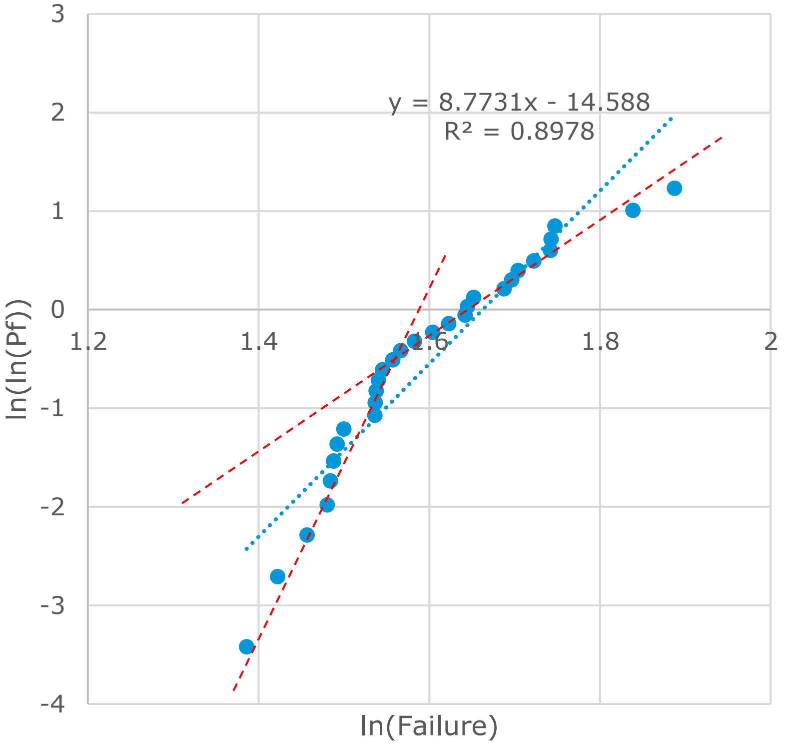
Poor assignment of failure probability

- Failure probability assigned on a linear scale
  - 30 samples ranked weakest to strongest
  - P_f assigned as [Rank/31]
  - Some models improve this distribution but the differences are marginal
- Small changes in probability distribution could bring the distribution to a straighter line
  - Least Squares fit particularly susceptible at extremes
  - MLE, Maximum likelihood Estimation, helps



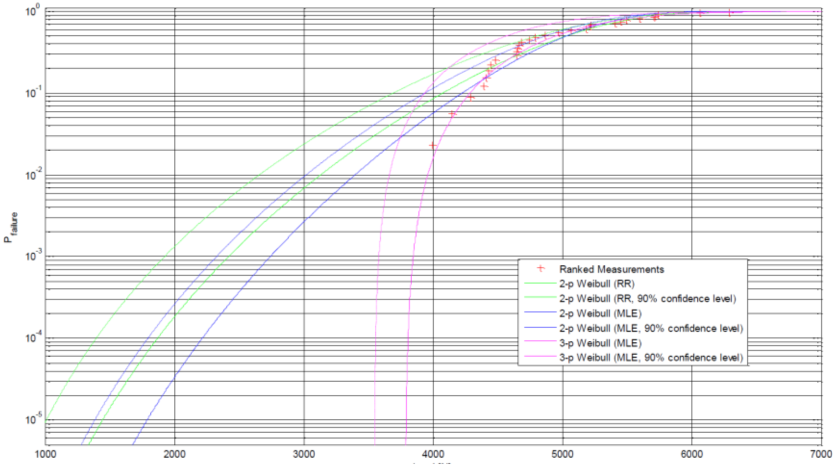
Multiple Fracture Modes

- Plot of $Ln(Ln(P_f))$ verses Ln(Failure Load) should be a straight line for a single failure mode
- Usually true for test samples
- May not be true for manufactured parts
    - E.g. Failure initiating at a machining defect might be expected to show a different distribution to material flaws
- Red dotted lines could fit with multiple failure modes



Threshold defect size

- Minimum defect size in the material
  - i.e. defects below a certain size do not affect failure
  - Location parameter >0
- MLE (Maximum likelihood Estimation) often used
  - EN 843-5 *Advanced Technical Ceramics –Mechanical properties at room temperature – Part 5: Statistical Analysis*
  - ISO 20501 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Weibull statistics for strength data*



Miscellaneous non-metallic materials in Space Environment

Vacuum	Vacuum can provoke outgassing of residual processing-related materials or moisture. For fibrous materials a baking process prior to assembly shall be performed. Application of coatings also includes a baking out process. Shaped ceramic parts are often sealed (glazed) to prevent outgassing.
Radiation	Radiation at the levels experienced in space, does not affect the characteristics of ceramics.
Temperature	Ceramics are selected for their high-temperature and service environment resistance. Aggressive environments can attack some ceramics. Thermal gradients can induce significant stresses and lead to failure. Thermal-cycling can promote cracking in solid shapes and coatings. Differences in CTE between the substrate and the applied coating can promote cracking and spalling of the coating.
Atomic oxygen	No evidence that ceramics are susceptible to ATOX.

MECHANICAL PARTS

Mechanical part group numbers

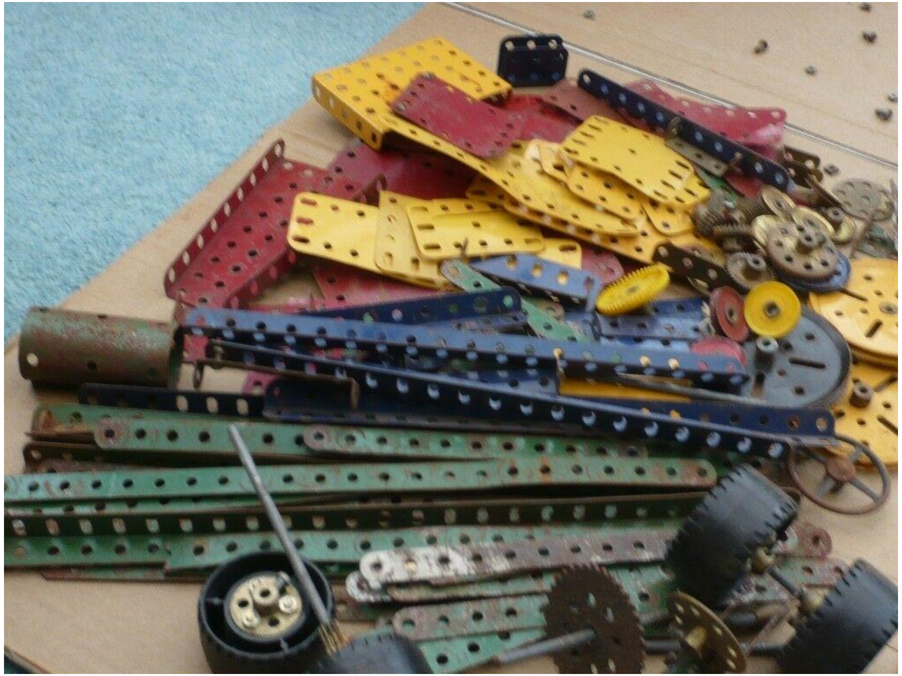
Group number	Description
51	Spacing parts (e.g. washers and spacers)
52	Connecting parts (e.g. bolts, nuts, rivets, inserts and clips)
53	Bearing parts (e.g. ballbearings and needle bearings)
54	Separating parts (e.g. pyrotechnics, springs and cutters)
55	Control parts (e.g. gears)
56	Fluid handling parts (e.g. diffusers)
57	Heating parts
58	Measuring instruments (e.g. gauges and thermocouples)
59	Optical passive equipment
60	Magnetic parts
61	Other parts

DMPL

DECLARED MECHANICAL PARTS LIST (DMPL)										
Programme name: ABCDEFG				CI no.: 12345676890 Group (Title): abcdefg		Doc no.: 001 Issue/Revision: 1/4		Date: 01.10.2000 Page: 1		
								9		
1	2	3	4	5	6	7	8	9.1	9.2	10
Item no. and user code	Commercial identification	Type of part	1) Procurement specification 2) Issue/Revision/ Date	1) Elementary function 2) Main characteristics	1) Subsystem 2) Equipment 3) Use	1) R 2) A 3) T	1) Criticality 2) Reason and method of control	1) Supplier Reference 2) prime comments	Prime approval status	Customer approval status/comments
51.2.1.ACSA	ESA003521000 120	Copper/AL bimetal ring	1) AIEV 2) From catalogue	1) Separator ring 2) Heat conductor	1) TC 2) Plate interface 3) Spacing and heat inspection	1) G 2) V 3) 3-4	1) N 2)	1) Used on all projects 2)	A	A
52.2.1.ASAD	A0090TX...XA	Ti6Al4V screws > M4	1) White areo 2) ASNA0090 DSN2413	1) assembly 2)	1) PTANK 2) plate 3) fixing	1) G 2) V 3) 3-4	1) N 2)	1) Used on TC2 2)	A	A
60.1.1.ACSA	42908TC/F	Ferrite cores magnetic	1) Magnetics, Data sheet 2) SP/MAGN/003 01.02/03.06.1999	1) Coil core of transformer 2) Magnetic component	1) TC 2) South face 3) Heat regulation	1) G 2) V 3) 3-4	1) C 2) to be qualified	1) 2)		

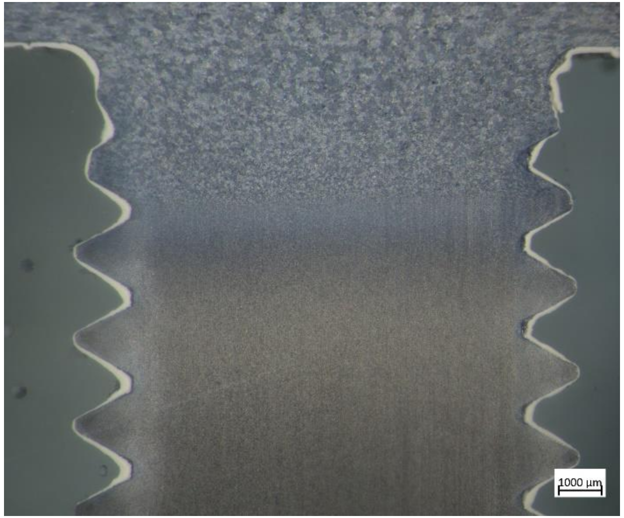
Mechanical Parts

- Almost all can be considered in terms of their materials
- Exceptions are:
  - Screws
  - Bearings
  - Magnetic Parts



Group 52: Connecting Parts

- ECSS-Q-ST-70-46C *Requirements for manufacturing and procurement of threaded fasteners*
- Primary Structure: ECSS-Q-ST-70-46C
- Secondary Structure: Aerospace Grade
    - Differences covered by the degree of NDI
- Avoid getting substandard screws into the supply chain
    - They will get incorporated into flight hardware!
        - DIN 912, ISO 4762, etc
        - Zinc and Cadmium plated



DIN 912 Ti6Al4V M8 screw
Drawn bar, cut thread, upset forged head

Connecting Parts

Stainless Steel

A2, A4, 660, Inconel

- 718, MP35N (Not stainless)

>30% elongation to failure

Can take abuse

Smaller than M5 shall not be used for safe life applications

Slightly magnetic from δ-ferrite

Use Phosphor Bronze Inserts

- Stainless steel inserts cold weld and cannot be removed without damage
- Can be silver plated as a lubricant

Titanium

Grade 5, Ti6Al4V

Non-magnetic

Strong

Failure if overtightened

- Shall not be used for safe life applications
- Now allowed under some conditions

Use stainless steel helicoils

Solid Metal Embrittlement in contact with hot silver

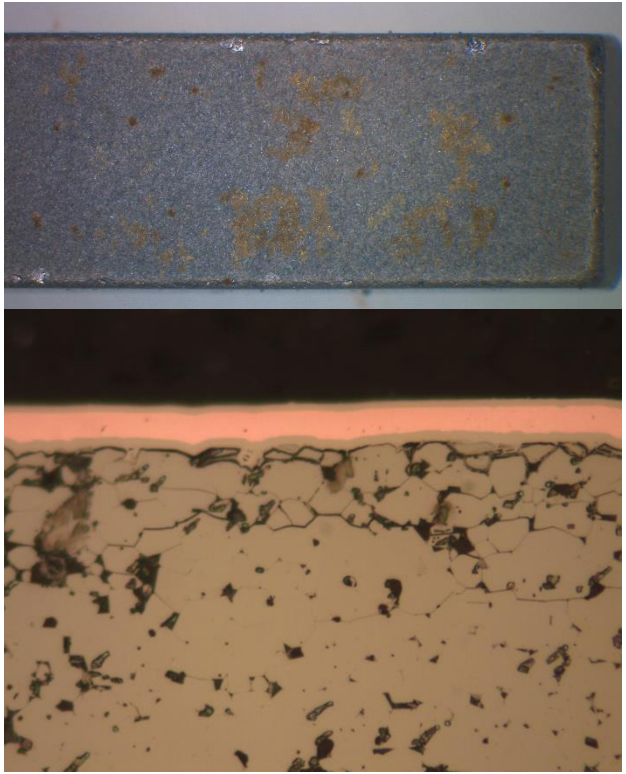
- Do not use with silver plated nuts designed for stainless screws

Group 53: Bearings

- Most good bearings have a martensitic structure
  - Sensitive to hydrogen embrittlement
    - MoS_2 makes this worse
  - Only acceptable because bearings in compression
  - Light-weighting of bearing structure can lead to tensile stresses
  - Avoid acid treatments such as passivation
- Most systems now use 440C
  - 16% Chromium so classed as stainless
  - 1% Carbon ties up a significant proportion of the Cr
    - Effective Cr ≈12% so corrosion can be an issue
    - Bearings need to be clean, dry and correctly stored to avoid corrosion.
  - CTE of 440C matches titanium alloys
    - Can be convenient when building mechanisms

Group 60 Magnetic parts

- Neodymium-Iron-Boron, NdFeB
- Very effective magnet material
- Needs a slight excess of Nd rich phase
    - Very reactive and will corrode
- System difficult to plate
- Can be easier to select SmCo system instead

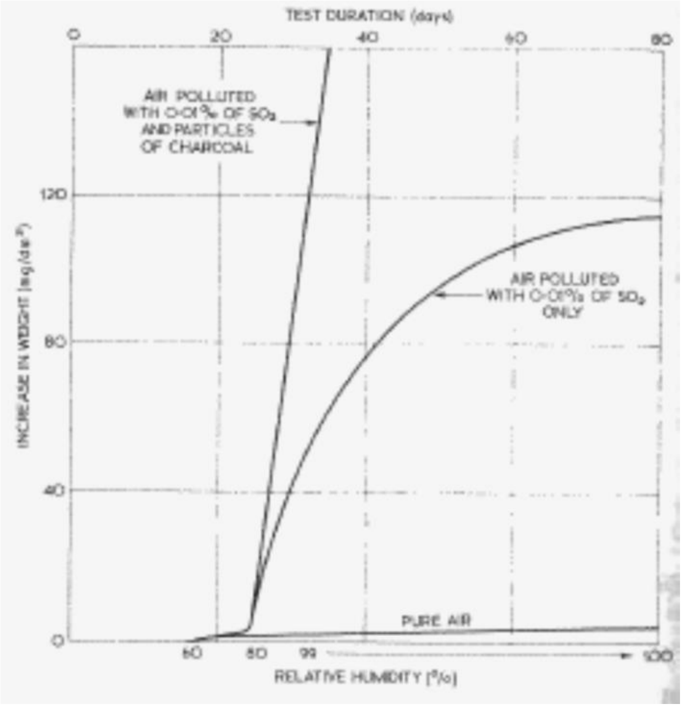


MAIT

ENVIRONMENTS

Clean Room Conditions

- Based on work from Vernon in 1922
  - Tests were short term <100 days
- Corrosion of Steel stopped below 60%RH
  - Clean rooms maintained at 55%RH ±10%RH
  - Humidity requirements a balance
    - Corrosion prevented by low humidity
    - ESD prevented by high humidity



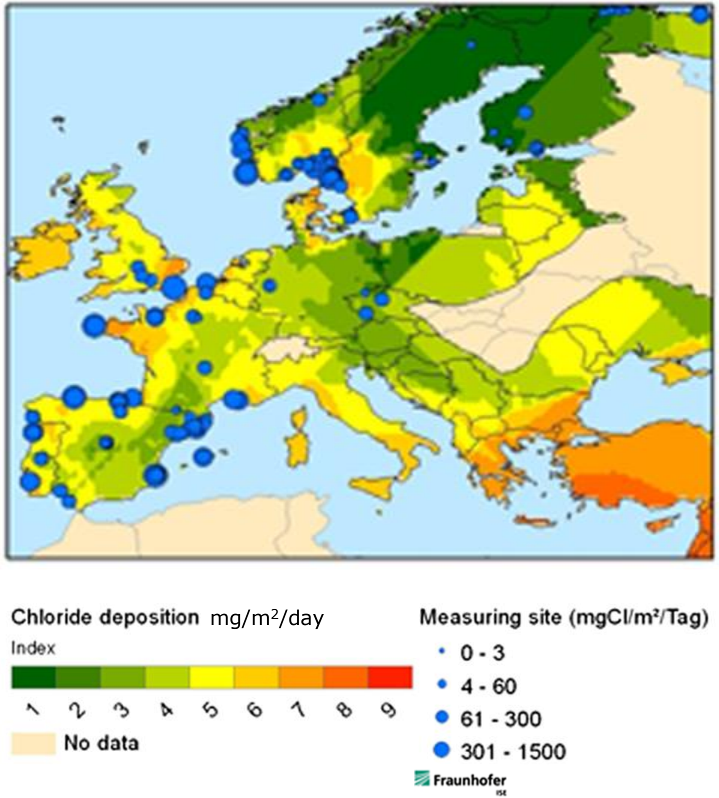
MAIT

- Cleanroom with controlled humidity and temperature
  - 22°C±3°C, 55%RH±10%RH
  - Only temperature, humidity and particulates controlled
    - No atmospheric control
  - People are often the worst sources of contaminants
    - … and people smell!

Activity	Particles (>0.3µm) /minute
Motionless	10^5
Slow Walking	$5x10^6$
Active	10^8

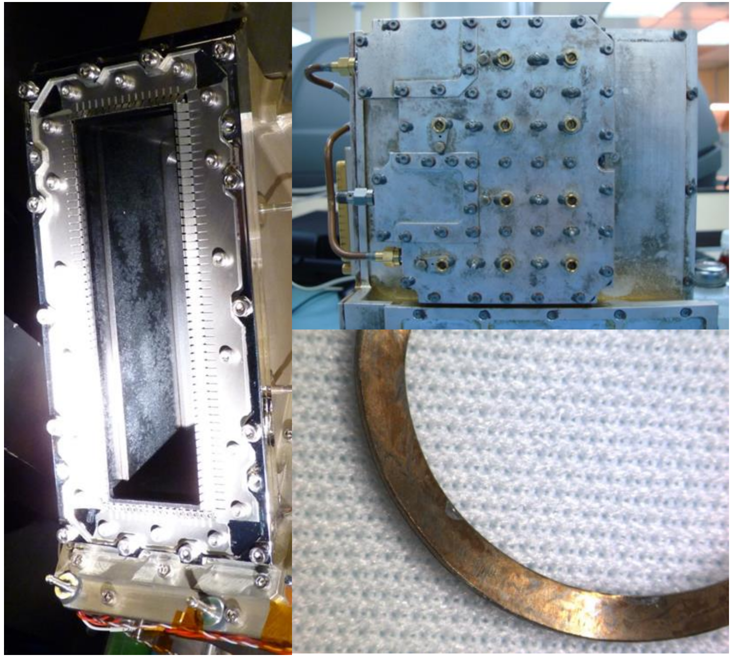
Chloride deposition Rates

- Based on modelling marine chloride distribution
- Actual values for Bavaria and Austria are higher due to road de-icing
- Data for Switzerland not available
- Clean rooms reduce (not eliminate) deposition



Corrosion

- Corrosion in clean rooms is uncommon but not unknown
- Corrosion products hydroscopic
  - absorb water
  - lowers humidity needed to propagate corrosion
- Typical causes:
  - Restricting airflow allows microclimates
  - Contamination
  - Inadequate cleaning procedures
  - Introduction of cold materials into the clean room
- Galvanic effects can make the situation worse
- Corrosion rating 'A' or 'B'
  - B needs additional protection



Corrosion Requirements

ECSS-Q-70C 5.1.9 Corrosion

For all materials that come into contact with atmospheric gases, cleaning fluids or other chemicals, it shall be demonstrated that the degradation of properties during their anticipated service life does not prevent to meet the performance and integrity requirements.

All mechanical parts, assemblies and equipment, including spares, shall be finished to provide protection from corrosion.

NOTE This applies equally to fasteners and other fixing devices, such as insert systems.

ECSS-Q-70-14 Corrosion provides detail

Principles of Corrosion

Metal, eg iron, in the presence of water and oxygen

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$$

Made up from two independent half-reactions:

anodic oxidation of iron

$$2Fe \rightarrow 2Fe^{2+} + 4e^-$$

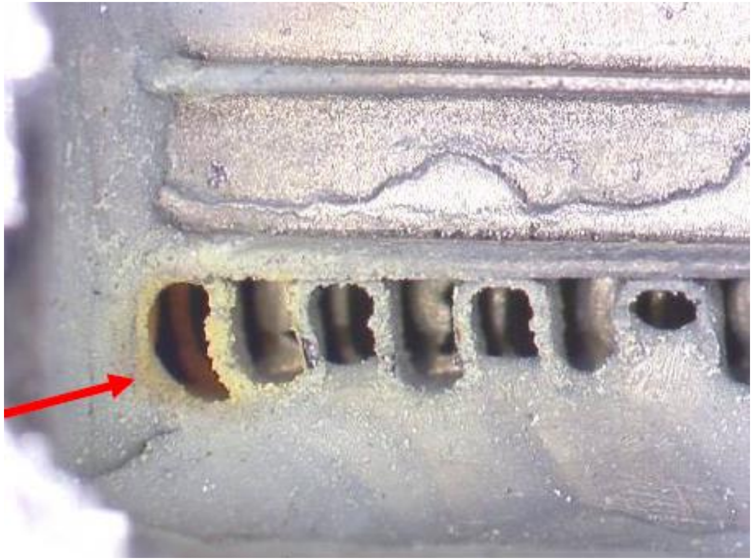
reduction of oxygen and water, the cathodic reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

In reality iron hydroxide usually oxidises further to form magnetite (Fe3O4) or a hydrated ferric oxide (FeOOH).

Eight forms of Corrosion

- General
  - General Corrosion
  - Bimetallic corrosion
- Localised Corrosion
  - Pitting
  - Crevice Corrosion
  - Intergranular Corrosion
- Mechanical Effects
  - Stress Corrosion Cracking
  - Erosion Corrosion
- Dealloying or selective leaching
- Hydrogen damage

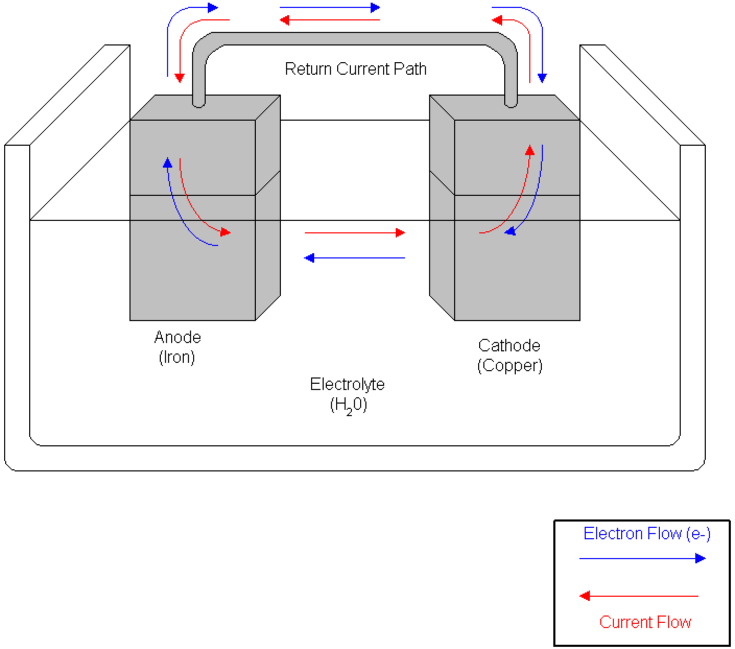


Galvanic Compatibility

- A current will flow between two metals in contact electrically and through and electrolyte
    - Anodic oxidation of iron

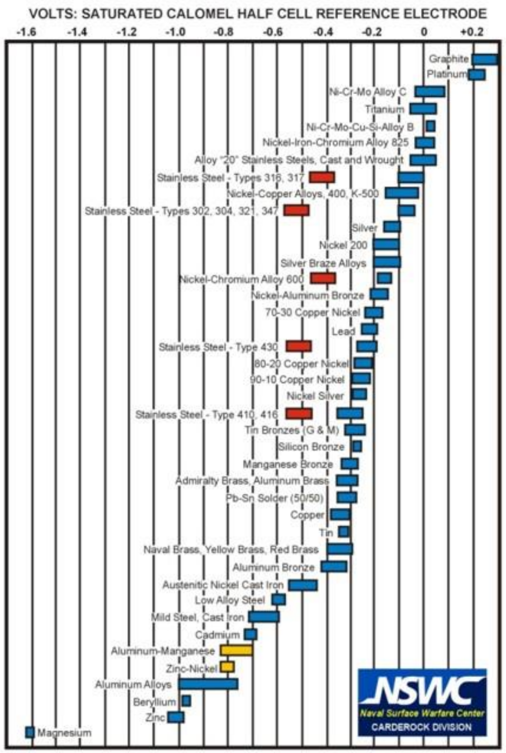
      $2Fe \rightarrow 2Fe^{2+} + 4e^{-}$
    - Reduction of oxygen and water, the cathodic reaction

      $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$
- Voltage depends on the thermodynamics
- Current depends on kinetics



Galvanic Compatibility cont

- Originally Thermodynamic
  - 250 mV in uncontrolled environment
  - 500 mV controlled environment
- Electrochemical series
- Based on a metal in equilibrium with a molar solution of its ions
- Tells how hard reaction is pushed, not how fast it goes
- Still used in some PARDs



Galvanic Compatibility cont

- Now includes kinetic effects

0	Used without restriction.
1	Used in a non-controlled environment (e.g. assembly area and general non-clean room environment).
2	Used in a clean room environment.
3	Needs specific measures to avoid galvanic corrosion when these combinations are selected.

Table 5-1 Compatible couples for bimetallic contacts

Pure metals and alloys in alphabetical order (including carbon)	Aluminium-Copper alloys	Al (pure), Al-Zinc alloys	Cadmium	Cast iron (austenic)	Chromium	Copper, Brasses	Cupro-Nickel, Al-bronzes, Si-bronzes	Gold, Platinum, Carbon, Rhodium	Gun-metal (CuZn10 alloy), P-bronzes, Sn-bronzes	Magnesium	Nickel, Monel, Inconel, Nickel/Molybdenum-alloys	Silver	Sn-Pb alloys (all), Tin, Lead	Stainless steel 18/8 (300 series)	Stainless steel 13Cr (400 series)	Steel (carbon, low alloy), Cast iron	Titanium and Ti-alloys	Zinc, Beryllium
Aluminium-Copper alloys		1	1	3	3	3	3	3	3	2	2	3	1	2	2	3	2	2
Al (pure) Al-Zinc alloys			1	3	3	3	3	3	3	2	3	3	2	3	3	3	3	2
Cadmium				2	2	2	2	2	2	1	2	2	0	1	1	2	2	2
Cast iron (austenic)					1	1	1	2	1	3	1	2	1	1	1	2	1	3
Chromium						1	0	0	1	3	1	0	2	0	0	2	0	3
Copper, Brasses							0	2	0	3	1	1	2	1	1	3	0	3
Cupro-Nickel Al-bronzes Si-bronzes								2	0	3	1	1	2	2	1	3	0	3
Gold Platinum, Carbon Rhodium									2	3	2	0	3	0	1	3	0	3
Gun-metal(CuZn10 alloy) P-bronzes Sn-bronzes										3	1	1	1	0	0	3	0	3
Magnesium											3	3	2	3	3	3	3	3
Nickel Monel Inconel Nickel/Molybdenum-alloys												2	2	1	0	2	1	3
Silver													3	0	0	3	0	3
Sn-Pb alloys (all) Tin, Lead														1	1	1	3	1
Stainless steel 18/8 (300 series)															1	3	0	3
Stainless steel 13Cr (400 series)																3	0	3
Steel (carbon, low alloy) Cast iron																	0	3
Titanium and Ti-alloys																		3
Zinc Beryllium																		

Key:

0 - Can be used without restriction.

1 - Can be used in a non-controlled environment (e.g. assembly area and general non-clean room environment).

2 - Can be used in a clean room environment.

3 - Needs specific measures to avoid galvanic corrosion when these combinations are selected.

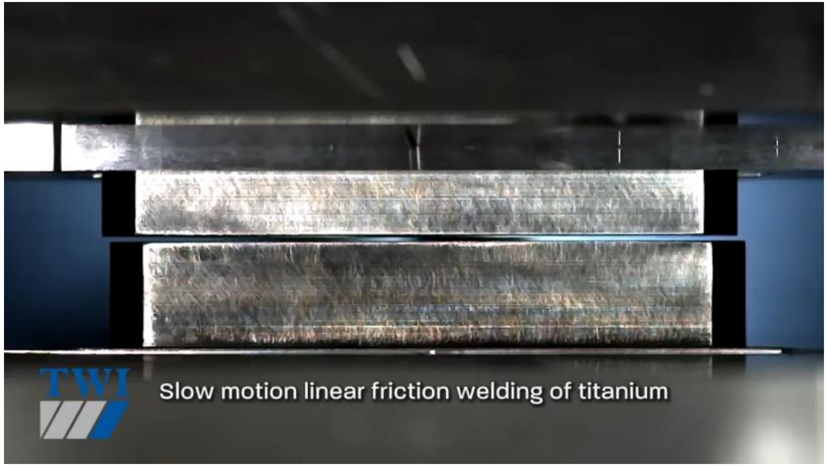
Stress Corrosion Cracking

- A major cause of failure during the Apollo programme
- SCC susceptible materials not accepted
    - therefore very few failures
- Requires:
    - Susceptible material
    - Tensile stress
    - Environment
- Crack Growth Rates between 10^{-7} and 10^{-9} m/s for stainless steels
- Susceptibility often depends on grain orientation

PROCESSES

Processes

- Any combinations used to transform a material or mechanical part
    - Eg welding, machining, bake out, coating, etc.
- All processes shall be documented and traceable
- Process executors shall be trained and approved
- **If required in process specimens shall be taken and stored**



Process group numbers

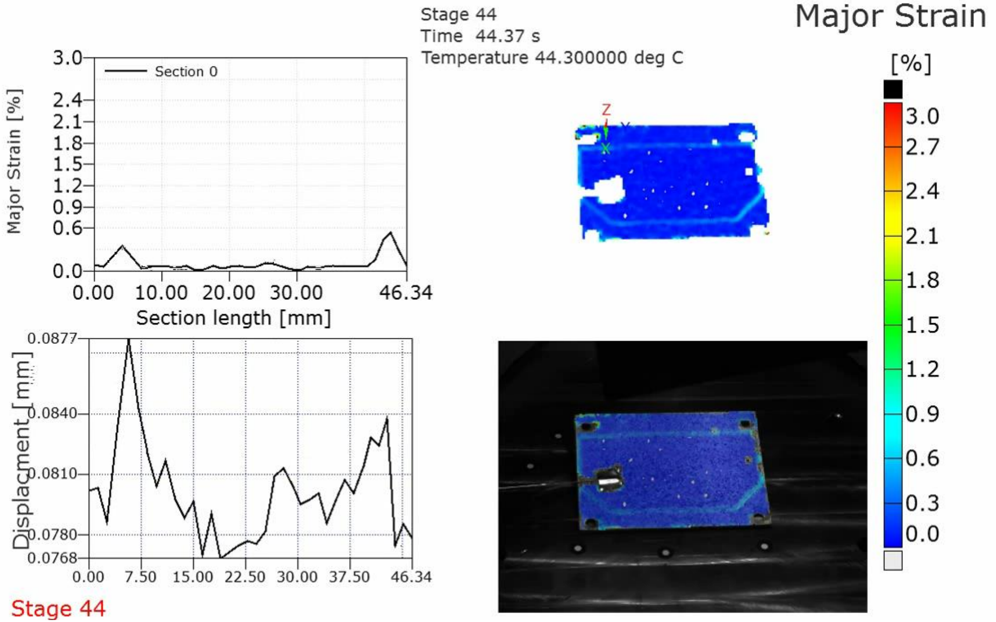
Group number	Description
1	Adhesive bonding
2	Composite manufacture
3	Encapsulation/moulding
4	Painting/coating
5	Cleaning
6	Welding/brazing
7	Crimping/stripping/wire wrapping
8	Soldering
9	Surface treatments
10	Plating
11	Machining
12	Forming
13	Heat treatment
14	Special fabrication: processes developed specifically for the programme
15	Marking
16	Miscellaneous processes
17	Inspection procedures

DPL

DECLARED PROCESS LIST (DPL)									
Programme name: ABCDEFG		CI no.: 1234567890 Group (Title): abcdefg		Doc no.: 001 Issue/Revision: 1/5			Date: 14.05.2000 Page: 1		
							9		
1	2	3	4	5	7	8	9.1	9.2	10
Item no. and user code	Process identification	1) User name 2) Associated procedure issue/revision/ date	Process description	1) Subsystem code 2) Equipment code 3) Use	Associated DML or DMPL item number	1) Criticality 2) Reason for criticality	1) Supplier Reference 2) Prime comments	Prime approval status	Customer approval status/ comments
1.2.1.SSEX	Bonding	1) EREMS 2) E/SQ/PI/012 02/01/02.08.1984	Applying a spot of glue with a stainless steel dispenser	1) BE3 2) CS board 3) To fix parts	6.1.2.ETC	1) N 2)	1) Used on ANTARES 2)	A	A
4.3.1.KOF	Coating	1) CERCO 2) E/SQ/PI/023 02/01/08.12.1985	Coating by paintbrush or by immersion in the resin	1) BE3 2) C1 C2 boards 3) Protection of CI and EEE parts	2.1.1.KOF	1) N 2)	1) Used on PASTEC, ANTARES 2)	A	A
8.3.1.KOF	Vapour phase soldering of SMDs	1) EREMS 2) E/SQ/PI/026 01/02/09.09.1997	ECSS-Q-ST-70-38	1) BE3 2) C3 3)	15.1.1.AST	1) C 2)	1) QM/04L123/ BD/MH Table 1 2)	A	A

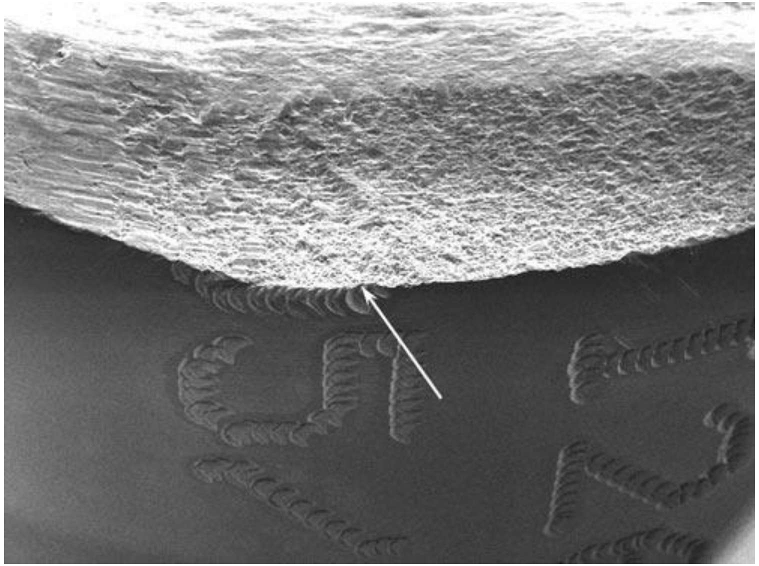
Coatings and Adhesion

- Surface preparation
- Surface preparation
- Surface preparation
- Strength
    - Needs representative substrate
    - Peel forces
- Durability
    - Ground storage
- ECSS-Q-ST-70-17C *Durability testing of coatings*
    - Mainly optical



Marking

- Solvents in inks should not attack substrates.
- Inks shall have low outgassing properties, see ECSS-Q-ST-70-02.
- Engraving of painted, plated or coated parts shall be avoided.
- Stamping resulting in stress-raisers shall be avoided.



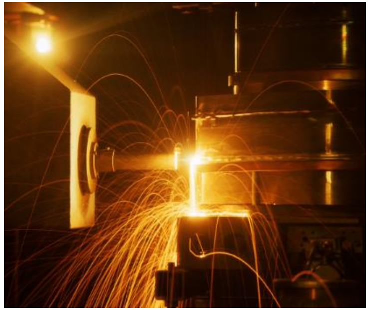
Welding and Brazing

- Welding
  - Defined as parent metal melting
  - Not true for some modern sold state welds
  - May involve the addition of a filler metal
  - ECSS-Q-ST-70-39C Welding
- Brazing & Soldering
  - Filler metal melts and parent remains solid
  - Brazing and soldering only differ in temperature
    - Brazing >450°C, Soldering <450°C
  - Significant number of NCRs in proportion to its use
    - ECSS-Q-ST-70-40C Brazing about to be released

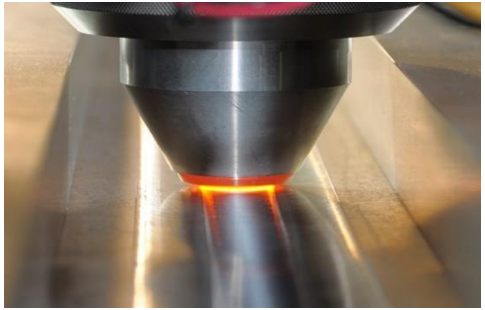
Welding Processes



Manual / Mechanised Arc Welding (TIG / MIG)

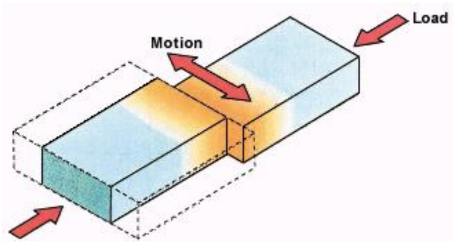


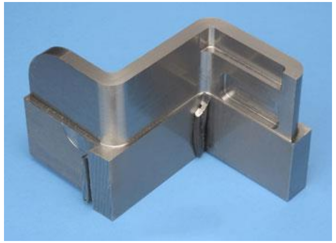

Electron and Laser Beam Welding



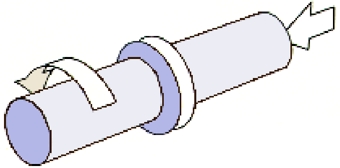
Friction Stir Welding

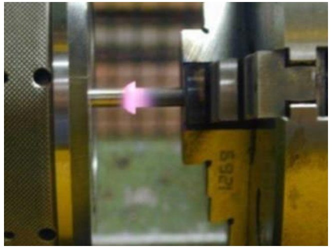
Solid State Welding Processes



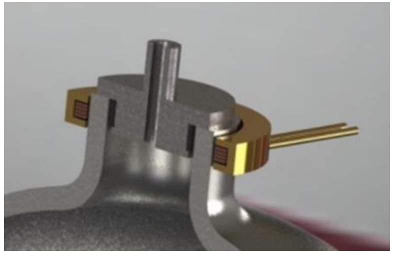


Linear Friction Welding





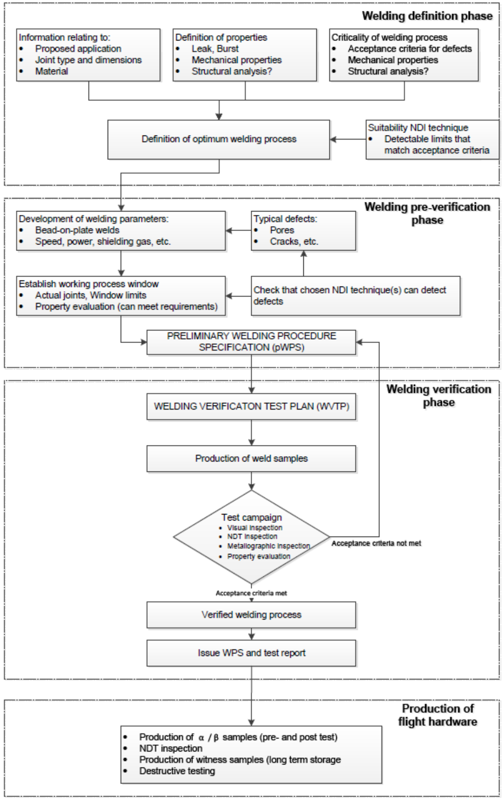
Rotary Friction Welding



Magnetic Pulse Welding

ECSS-Q-ST-70-39C Welding

- Definition
  - Application, Material, Acceptance criteria
- Verification
  - Process and Parameters
  - NDI: Will it match acceptance criteria?
  - Welding Procedure
  - Testing
- Welding procedure specification (WPS)
- Production
  - α/β and witness samples
  - NDI, DPA



Weld Classification

Class	Failure Consequence	Visual Dimensional	Penetrant	Radiographic or Ultrasonic
1	Loss of spacecraft, major components, loss of life, or loss of control of the spacecraft.	100%	100%	100%
2	Reduction in efficiency of the system but not cause the loss of the spacecraft	100%	100%	As appropriate for use
3	Does not affect other flight elements.	100%	N/A	N/A

ECSS-Q-ST-70-15C NDT

- Design definition authority specifies NDT acceptance criteria
- Performed by certified NDT inspectors
- Capability to detect flaws must be demonstrated
    - Certification or demonstration
    - 90% probability of detection at a 95% confidence level
- Cleaning or etching must not affect engineering tolerances
- Consider the strengths and weakness of the technique
    - CT very good for small defects but very bad for closed defects
- Not standardised for Composites etc
    - Consider as Special fracture control

Defect size 1

Table 9-1: Initial crack size summary, Standard fracture control NDT

NDT method	Crack location	Part thickness *t* [mm]	Crack configuration number (see NOTE 1)	Crack type	Crack depth *a* [mm]	Crack length *c* [mm]
Eddy current NDT	Open surface	$t \leq 1{,}27$ $t > 1{,}27$	4 1, 3, 8	Through surface	*T* 0,51 1,27	1,27 2,54 1,27
	Edge or hole	$t \leq 1{,}91$ $t > 1{,}91$	5, 9 2, 7	Through corner	*t* 1,91	2,54 1,91
	Cylinder	N/A	10	Surface	see Note 2	1,27
Penetrant NDT Sensitivity Level ≥3	Open surface	$t \leq 1{,}27$ $1{,}27 \leq t \leq 1{,}91$ $t > 1{,}91$	4 4 1, 3, 8	Through surface	*t* *t* 0,81 1,91	2,54 3,82 - *t* 4,05 1,91
	Edge or hole	$t \leq 2{,}54$ $t > 2{,}54$	5, 9 2, 7	Through corner	*t* 2,54	3,81 3,81
	Cylinder	N/A	10	Surface	see Note 2	1,91
Penetrant NDT of welds with Sensitivity Level 3 or better. Sensitivity Level 2 for all other materials in unmanned applications	Open surface	$t \leq 3{,}0$ $t > 3{,}0$	4 1, 3, 8	Through surface	*t* 3,00 1,50	3,00 3,00 7,50
	Edge or hole	$t \leq 3{,}0$ $t > 3{,}0$	5, 9 2, 7	Through surface	*t* 3,00	3,81 3,81
	Cylinder	N/A	10	Surface	see Note 2	3,00

Defect size 2

NDT method	Crack location	Part thickness t [mm]	Crack configuration number (see NOTE 1)	Crack type	Crack depth a [mm]	Crack length c [mm]
Magnetic Particle NDT	Open surface	$t \leq 1{,}91$ $t > 1{,}91$	4 1, 3, 8	Through surface	t 0,97 1,91	3,18 4,78 3,18
	Edge or hole	$t \leq 1{,}91$ $t > 1{,}91$	5, 9 2, 7	Through corner	t 1,91	6,35 6,35
	Cylinder	N/A	10	Surface	see Note 2	3,18
X-ray radiographic NDT	Open surface	$0{,}63 \leq t \leq 2{,}72$ $t > 2{,}72$	1, 2, 3, 7, 8	Surface	$0{,}7 \times t$ $0{,}7 \times t$	1,91 $0{,}7 \times t$
	Internal	$t > 2{,}72$	6	Embedded	$0{,}35 \times t$	$0{,}7 \times t$
Ultrasonic NDT	Open surface	$t \geq 2{,}54$	1, 2, 3, 7, 8	Surface	0,76 1,65	3,81 1,65
	Internal	$t \geq 2{,}54$	6	Embedded	0,43 0,99	2,21 0,99

NOTE 1 The crack configuration numbers refer to the crack configurations shown in Figure 9-1, Figure 9-2 and Figure 9-3.

NOTE 2 For cylindrically shaped items (see Figure 9-3) the crack depth a can be derived from the crack length c of this table for a/c = 1,0 with the following formula:

$$a = r\left(1 + \tan\frac{c}{r} - \sec\frac{c}{r}\right)$$

Exception: Fastener thread and fillets, to which the crack size for a/c=1,0 applies.

Additive manufacturing

- 3d printing
- Efficient use of resources
- Unconventional geometries
- Requires new materials
- ECSS-Q-ST-70-80C Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications

Electronic Assembly

PROCESSES

Different types of electronic assemblies

-Connection made by using solder

-Connection made by using crimping

-Connection made by using wire warping

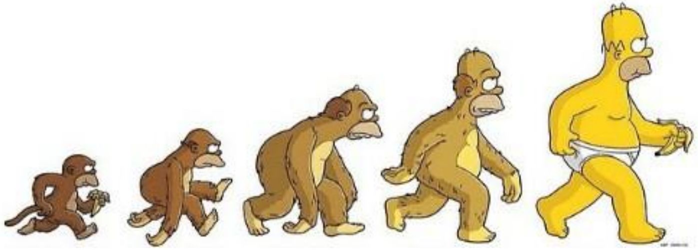
-Connection made by using solderless connection

QUALIFICATION

Process Verification (Qualification)

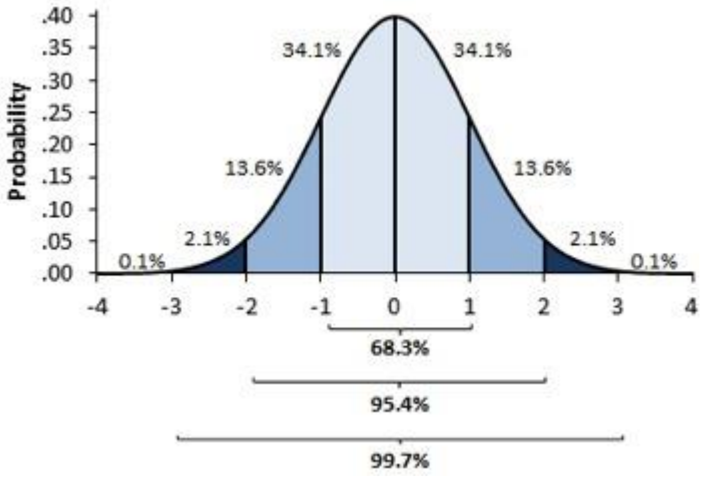
ECSS-Q-ST-70C states that all processes shall be ‘verified’ in accordance with the applicable ECSS. Critical processes subject to verification shall be detailed using the Request for Approval (RFA) system.

What is the validity of any qualification if a company does not have good procedures (QMS)? Companies procedures and processes evolve with time…



Process Monitoring

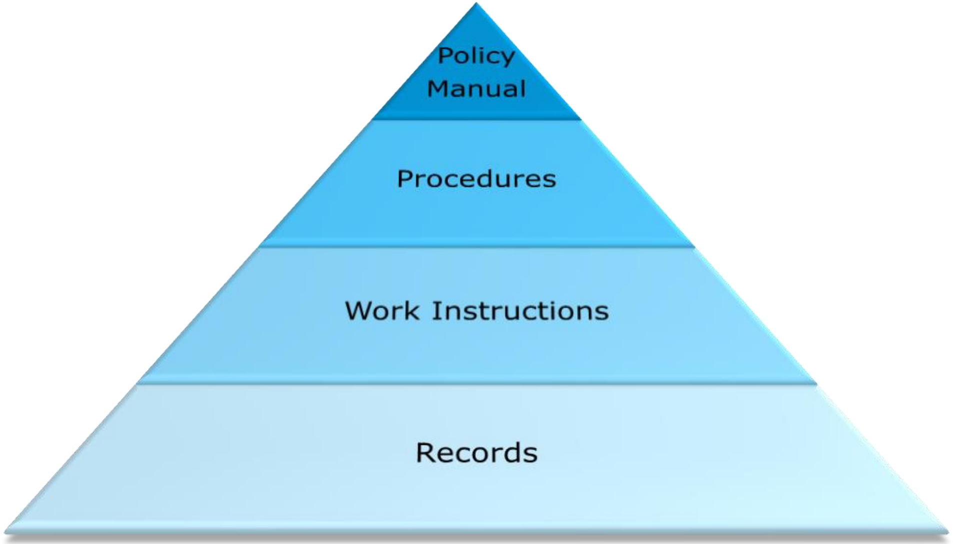
- It is not possible to capture the distribution of all process variables within a process verification.
- The verification will always be too small a data-set to represent the full distribution.
- With time the distribution will always become broader (process drift/ evolution).
    - This will be evident in most measured outputs (eg. weld width, material hardness, composite strength).
- **Statistical Process Control (SPC) is an important tool in production.**



Process Documentation

Most of the important information contained within a companies documentation cannot be reviewed from your desk

- QMS
- Process specifications
- Certificates of conformity
- Drawings
- Shop travelers/ Routers
- Datacards
- SPC data
- Internal NCRs



DML/ DPLs are just a presentation and do not always reflect the reality!

Qualification

Qualification overused

- Materials
  - Validated
- Mechanical parts
  - Qualified
- Processes
  - Verified

Table 4-1: Steps to be taken to get approval for materials, mechanical parts and processes (MMPP)

Phase	Materials		Mechanical parts		Processes	
	Step	Comments	Step	Comments	Step	Comments
Critical Analysis	1		1		1	
Evaluation (usually by test methods defined by ECSS standards)	2	Critical materials are tested, e.g. outgassing, SCC, flammability.	2	Mechanical parts are tested by, for example, vibration, thermal analysis, off-gassing and life test.	2	Critical processes are evaluated by testing "technology samples" including all, for example, electrical interconnection processes and painting, adhesive bonding.
Verification	Not applicable		Not applicable		3	Verification tests usually defined in ECSS standards
Validation	3		Not applicable		Not applicable	
Qualification	Not applicable		3		Not applicable	
Approval		By RFA (Annex D) or DML		By RFA (Annex D) or DMPL/DPL		By RFA (Annex D) or DPL

Qualification 2

- Fit for purpose over the life of the mission
- 'Test as you fly, fly as you test'
- Consider Mission Phases
- On ground, Launch, Space
    - Environmental degradation, vibration, thermal cycling
    - Remember the post launch phase may be complex
        - JUICE is a cold mission but to get to Jupiter must slingshot around Venus
- Easiest to show still works at End of Life

Qualification 3

- Most qualification covered by ECSS
- Approaches based on experience
    - Infant mortality
        - PCB, Printed circuit boards
        - SMT, Surface mount technology
    - Empirical
        - SCC, Stress corrosion cracking
        - Red Plague
    - Statistical over testing
        - Fatigue (4x life)
    - Design Data
        - Strength from MMPDS A-Values
            - Based on 99% of properties are better than value at 95% confidence level

TC and degradation

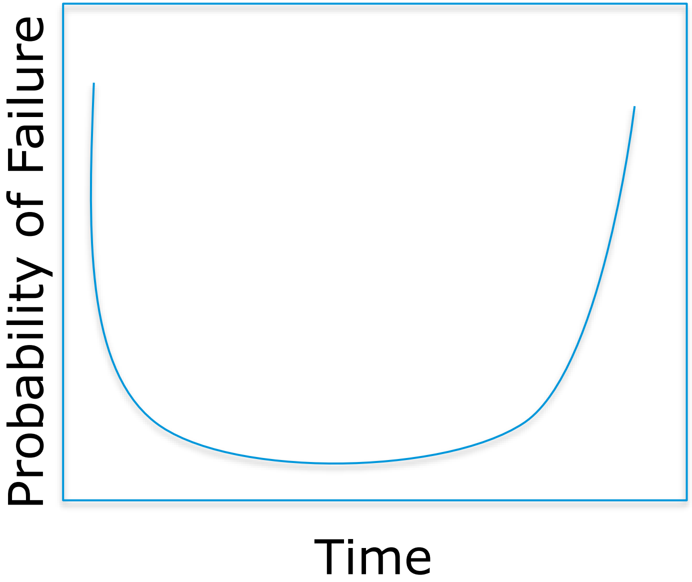
- Power for spacecraft passes from the solar arrays through a SADM
    - Solar Array Drive Mechanism
- Soldered joint used to make electrical connection between components
- Power through the joint varies through the orbit
    - Temperature of the joint varies with power (Thermal Cycling)
- Space craft heats and cools depending on the position of the Sun

SADM Solder Joint

- Metallurgical degradation at high temperatures
  - Solder reacts with substrate to form brittle intermetallics
- CTE mismatch generates strain as temperature varies
  - Coefficient of thermal expansion, CTE
  - Leads to fatigue
- TC between -10°C and +95°C
  - Actual Tc likely to be smaller but this is worst case
- Will the joint last 7.5 years ?

Qualification Approaches

- Analysis
- Infant mortality tests
  - Bath tub curve
- Life test
  - Expensive
- EoL aging followed by infant mortality TC.
- Norris-Landzberg type models



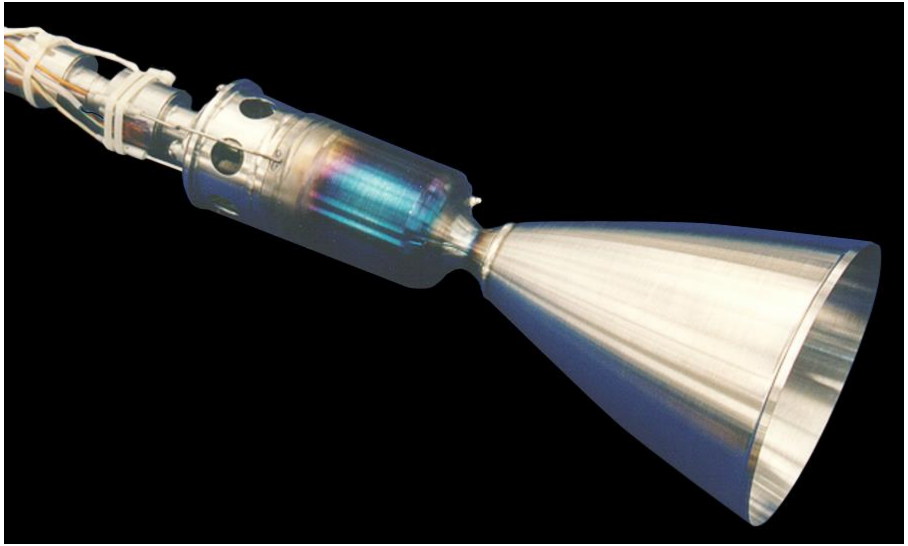
$$AF = \frac{N_{Life}}{N_{Test}} = \left(\frac{Freq_{Life}}{Freq_{Test}}\right)^{-m} \left(\frac{\Delta T_{Life}}{\Delta T_{Test}}\right)^{-n} \left(e^{\frac{E_a}{k}\left(\frac{1}{T_{Max,Life}} - \frac{1}{T_{Max,Test}}\right)}\right)$$

Artificial ageing and TC

- Sinusoidal variation
  - Steady state behaviour about RMS peak
  - 95°C + 15°C margin
    - Margin because the model is wrong
  - Steady state temperature $110/2^{½} = 78°C$
    - Use 80°C for convenience
- For Arrhenius type behaviour 10°C temperature increase doubles reaction rates
  - Be careful with this approximation, only applies in limited energy ranges
- Accelerated test could be carried out at 140°C
  - Acceleration factor would be $2^{(140°C-80°C)/10} = 64$
  - 7.5 years is 90 Months, 90/64 ≈ 1.5 months
- Qualification programme
  - Artificially age for 1.5 months at 140°C
  - Thermally cycle between - 25°C and 110°C
  - Demonstrate still works

Creep Qualification 1

- Small Thruster
- Wanted for an interplanetary mission
- Has space heritage
    - not for a long mission
- Primary failure mechanism creep rupture of the combustion chamber
- How long must we test ?

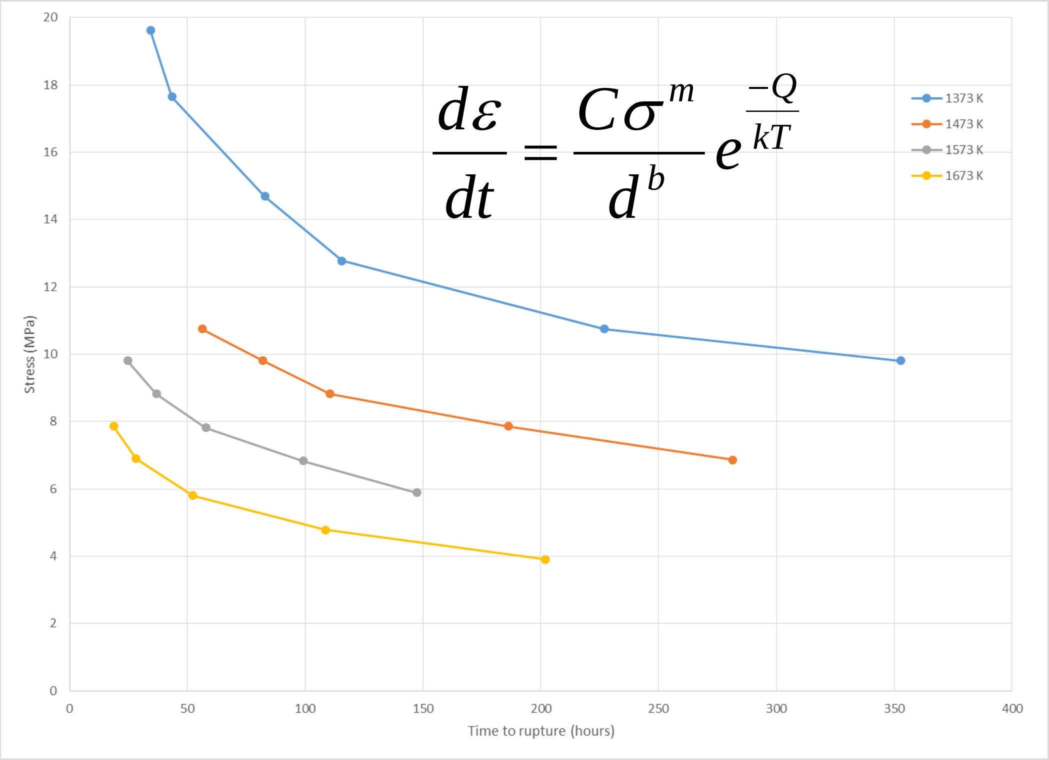


For illustration. Not the actual system

Vega Engine Test

Creep Qualification 2

- Data
- Model
- Prediction
    - All models are <u>WRONG</u>
- Confidence
    - How Wrong ?



$$\frac{d\varepsilon}{dt} = \frac{C\sigma^{m}}{d^{b}} e^{\frac{-Q}{kT}}$$

Creep Qualification 3

							Predicted	Predicted			Lower	Upper	Lower	Upper	4.7
Temp (K)	Time to ru	Stress (Mpa)	Log(t)	Log(Stress	1/T	log(stress)/T	Log10(t)	t	residual	residual	Log10(t)	Log10(t)	t	t	Multiple
1373	34.3	19.6	1.535895	1.292666	0.000728	0.000941	1.5	30.4	4.0	12%	0.7	2.2	5.5	169.3	5.6
1373	43.4	17.6	1.637416	1.246661	0.000728	0.000908	1.6	43.7	-0.3	-1%	0.9	2.4	7.9	239.8	5.5
1373	82.9	14.7	1.918594	1.167196	0.000728	0.00085	1.9	81.7	1.2	2%	1.2	2.6	15.2	437.3	5.4
1373	115.6	12.8	2.063071	1.106555	0.000728	0.000806	2.1	131.7	-16.1	-14%	1.4	2.8	25.1	691.6	5.3
1373	227.0	10.7	2.35597	1.031271	0.000728	0.000751	2.4	238.3	-11.3	-5%	1.7	3.1	46.5	1222.0	5.1
1373	352.6	9.8	2.547341	0.991541	0.000728	0.000722	2.5	325.9	26.7	8%	1.8	3.2	64.4	1650.1	5.1
1473	56.3	10.7	1.750502	1.031271	0.000679	0.0007	1.8	61.0	-4.7	-8%	1.1	2.5	12.5	296.1	4.9
1473	82.1	9.8	1.914528	0.991541	0.000679	0.000673	1.9	83.4	-1.2	-1%	1.2	2.6	17.4	399.9	4.8
1473	110.5	8.8	2.043394	0.945537	0.000679	0.000642	2.1	119.8	-9.3	-8%	1.4	2.8	25.3	566.2	4.7
1473	186.2	7.9	2.26991	0.895349	0.000679	0.000608	2.3	177.9	8.3	4%	1.6	2.9	38.2	827.5	4.7
1473	281.5	6.9	2.449545	0.836797	0.000679	0.000568	2.5	282.2	-0.6	0%	1.8	3.1	61.8	1288.3	4.6
1573	24.6	9.8	1.39109	0.991541	0.000636	0.00063	1.4	25.4	-0.8	-3%	0.7	2.1	5.5	116.0	4.6
1573	36.9	8.8	1.566831	0.945537	0.000636	0.000601	1.6	36.4	0.4	1%	0.9	2.2	8.1	164.3	4.5
1573	57.8	7.8	1.762095	0.893258	0.000636	0.000568	1.7	55.0	2.8	5%	1.1	2.4	12.4	244.0	4.4
1573	99.2	6.8	1.996418	0.834706	0.000636	0.000531	1.9	87.3	11.9	12%	1.3	2.6	20.1	379.8	4.4
1573	147.3	5.9	2.168235	0.769881	0.000636	0.000489	2.2	145.4	1.9	1%	1.5	2.8	34.1	620.0	4.3
1673	18.6	7.9	1.26991	0.895349	0.000598	0.000535	1.3	19.0	-0.4	-2%	0.6	1.9	4.5	80.8	4.3
1673	28.2	6.9	1.449546	0.838888	0.000598	0.000501	1.5	29.6	-1.5	-5%	0.9	2.1	7.1	123.8	4.2
1673	52.4	5.8	1.71901	0.763607	0.000598	0.000456	1.7	53.6	-1.2	-2%	1.1	2.3	13.1	218.7	4.1
1673	108.5	4.8	2.035342	0.679962	0.000598	0.000406	2.0	103.6	4.9	5%	1.4	2.6	26.1	411.7	4.0
1673	201.7	3.9	2.304792	0.592133	0.000598	0.000354	2.3	207.0	-5.2	-3%	1.7	2.9	53.6	799.7	3.9

Regression Statistics

How good is the fit ?
99.3% of variation accounted for

SUMMARY OUTPUT	
Regression Statistics	
Multiple F	0.99709
R Square	0.994189
Adjusted I	0.993164
Standard I	0.029923
Observati	21

Statistical significance needs to be less than 0.05

ANOVA

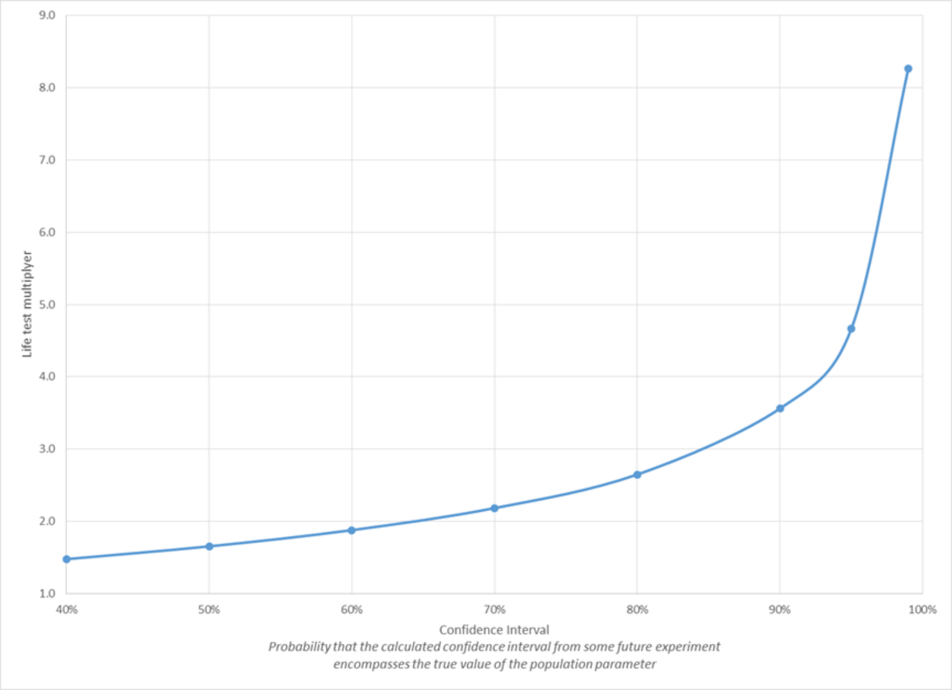
	df	*SS*	*MS*	*F*	*Significance F*
Regressio	3	2.6043	0.8681	969.5214	3.3924E-19
Residual	17	0.015222	0.000895		
Total	20	2.619521			

Large P values indicate poor correlations

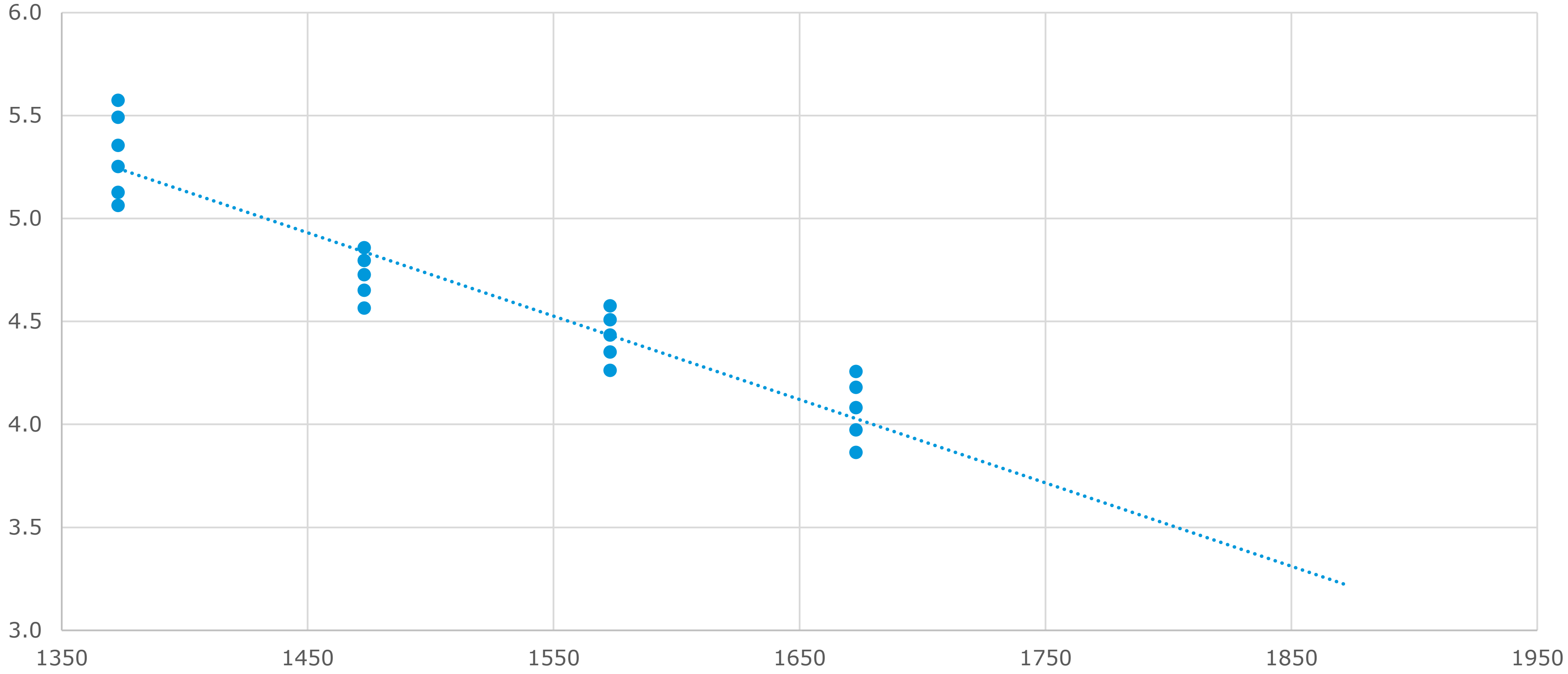
	Coefficient	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2.52601	0.525369	-4.80805	0.000164	-3.63443805	-1.417572561	-3.63443805	-1.417572561
Log(Stress	-3.73601	0.56133	-6.65564	4.06E-06	-4.920315167	-2.551709507	-4.920315167	-2.551709507
1/T	11538.93	807.9401	14.28191	6.73E-11	9834.324511	13243.53374	9834.324511	13243.53374
log(stress)	467.5852	829.9113	0.563416	0.580508	-1283.374687	2218.545092	-1283.374687	2218.545092

Example Qualification 4

- Longer testing increases confidence
    - costs money
    - Can never be 100% confident
- Qualification always a compromise
- In this case testing to 5x required life would be 95% confidence level
- NB 3.5x would be acceptable because of temperature dependence



Temperature Extrapolation



REVIEWS

Major Nonconformance

ECSS-Q-ST-10-09 *Nonconformance control system*

Major Nonconformance

safety of people or equipment,

operational, functional or any technical requirements imposed by the business agreement,

reliability, maintainability, availability, lifetime,

functional or dimensional interchangeability,

interfaces with hardware or software regulated by different business agreements,

changes to or deviations from approved qualification or acceptance test procedures,

project specific items which are proposed to be scrapped

Otherwise Minor

Customer must be informed of a major nonconformance

Metallic Issues

Corrosion

- Stress Corrosion Cracking
- General Corrosion
- Galvanic compatibility
- No corrosion in vacuum

Tribology

- Wear resistance
- Galling, fretting and cold welding

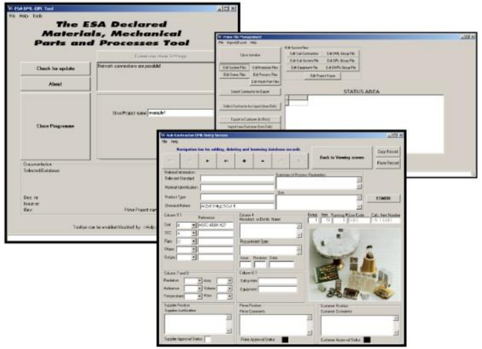
Temperature

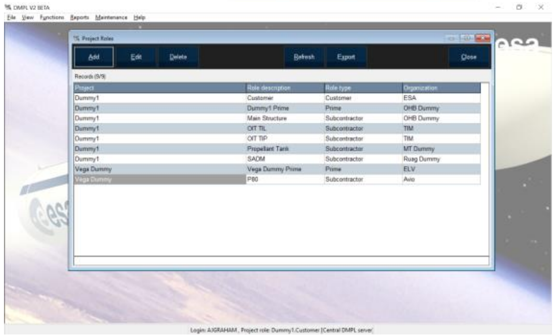
- May affect heat treatment and change properties

Fracture toughness

DMMPPL

- Declared Materials, Mechanical Parts and Process Lists
- All materials, mechanical parts and processes have to be declared
- Content and format of the lists are defined in ECSS-Q-ST-70
- Lists are contractual deliverables at all major reviews
- Lists are reviewed and approved by the Prime and Customer
- ESA DMPL tool available to support managing lists
    - https://dmpl-web.esa.int/login





Management of the lists

The MMPP lists shall be provided in a form that is exchangeable, searchable and sort-able, and suitable for storage and retrieval in accordance with business agreement.

Each customer shall process the lists from his suppliers as necessary to achieve the objectives of exchangeability, searchability, sortability, storability and retrivability for that set of lists before releasing it for use by the higher-level customer.

ECSS-Q-ST-70 Procurement of materials

5.6.1 Procurement specifications

a. All materials shall be procured to an internationally or nationally specification approved by the supplier quality system, **or** an in-house fully configured procurement specification which defines the materials properties, the materials requirements, the test methods, the acceptance criteria for the specific applications, source inspection (if any) and material supplier inspection.

b. Where material suppliers do not accept specifications and procurement is by means of a datasheet the supplier shall introduce internal, in-house receipt inspection to ensure that the validation status of the material is maintained during the subsequent procurements.

c. Materials with long lead times or long procurement delays, versus the project schedule, shall be identified before the formal subsystem PDR.

d. Procurement shall be planned, documented and implemented to obtain reliable product assurance provision at CDR.

e. Back-up plans shall be prepared and initiated whenever there is evidence of delays or technical problems.

f. The material requirements shall be accepted by the material supplier or manufacturer.

5.6.2 Incoming inspection procedure

a. All materials shall be submitted to an incoming inspection.

b. An incoming inspection procedure shall define the inspections and tests to be carried out, particularly for materials that are known to be variable in their final properties.

Approval Status

Code	Description
A	**Approved**: All materials, mechanical parts or processes classified “A” may be used without restriction.
X	**Approved with an RFA**: This processes is subjected to an evaluation or validation programme. The RFA number is entered as a comment.
W	**Approved with a concession**: These processes do not meet the requirements but are used for functional reasons. It is important to reduce the use of such processes to a minimum. All deviation requests are approved by the customer. The concession number is entered as a comment.
Y	**Approved with restriction**: Materials do not meet the requirements but may be used in the specified project(s). Use in the specified project(s) **shall not** provide justification for use in another project.
P	**Pending a decision**: Processes for which an evaluation report or a concession is waiting for the customer’s provisional or definitive approval.
O	**Open**: New processes or processes for which investigations and validations are in progress.
R	**Rejected**.
D	**Deleted**: This classification is used for a process that is no longer used.
If approval cannot be given and one of the other codes are entered, enter the comments in the appropriate column.	

DEALING WITH FAILURE


DON'T PANIC
Earth
Mostly harmless.

Non Conformance

- All systems have failures
- Root cause of failure needs to be established
- Engineering team provide recommendations based on **TECHNICAL** solutions
- Management team decides on the solution based on all the information available
- Lessons learned need to be feed into the next programme.

When you are in a hole stop digging

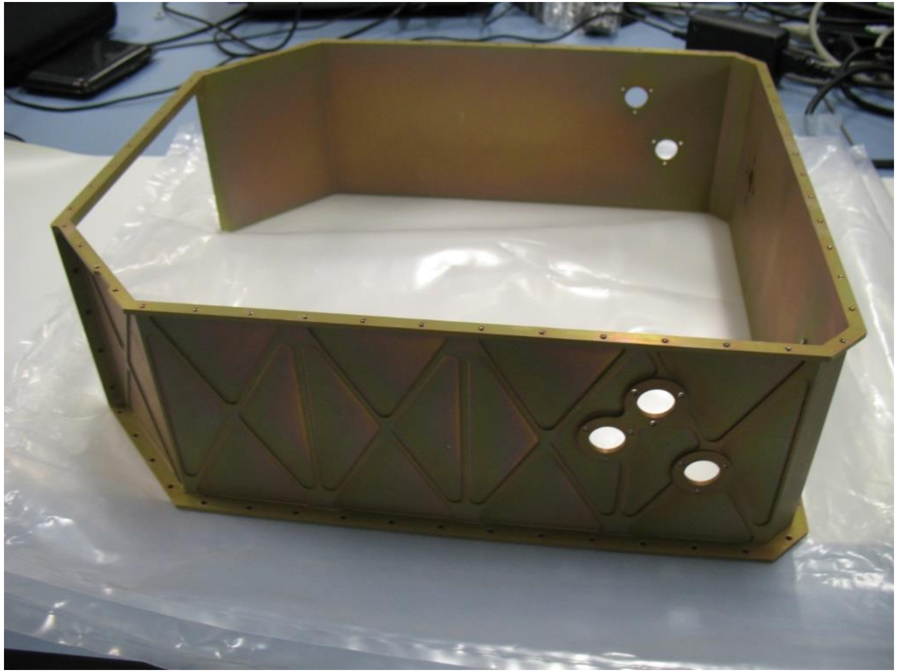
- Stay Calm
  - Do not blame
  - Do not be clouded by convenient explanations
    - Avoid Conformation Bias
- Collect the Evidence
  - Samples documents etc;
  - Avoid contamination;
  - Record as much as possible;
  - Talk to those involved.
- Use your eyes
  - Much of the evidence is in plane sight
  - Inspect everything, look for the unexpected
  - Do not damage anything
    - Even putting fracture surfaces back together can damage the evidence
    - Poor choice of bags or wrapping can contaminate evidence
- Make a plan
  - Avoid destructive examinations until non-destructive inspection can be completed

FAILURE INVESTIGATION

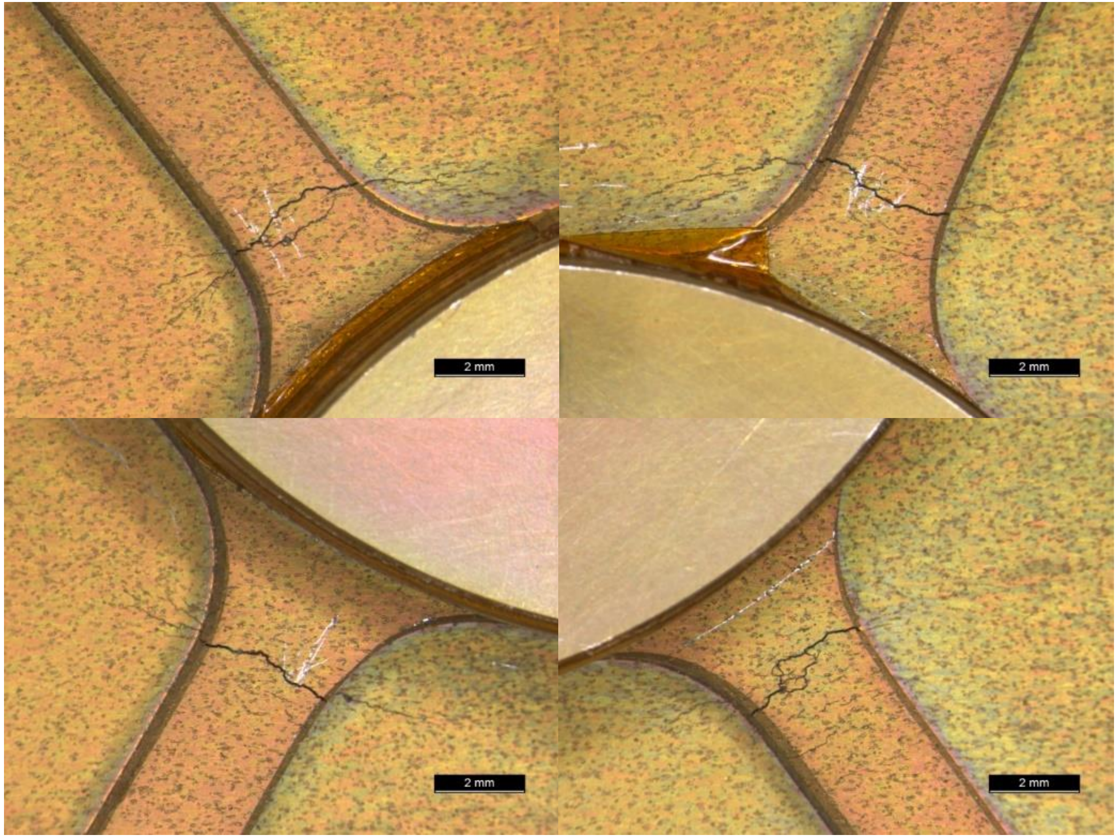
Evidence of failure

- Failure mechanisms usually leave characteristic evidence
  - Visual inspection can often provide enough to diagnose the failure
- Horseshoe shaped pits in a copper tube (Top)
  - Removed from a whisky distillation column after it leaked
  - Erosion corrosion
    - Combination of chemical attack and mechanical flow
    - Horse walks upstream
  - Occurred after a distillery changed grain supply
- Concentric rings around black pits in a NAB ball valve (Bottom)
  - Removed from a nuclear submarine after valve leaked during sea trails
  - Microbially Induced Corrosion (MIC) in stagnant dirty water
    - Valve had been flushed with dirty dock water prior to a major refit
    - Central pit created around microbe colony
      - Black pits are sulphides produced as metabolites from the colony
    - Rings mark biofilms generated to protect the colony

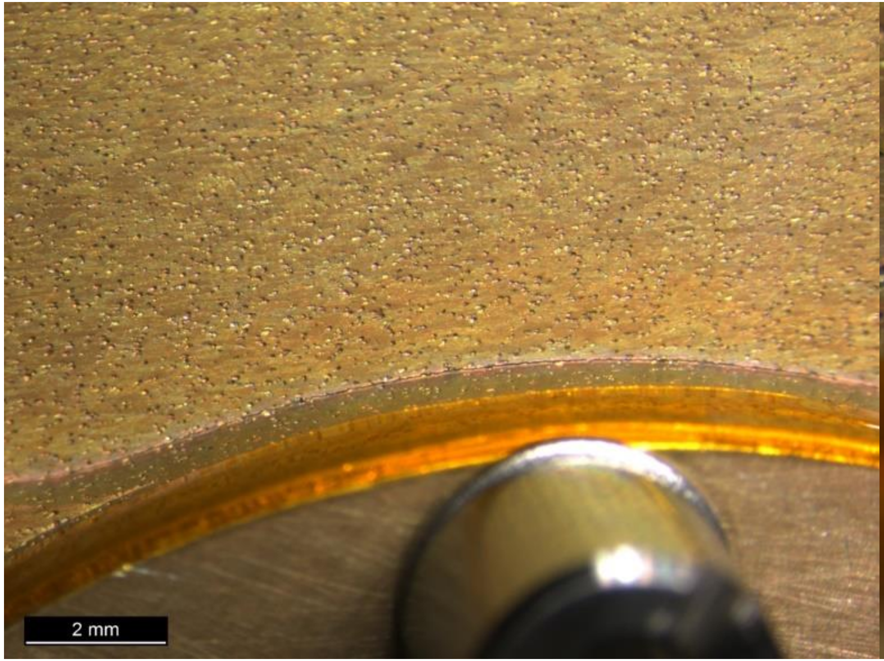
Failure of Frame Windows

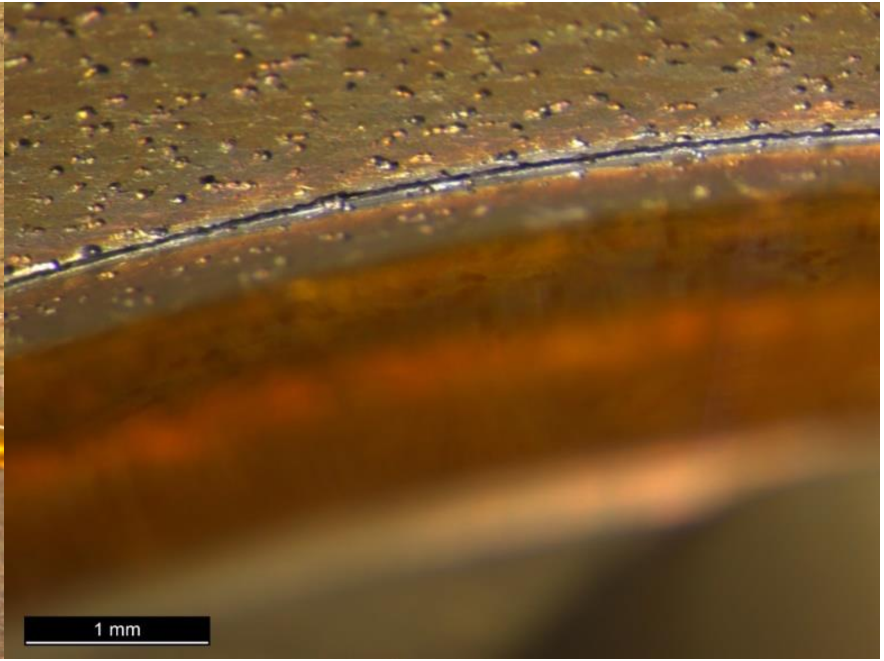


Cracks in ABS ribs found after firing

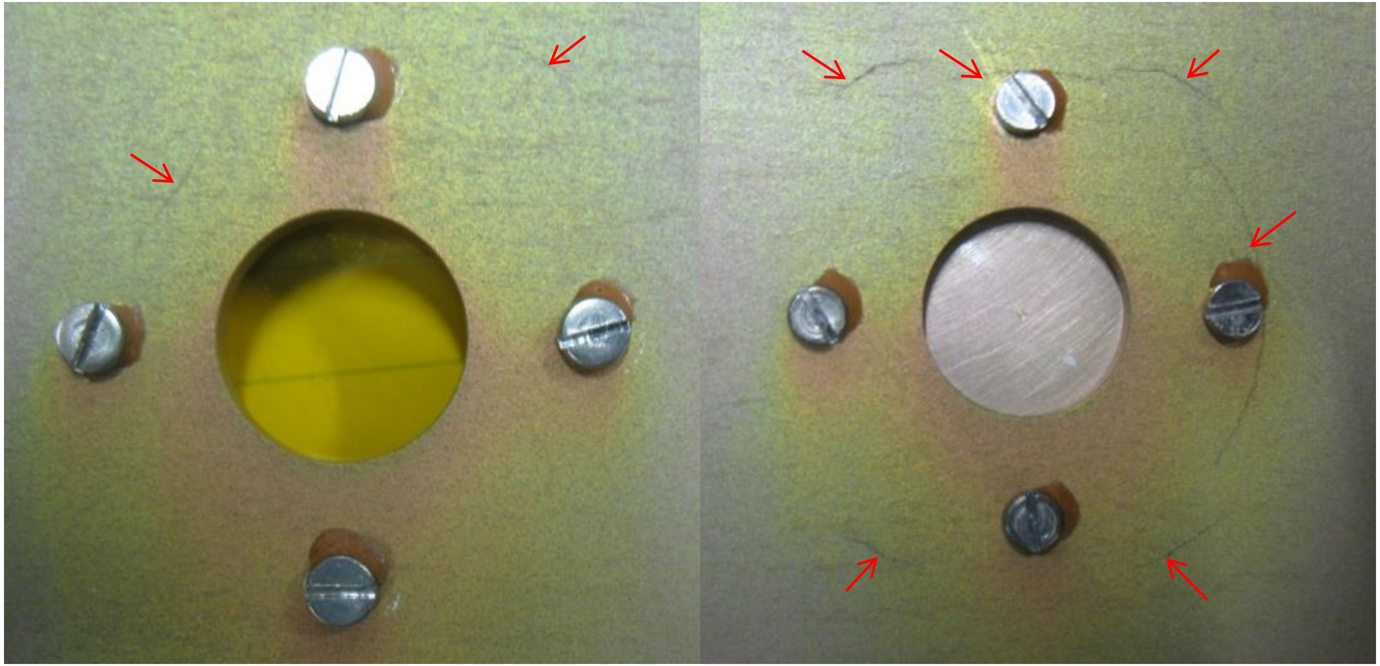


Thinning of CCC near ABS boss crack



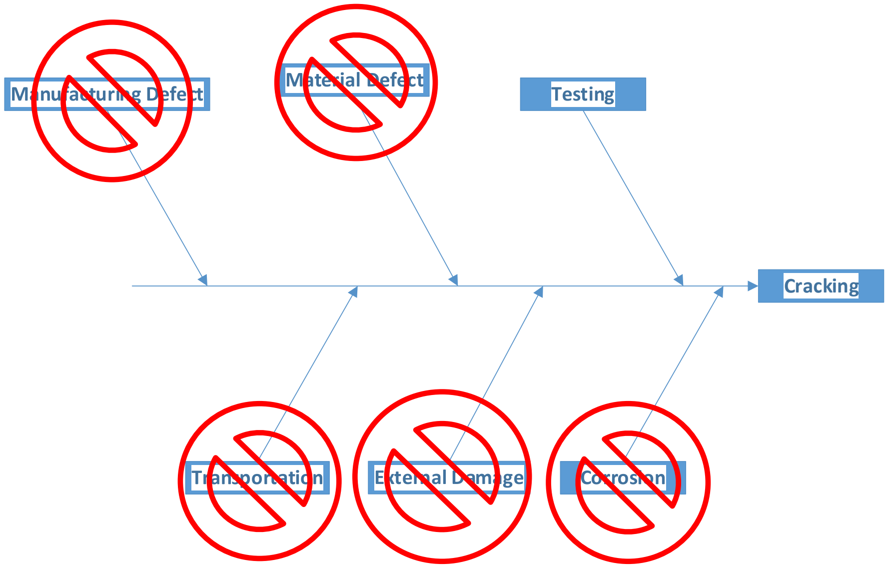


Cracks visible internally



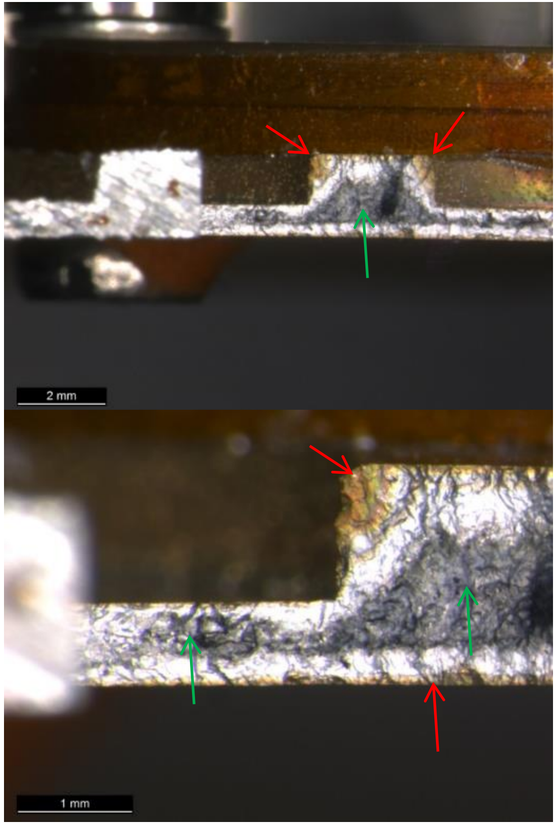
Ishikawa (Fishbone) Diagrams

- What could have gone wrong?
- Manufactured 9 years earlier
    - Materials certificates correct
    - Manufacturing travellers show no issues
- Inspection certificates show no issues
- Corrosion protection intact
    - Storage in controlled environment
    - No evidence of corrosion



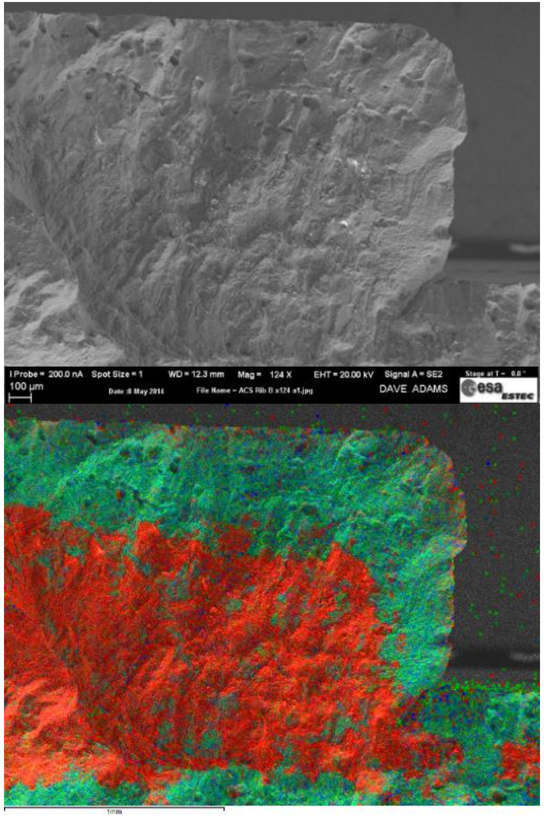
Alodine CCC on crack

- Yellow Alodine found on crack
  - Red arrows
- Crack must predate the Alodine application
- Thick dark oxide layer
  - Crack must be old
  - Green arrows



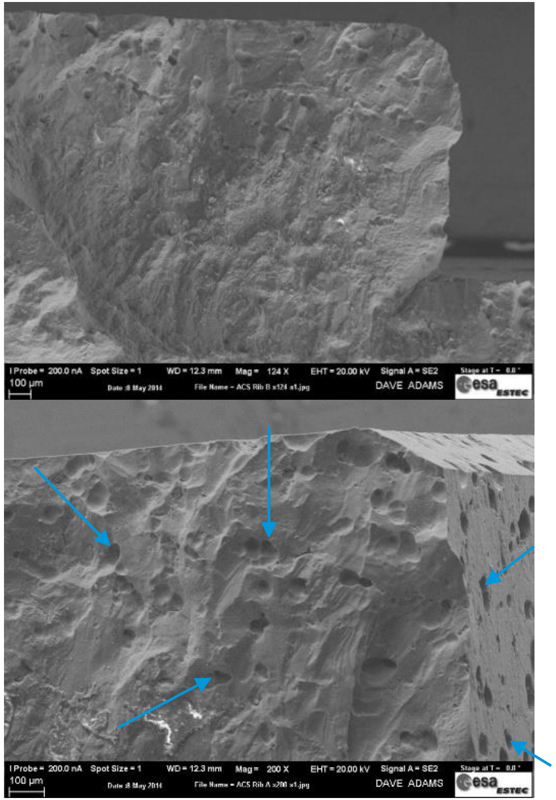
Thick oxide in crack

- Alodine has protected crack edge from corrosion
- Centre of crack covered in thick oxide layer
    - Oxygen depicted as red in lower pseudo-colour image



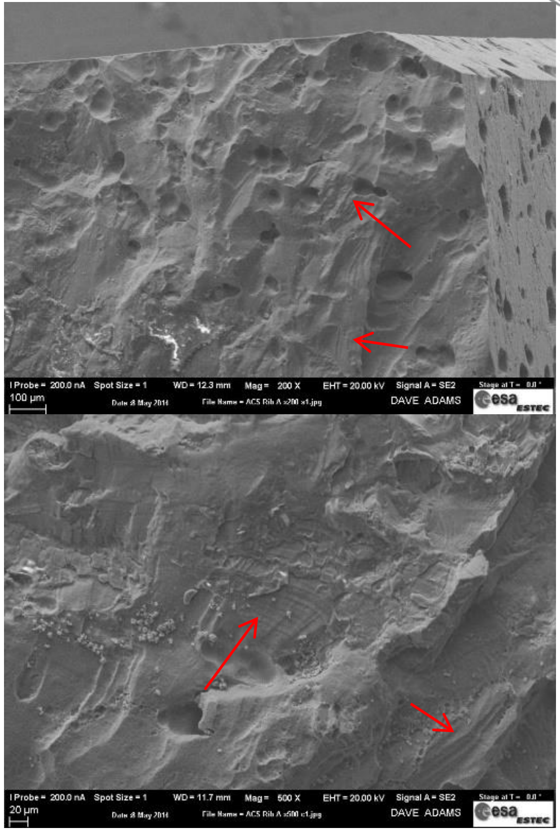
Etch pits on crack

- Etch pits on crack surface
    - Crack predates etch process



Fatigue

- Crack propagation by fatigue
- Direction of growth indicated by arrows
- Fatigue striations on etched surface
    - Fatigue predates etch
- Cracks predate etching and Chemical Conversion Coating
- Failure took place during manufacture
- Not spotted for 9 years



Findings

- Failure through fatigue
- Occurred during manufacture 9 years previously
- Possibility discounted during fault tree analysis because of:
    - Manufacturing travellers
    - Inspection reports
- In this case the documentation was worthless

- **NOTE**: Ishikawa (Fishbone) Diagrams can be an incredibly powerful tool
    - Can be a very good way of providing distraction
        - eg Challenger investigation

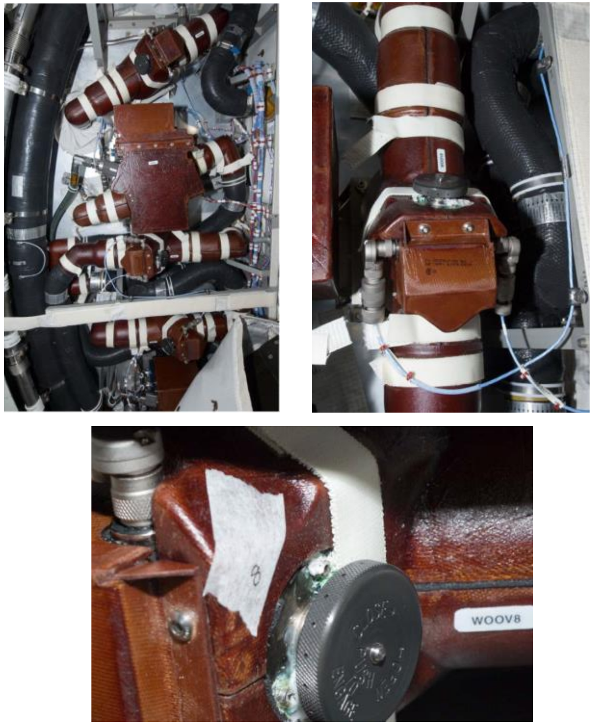
Documentation can be misleading

- AI-1: Check if 1,5D M5 helicoils are mechanically acceptable for these interface (Refer previous slide) =>OK to be confirmed also by test.
- AI-2: Check helicoils availability to perform the activity => OK helicoils are available on [redacted] side
- AI-3: Check [redacted] operator availability
- AI-4: Prepare a sample with five 1,5D helicoils and five 1D helicoils to perform representative proof test load (12000N) Aluminium plate as to be similar than inserts. Test procedure has to be approved by [redacted] prior the test.
- AI-5: Check traceability document from [redacted] (Helicoils mounting) => No anomaly or deviation mentioned
- AI-6: Check traceability document from [redacted] (Dummies mounting) => No anomaly or deviation mentioned
- AI-7: For the future, controls have to be reinforced at subcontractor levels, this kind of discrepancy in term of HW configuration is not acceptable. Dedicated point with preventive action plan has to be held.

- Failures cause embarrassment
- Embarrassment can lead to some economy with the truth
- Understand the embarrassment
    - Treat evidence with caution

Success through failure

- Non conformances are an important part of the design process
- From experience: 50% preventable at design
- The later in time the problems are found, the more expensive they become



NRB

Nonconformance Review Board

Convened when NC is Major

Identifies the **TECHNICAL** problems and solutions

Cost and Schedule are not relevant to this discussion

Management decide how to proceed based on technical solutions, cost and schedule

Cyclic Nature of Failure

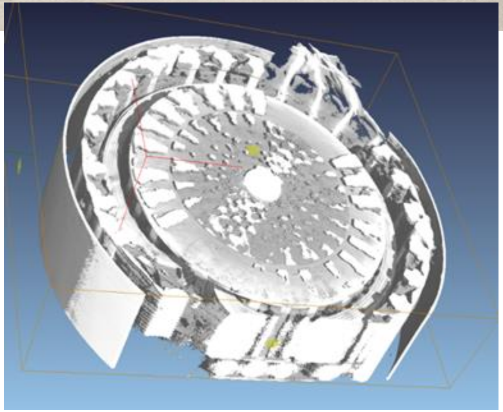
AVOIDING FAILURE

Failures repeat

- 50% of NCRs could have been caught during a review
- Experience says 7 year repeat cycle in general engineering industry
- Everyone involved in the previous failure has:
    - Moved on or left the company;
    - Been promoted to a point they are not told about the problem.
- Space industry cycle estimated at 11 years
    - Customers keep technical groups for longer periods

Water On Off Valves (WOOV)

- Remove heat from experiments
- Based on a design from the nuclear industry for reliability
- Cold water valves started failing
    - €2+ billion facility at risk
- Corrosion observed around valves
    - Initially appeared to be a process water leak
- Returned on *Endeavour's* last flight

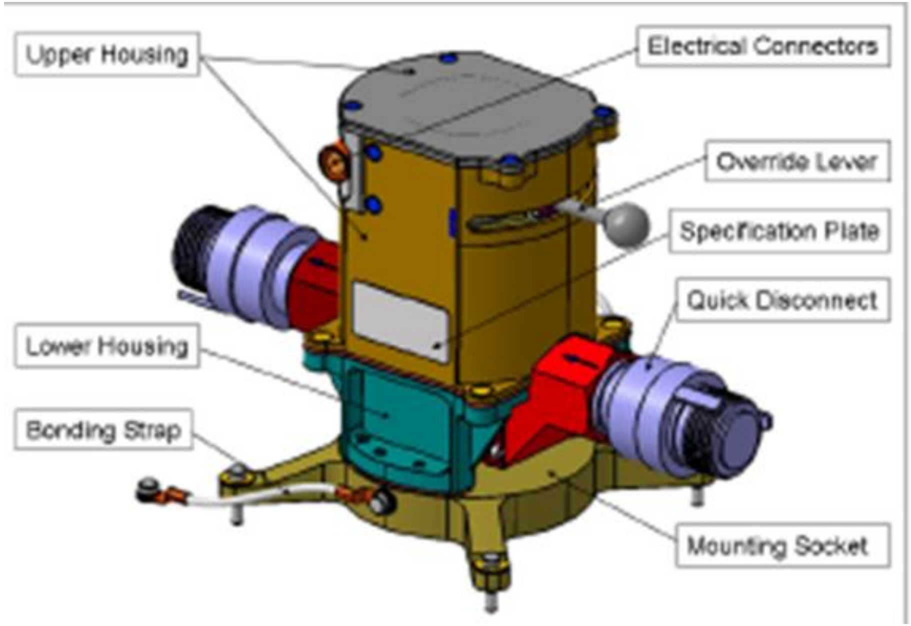


Unintended consequences

- Insulation had been removed late in the design stage to mitigate low torque margins.
  - Insulation would have reduced vapour ingress
- Selection of a COTS motor did not take condensation into account
  - Nickel plating was cosmetic not protective
- Manual override had a torque limiter installed to avoid poppet damage
  - Made override impossible

Lessons Learnt

- Don't Jump to Conclusions
  - Time wasted solving the 'obvious' problem
- Consider the environment in detail
  - Especially if not usual
  - Condensation was not adequately addressed for the Mark 1 Valve
- Late design modifications can have unintended consequences
- Lessons learnt led to Mark 2 design

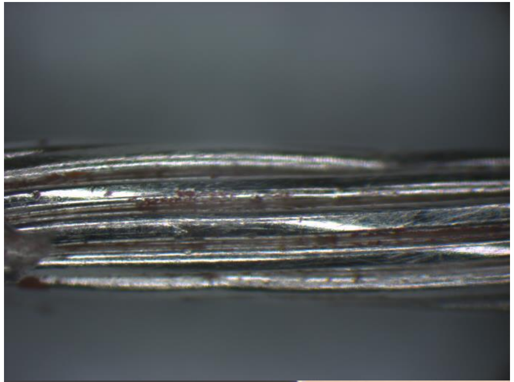


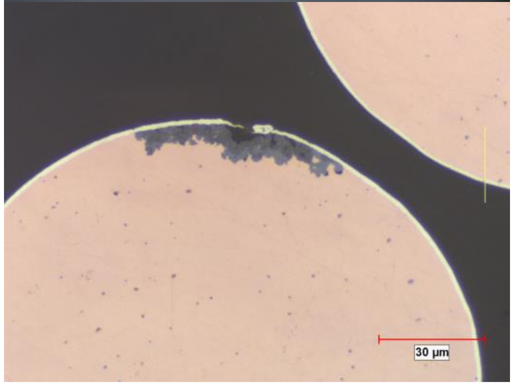
Understanding Risk

AVOIDING FAILURE

Everything has Risk

- MMPDS (MIL-HDBK-5) A-Value
  - At least 99% of population equals or exceeds value with 95% confidence
  - Metals, Fasteners, etc
  - Assuming Normal distribution equates to failure probability of about 1 in 100,000
- Ceramic Structures
  - NIRSpec, Euclid, etc
  - Designed based on 1 in 100,000 for base material
  - New ECSS may allow 1 in 10,000
- Silver Plated Copper Wire
  - Failure probability of 2 µm silver is just under 1 in 100,000
  - Failure probability of 1 µm silver is just over 1 in 100,000
  - Europe requires 2 µm silver for ECSS and ESCC and does not test
  - NASA require 1 µm silver in MIL Spec. and batch test
    - Additional batch testing brings failure probability to just under 1 in 100,000
- **1 in 100,000 appears to be the threshold for the space industry**





Risks Needed

- EDM of Titanium Bipods
  - Embrittlement of surface from EDM
  - Failure predicted during launch
  - Instrument expected to detach from spacecraft and punch through launcher tanks
- Industrial management team understood issue
  - Supported remediation work
  - Project team told they would be closed down if it happened again
- **Project stalled when industry could not take a risk**

Conclusions

- Very few materials are restricted
- Need to show fit for purpose over the life of the mission
- Select materials from preferred lists
- Consider Ground Life as well as flight
- Decide the material requirements early
- “Test as you fly, Fly as you test”
- Testing is about managing risk, there are no guarantees