Technical Evaluation Report

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ABSTRACT

Life cycle costs, sustainability and availability are continuing themes in AVT's contributions to warfighter assets and processes. This Symposium (15-19 Nov. 2021) shared knowledge of physics of failure of subsystems within the NATO community aimed at land, maritime and aerospace asset management. Military relevance requires a common understanding for prediction of usable life, sustainability and availability of current and future vehicles. This report summarizes the symposium contributions: novelty, case studies, collaboration and needs. Within the evaluation, conclusions cover: new solutions approaches, key challenges and opportunities, and connections for research and development collaboration. Scientific foci would be: method development, integrated multi-disciplinary analyses and data exploitation. Military foci would be: fabrication, repair and lifing tools; linking technology transition to asset management and certification systems; compilation of technology programs and tools; and risk and accuracy guidelines. Recommendations concern: compendia for asset failure modes, mid to high readiness technology, and case studies; compiling military needs for training and support; and bridging technology transition gaps by developing: guidelines for risk and uncertainty criteria, and data exploitation as well as near and medium term requirements for hybrid (data + physics) tools, and inspection and fault characterisation tools. Further work could leverage existing technology organizations for military applications with niche and complementary contributions by AVT drafting frameworks for the compendia, guidelines and requirements. These would be developed for rapid use in a broad-based workshop for which planning guidelines are suggested.

1.0 INTRODUCTION AND BACKGROUND

Life cycle costs, sustainability and availability are continuing themes in AVT's contributions to warfighter assets and processes. The studies of transition of technology to impact asset management has identified a number of key needs.

1. **AVT-144 Enhanced Aircraft Availability through Advanced Maintenance Concepts and Technology:** Identify and develop physics of failure, data streams, and cost understanding; Scheduled maintenance, detection and isolation of failures drive availability.

2. **AVT-157 Military Platform Ensured Availability:** Need usage and condition data, better corrosion and fatigue models, and life extension.

3. **AVT-222 Continuing Airworthiness of Ageing Aircraft Systems:** Consequence/risk ranking of issues, non-fatigue, degradation, and certification.

4. **AVT-242 Coated Component Condition Assessment and Remaining Life Prediction for Advanced Military Air Vehicles:** Need better Thermal Barrier Coating (TBC) physics-based

methods, sharing evaluation experience, and in-service issues.

5. **AVT-250: Gas Turbine Engine Environmental Particulate Foreign Object Damage in Land, Sea, and Air Vehicles:** Particulate characterized by geologists; component damage, dosage models, but operations are hindered by lack of damage prediction and a risk based approach.

The IVHM technology watch identified the need for systems approaches to be broken down into key domains: sensors (2018), now Physics of Failure (PoF), with the next steps on data analytics, repair/remanufacturing, and additive, among others.

2.0 THEME SELECTION

Existing weapon systems sustainment challenges require technology to ensure availability and reduce costs of aging aircraft fleets through more accurate life prediction, and new or increased capability repair. New (including attritable type) weapon system acquisition and life cycle costs can also be controlled through by risk management of life prediction at design, manufacturing/repair and in-service.

The intention of the Symposium is to share and expand the knowledge of physics of failure of critical military subsystems within the NATO community. Military relevance requires a common knowledge in the understanding and prediction of the usable life of current and future vehicles. Such products provide nations an ability to address military system availability and sustainment cost that are accelerating challenges. New physics-based failure models promise more accurate determination of life for extended operations as well as an increase in repair limits. Results desired from the symposium are:

- Expected outcomes: New solution approaches, key challenges and opportunities, connections for research and development collaboration, and

- Planned impacts: Improve reliability, availability and affordability for legacy and future weapon systems through new collaborations and accelerated development of new design, manufacturing and in-service support methods, and processes.

3.0 PURPOSE AND SCOPE OF MEETING

To organize a symposium of experts to identify the characteristics of new approaches, and applications to synthesize current technical challenges, common interests and opportunities, particularly amenable to collaboration within NATO. Specifically:

The why: we need to impact life and risk management, and directly, availability, sustainment, repair, and new product development for vehicle fleets including low cost and attritable.
And how: Identify weapon system lifing requirements and identify necessary prediction method developments to solve strength, fracture mechanics, low cycle fatigue, high cycle fatigue, creep, thermomechanical fatigue, corrosion and other life cycle challenges. Develop strategies to exploit emerging technologies for advanced measurement of degradation, diagnostics and prognostics, analytics/machine learning and advanced and additive manufacturing methods.

4.0 EVALUATION

The NATO community represented in the symposium is characterized in Appendix A: Participation at the virtual conference averaged about 25 per session from a registration of 42 (11 countries). The paper and presentation contributions are summarized in Appendix B: novelty, case studies, identified needs and collaborators. The discussions after individual papers and during the open plenary session are tabulated in

Appendices C and D.

4.1 Contributions

Observations by chair Brown identified four main groups from the content delivered: accelerating transition of new materials through reduction in experimental data requirements, Process-Property-Performance approaches, Targeted efforts on small crack and flaw effects on fatigue life, and Machine learning for material modeling. To assess the breadth of the contributions, symposium session content (paper #) has been nominally categorized: over the asset life cycle, methods used, application level and warfighter impacts, in the following tables.

Life Cycle Application	**Design**	**Fabrication**	**In service**	**Land, Air, Maritime**
Key notes	A	B	A, B	A, M, All
Damage Physics	1, 2, 11	(1, 2)	2, 3	All
Fatigue ICME	**4, 6**	**4, 6**	**4**, 5, **6**	All
Applications			7, 8, 9	All
High Temperature	11	10, 11, 12	11	A, (M)
Additive Materials	13, 14	12, 13, 15	13, 15	All
Super Alloys NI-SX	4, 17	12, 16, 17	16, 17	A, (M)

There is limited emphasis on in-service applications but exemplar repair tools are described. These developments also apply to fabrication uses. They show a full life cycle capability to trace defects and damage from billet/ingot to in-service. Applications are possible beyond what is presented in the papers: to all vehicle domains but the emphasis is on the higher cost aerospace and gas turbine applications.

Methods	**Inspection**	**Metallurgy/Physics**	**AI Analytics**	**Hybrid**
Key notes	A, B	A, B	B	B
Damage Physics	3	1, 2, 3		
Fatigue ICME	5, 6	4, 5, 6	5	5
Applications	7, 9	7, 8	8, 9	8
High Temperature	11, 12	10, 11, 12		
Additive Materials	12, 13, 14, 15	12, 13, 14, 15	13	
Super Alloys NI-SX	16, 17	16, 17		

Most methods have physics or metallurgical bases. In many cases they would be helpful for enhanced inspection processes especially when associated failure mode characteristics are also known. Some Artificial Intelligence (AI)/data analytics methods are included with demonstrated enhancements. Elements of (multi-disciplinary) hybrid models are evident in uncertainty, risk and tailored data requirements but not yet widespread.

Application Level	**Element**	**Component**	**System**	**Platform**
Key notes		A, (B)	A, B	A, B

Damage Physics	1, 2	3	3	
Fatigue ICME	4	5, 6	5, 6	5
Applications		7, 9	7, 8, 9	
High Temperature	10, 11, 12	11	11	
Additive Materials	12, 13, 14	11, 14, 15	11, 15	
Super Alloys NI-SX	16, 17	(16)		

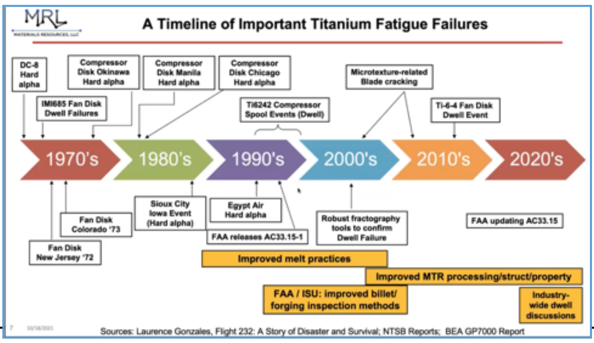
Most work presented was for elements like coupons or tubes to validate models. However applications to complete turbines and systems are discussed or are surmised. Incorporation of physics models into design, forming and repair assessment tools to apply to fleet assets is noteworthy. The keynotes certainly identified the need for an asset management viewpoint at the systems and component level.

Warfighter Impact	**Life Cycle Cost**	**Availability Reliability**	**Capability**	**Land, Air, Maritime**
Key notes	A, B	A, B	A	A, M, All
Damage Physics	1, 2	1, 2, 3	2	All
Fatigue ICME	4, 5, 6	4, 5, 6	4, (5)	All
Applications	7, 8, 9	7, 8, 9	8, (9)	All
High Temperature	10, 11, 12	12	10, 11	A, (M)
Additive Materials	12, 13, 14, 15	12, 13, 14, 15		All
Super Alloys NI-SX	4, 16, 17	4, 16, 17	4, 17	A, (M)

Emphasis on how the technology might be applied is on cost, availability and reliability drivers and less on capability building. While impact is aimed at higher cost aerospace applications, maritime and land opportunities are possible and may be easier to trial and introduce.

Case studies included in many papers provide lessons learned in demonstrating or fielding technology. They also show connections for asset owners to see return on investment to their fleets. Technology development is shown or surmisable for multiple fleets in land, maritime and aerospace, supporting the AVT mission.

As collaboration and development tools three charts from symposium authors are highlighted as exemplars.



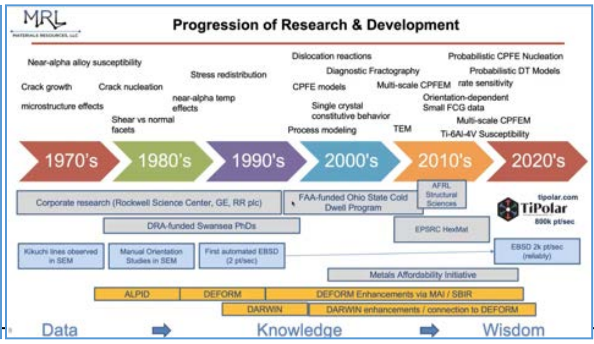


Figure 1: Impact, Progression, and Tools Charts (Pilcak, Paper 6)

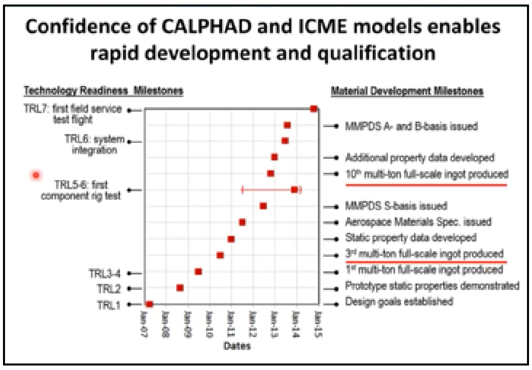


Figure 2: TRL Viewpoint Chart (Engstrom, Paper 4)

Failure types covered in the papers are primarily for metallic, with limited ceramic and composite for: External: Fretting, erosion, oxidation, wear, (hot) corrosion, FOD; and Internal: Microstructure (MS) degradation, inclusions/defects, metallurgical aging, cold dwell, distortion and cracking, creep, thermal fatigue, and thermo-mechanical fatigue (TMF), LCF and HCF. But multi-mode, varying conditions are needed for and in-service and life cycle view: forming-processing-use-repair which track defects, inclusions, and damage. A more complete taxonomy of damage with criticality and cost priorities for military systems would be a useful collaboration tool, starting with the approach of Kumar (Paper 7).

5.0 CONCLUSIONS

Progress toward the expected outcomes has been achieved through this survey of the physics of failure domain, a key foundational enabler for asset management with explicit risk, cost effectiveness and performance:

1. New solution approaches: Integration (two or more): physics, reliability analysis, damage characterization and data analytics have produced multi-disciplinary solutions and in some cases hybrid data-physics applications. Tools for use in fabrication and repair have been demonstrated in pilot applications for alloy design and damage assessment at multiple scales. These incorporate life prediction of elements and sometimes components. Often risk assessment/confidence features are paramount to account for variability in material properties and specific data. Model validations are included but may be limited in applicability with accuracy requirements unspecified. Some promising hybrid (data + physics) methodologies are explored but data analytics tools lack heuristics and knowledge of future applicability. Opportunities appear to exist to apply new failure characterizations to improved fabrication and in-service inspection processes and anomaly detection.

2. Key challenges and opportunities: Documented and prioritized failure and usage data are difficult to obtain for changing and diverse military operations- both for investment rationalization and model validation. Technology transition opportunities are limited: design criteria, component level applications, simulation tools and pilot demonstrations are needed. Emerging digital transformation opportunities are not easily prioritized and valuated for legacy and future fleets.

3. Connections for research and development collaboration: Examples of bi-lateral and consortium based advances have been highlighted: sectoral participation of universities, defence colleges, OEMs and the support industry are evident even in the proprietary environments of products and advanced materials, e.g., ceramics, super alloys. Specifically to develop strategies to exploit emerging

technologies for:

a. Advanced measurement of degradation: Component level inspection and assessment methods are well described but not automated or tied to the advanced models available. The mapping of models with new damage characterizations to emerging inspection techniques (e.g., acoustic emission and thermal) and machine vison/learning techniques would spur development of asset management products: capture *more* service exposure information, readily validate models, and improve repair processes.

b. Diagnostics and prognostics: Diagnostic methods are highlighted based on inspections and specific but usually single mode damage models. The prognostic use is encapsulated in the life prediction outputs of the models in terms of loading cycles or hours of exposure. These element- level life, risk-based predictions need to be extended to components and systems. The promising approach of tracking evolving defects and damage needs to be incorporated into Digital Twin approaches.

c. Analytics/machine learning: Readily available software packages allow the experimentation with existing data sets but lack guidance to develop robust and traceable results. The current community needs collaboration with the specialist data analytics community for more promising results, improved knowledge of the characteristics of damage and progression and optimization of model complexity/accuracy, especially for incorporation into digital twin products.

d. Advanced and additive manufacturing methods: The repair and fabrication assessment tools demonstrated the integration and application of physics and data sciences to small run product and component use. These allow the tracking of defects and damage in high interest applications but need higher volume demonstrations.

The limited engagement of the NATO community in the symposium, the many existing technology organizations, and the breadth of the topic limit the direct conclusions which may be drawn from a first meeting.

5.1 Scientific

To identify necessary prediction method developments to solve strength, fracture mechanics, low cycle fatigue, high cycle fatigue, creep, thermomechanical fatigue, corrosion and other life cycle challenges:

1. Exemplars of models/simulations of these damage modes have been shown with theoretical, data-based and/or computational material validations. Existing and evolving materials are examined. The goal is to link processing, structure properties and performance (strength, corrosion, fatigue, toughness, life) variations while tracking uncertainties. No comprehensive compilation is available of past, present and emerging damage type-material-application-tools for single and multi-mode damage up to the component level, for asset managers to use.

2. Integration of multi-disciplinary analysis methods (0-3D physics, statistics, computational design, machine learning) provides the necessary life and decision support information with the risk basis required for asset management. These tools also allow for reductions in testing while managing uncertainty. Fabrication, repair and in-service applications need to be integrated through the emerging computational tools to provide true life cycle views for asset managers. No clear guidelines appear to be available for data requirements, model accuracy requirements, and heuristics for application of black-box data analytical or hybrid methods. Opportunities exist for application of machine vision and feature engineering for rapid and quantitative characterization of material and

microstructure changes.

3. Collaboration opportunities may be actioned through AVT means: sharing test and failure data, sparse data and data aggregation methods and application to complex parts and components.

5.2 Military

To identify weapon system lifing requirements and asset management strategies:

1. Exemplars of fabrication and repair assessment, and lifing tools for a dominant failure mode are provided and validated for relevant legacy and evolving materials. Most are at the elemental level and nearing maturity for application to the component level but integration, extension for multi-mode damage, and validation are needed.

2. Clear linkages of plans and roadmaps to existing ENSIP, ASIP and other asset management processes and systems like avionics are not widely evident. Cost effectiveness rationale is not often included but examples of accelerated development are highlighted. Deployment of a repair or repair tool appears to be a pragmatic path to exploiting advances. While collaborative programs are identified, little is said about the mechanisms, advantages and lessons learned to accelerate technology transition and product delivery.

To develop a common knowledge in the prediction and understanding of usable life of current and future vehicles:

1. Extensive international organizations already operate in the materials domain but appear to be focused in specific applications, like super alloys or ceramics. Military asset management of multi-material platforms requires access and assessments across these many major programs, as well as to relevant standards and bodies of knowledge. Special compilations like those presented for Technology progression, R&D/tools and TRL would assist.

2. The risk-based predictions and those for structural integrity and repair assessment/integrity in development offer direct asset management support. Full life cycle views will be now be possible with the defect and damage tracking capabilities of fabrication and in-service analyses. New inspection technologies could be applied. Case studies were shown for some land, maritime and aerospace vehicles as well as for legacy and emerging (high temperature) materials. Certification by analytical tools will need explicit uncertainty and risk features.

To improve legacy and future weapon system reliability, availability and affordability through new collaborations and accelerated development of new design, manufacturing and in-service support methods, and processes:

1. Validated risk-based methods will now be able to support direct assessment of reliability and availability. More complete assessment packages with cost effectiveness measures will be needed for the key affordability aspect and especially rationalizing technology investments. Novel approaches like limited life extensions, predictable maintenance, Integrated Product Teams, cultural changes, training and technology wargaming are not documented or addressed in the necessarily technology-based content. Linkages to diverse, existing standards and multi-operator lessons learned need to available.

2. The life cycle continuum of design, manufacture/fabrication and in-service use is addressed in the range of contributions presented. Integration of knowledge and data as well as OEM-support provider-user collaboration will be necessary. Delivery of failure knowledge and prediction tools in

fleet level digital twins is seen as a significant opportunity, particularly for unmanned vehicles where on-board operator feedback is not available.

6.0 RECOMMENDATIONS

The limited engagement of the NATO community in the symposium, the many existing technology organizations, and the breadth of the topic require a novel approach for a timely, complementary AVT contribution. The asset management and warfighter foci underline the need to impact the delivery of products for the fleets in this proprietary and commercial domain. The recommendations are grouped by the planned impacts:

To improve legacy and future weapon system reliability, availability and affordability:

1. Develop compendia for ready access and use by vehicle asset managers:

    a. Military asset failure modes by component/material, cost, criticality and means of detection;

    b. Mid to high TRL technologies for asset management, starting with those highlighted here- digital twin, repair assessment, repair integrity: Impacts possible on availability, reliability, capability, cost and environment; technology readiness level for relevant vehicle systems; and collaboration opportunities;

    c. Success stories, case studies and lessons learned from asset management experience (fabrication, inspection, repair, in-service) particularly from life cycle, ENSIP and ASIP (and the like), collaborative and technology transitions (to components) programs, and specifically addressing proprietary accommodations. The case studies and technology charts highlighted in this report are good foundations.

2. Compile and share military input on requirements for enterprise wide training and specialist support for asset management decisions involving technical (predictable maintenance, life extension), risk analysis, safety and cost benefit considerations.

New collaborations and accelerated development of new design, manufacturing and in-service support methods, and processes to link processing, structure properties and performance while tracking uncertainties would benefit from:

3. Develop guidelines with lessons learned and linkages to existing or evolving standards to bridge the development-product gaps for:

    a. *Risk and uncertainty criteria* for damage accumulation, life prediction and asset management tools that would address components, explainability to asset managers, single and multi-mode failures, Additive Manufacturing and digital twin product requirements and cost benefit rationale;

    b. *Asset management data exploitation*: sharing test and failure data from operators and suppliers, as well as sparse data and data aggregation methods and technology war-gaming.

4. Develop challenge requirements (near and medium term targets) for technology transition and fleet implementation for:

    a. *Hybrid models for components* that would develop synergy among data and physics-based experts, explainability to asset managers, validation and data requirements and identify collaboration opportunities and cost benefit rationalization, particularly in sparse data circumstances.

b. *Inspections and fault characterizations* which would develop synergy among machine vision, feature engineering, NDT and failure experts and identify collaboration opportunities and cost benefit rationalization. Particular interest would be for small production, additive manufacturing and low cost applications.

6.1 Future work and meetings

Future work is recommended to leverage existing technology organizations for military applications with *niche and complementary contributions* through AVT for the recommended topics. Focused short term efforts tied to asset management impacts are proposed:

1. The existing or possibly expanded program committee should draft requirements for

a. Compendia on asset failure modes, product technology and success stories for asset management

b. Asset management technology transition guidelines: Risk and Uncertainty, and Data Exploitation

c. Development and implementation challenge requirements for hybrid model synergy, and inspection and fault characterization synergy for military asset management

The goal would be to provide a framework of broad requirements to drive technology transition for development in a workshop. The outlines would be applicable across the multi-disciplinary domains of materials science, manufacturing, in-service support, data analytics, information technology and operations. The agenda could cover: an initial video conference to agree on the scope and to identify leads to draft initial one page outlines for the seven topics, followed by joint email review and finalization before the next AVT meeting. The outlines would also form the basis for the workshop proposal below.

2. Workshop to develop a working outline for the compendia, guidelines and challenge requirements:

The goal would be to refine the draft requirements and validate the three components to asset management technology transition for the military (with dual use inputs). The agenda could cover: introduce a common framework, then break into working groups and then re-assemble to examine and confirm integration. Each group would develop high level outlines from an initial framework that would make a difference in technology transition for asset management. The participants should include technology developers as well as military operations and asset managers, including specialists in all of the indicated domains with experience in deploying applications to pilot or larger complex fleets/product lines.

7.0 APPENDICES

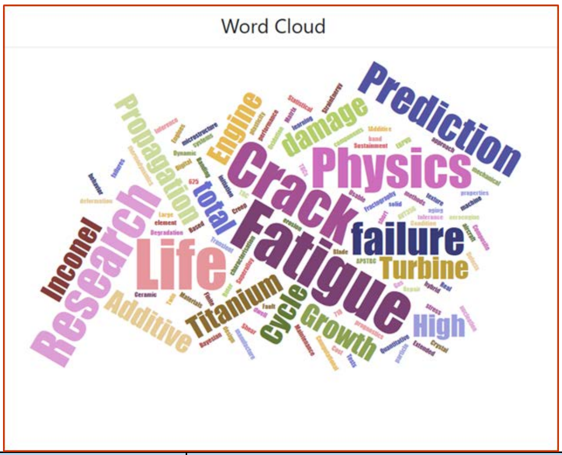
A. Participation Summary
Organizing Programme Committee: CAN-USA co-chairs and GBR, DEU, FRA, NLR, POL
Participation Basis: NATO Unclassified, AUS, SWE, FIN, JPN

Countries and Organizations (40 registrants, 2 NATO CSO and 20-30 participants/session):
CAN: National Research Council, RCAF, TECnos, Tecsis
DEU: MTU Aero Engines, Airbus Defence and Space
FRA: ESMA, Pprime
GBR: Cranfield U., DSTL, Rolls Royce
ITA: Secretariat General of Defence and National Armaments Directorate
NLR: Netherlands Defence Academy, NLR

NOR: NDRE (FFI)
POL: HSW, ITWL
SWE: QuesTek, Thermo-Calc
TUR: Istanbul Technical U., Maltepe U., ASALSAN
USA: Air Force Research Lab, BAE Systems, ONR, Raytheon, USAF

B. Content Summary

This summary highlights key contributions, identifies and credits collaborating partners, as well as follow-on needs (N:) and case studies (CS:). Paper numbers are final from the proceedings while those in [] are those in the original paper offerings. A compilation of the paper keywords is presented in the following word cloud indicating the emphasis on cracks, fatigue, life and physics with limited reference to cost, sustainment, degradation and learning.



Session 1: Keynotes		Chairs: J. Brown, AFRL USA and P. Patnaik, NRC CAN
Paper and number	Lead, Collaboration	Contributions and Identified **N**eeds
A Deformation and damage in Ni alloys for disc rotor applications	Rolls Royce, U Birmingham, Swansea U	Ni-SX design, simulation and fabrication for high pressure/temperature, safety critical components: fatigue, hot corrosion, oxidation, strain aging, inclusions N: Matching physics in experiment, physics models, simulation and service

B Strategic sustainment for the RCAF	RCAF, NRC	Asset owner priorities (capability, availability, cost, environment impact) and appreciation for R&D and collaboration N near term: Coatings, fuels, test, modifications, appropriate and predictable maintenance, IVHM, extended platform life, trade space tools; limited life extension through Digital Twin, environmental FOD, additive manufacturing N emerging: Open systems, Digital transformation, Net zero impacts, share NRE, electric aircraft, Apply to all systems (weapons, avionics), people and culture adaptation /evolution

Session 2: Damage Propagation Physics		Chair: H. J. Ten Hoeve, NLD
Paper and number	Lead, Collaboration	Contributions and Identified Needs
1 From small crack growth to fatigue life [1]	NLR, Netherlands Ministry of Economic Affairs and Climate Policy, the Netherlands Ministry of Defence, GKN Fokker, Embraer, Airbus, Wärtsilä and Lloyd's Register	Increased accuracy method for material FCGR data and small and long crack growth for design with physics-based approach coupling safe life and damage tolerance CS: Aluminium 7075-T7351 coupons N: Long crack growth life predication and maximum stress effects with large stress gradients
2 Structural integrity issues from crack nucleation, initiation and growth [2]	NRC, RCAF	Holistic fatigue approach for structural integrity, test, qualification and lifing use with crack initiation incorporated to lessen test and data requirements demonstrated on many materials CS: Cu, Ti, W, 316 SS, Waspaloy, Mar-M509, 7075-T6 N: Microstructure and uncertainty effects, high temperature creep and oxidation effects, collaboration on application to components, ML of microstructural effects
3 Interpretation of complex fatigue fractures… using quantitative fractography … [4]	Rolls Royce	LCF and/or transient HCF failure investigation methods for critical components demonstrated on compressor and turbine case studies for fleet management inspections. Including fretting, metal transfer, overheating N: Reliable in-service data; less subjective methods like digital image recognition; further physics correlation

Session 3: Integrated Computational Metallurgy Engineering (ICME) for Fatigue		Chair J. Cormier, Institut Pprime, FRA
Paper and number	Lead, Collaboration	Contributions and Identified Needs
4 Computational tools and data and its application in materials design based on failure physics [12]	Thermo-Calc and QuesTek	General (known or new) materials computational design tool from phase diagrams linking processing, structure properties and performance (strength, corrosion, fatigue, toughness, life) variations, uncertainties and predictions including TRL view CS: IN718, M54 steel N: Public domain data, Validation with other materials like Ni-SX including extension of models, transition mechanism models, e.g., precipitate
5 Predicting critical failures using physics of failures: opportunities and challenges [13]	Netherlands Defence Academy, U Twente	Asset management approach for maintenance, and data identification to predict life with physics for long reliable lives and variable conditions. CS: land wheel, air structure and maritime avionics N: Long life cost effective methods, availability focus, appropriate field and failure data, critical part identification, model validation, hybrid method development
6 History, Phenomenology, and Practical Management of Cold Dwell Fatigue Failure in Titanium Alloys [10]	MRL Materials Resources, Johns Hopkins U	Research and development contribution mapping and directions for cold dwell fatigue failures in Ti (low cycle peak load brittle failures) including design, processing and use including Micro Texture Regions, stress details, temperature effects CS: Ti-6Al N: Design and sustainment applications at mid to high TRL for total life cycle of components, damage criteria, complex mechanisms like thermal alleviation, inspection, data acquisition and aggregation

Session 4: Applications		Chair: A. Fischersworring-Bunk, MTU Aero Engines
Paper and number	Lead, Collaboration	Contributions and Identified Needs

7 Physics of Failure in Aging Aircraft Systems and Components [7]	NRC, TECSIS, RCAF	Compendium of failure modes focused on turbine engines at the component level for range of materials with dual use aspects. Including composite, ceramic and TBC CS: Helicopter structure, gas turbine blade failure, disc failure, rotor blade failure N: Physics for novel materials, damage accumulation models, performance modeling
8 Digital Twin for In-Line Fault Prediction in Military Unmanned Vehicles [9]	Babcock International , Surrey U	Digital twin hybrid model design and application process for sustainability. Hybrid uses anomaly detection from normal experience. Operator-less implications on monitoring. CS: diesel engine failures N: Data availability, model accuracy/validation especially faults and transient and unsteady operation; integration of black and white box models
9 Application of Machine Learning to Solid Particle Erosion of APS-TBC and EB-PVD TBC at Elevated Temperatures [15]	NRC, TECSIS, RCAF	Coating (two types) degradation data compendium and ML model development considering various tools for erosion rate CS: Two TBC coating methods N: ML/DL tools and processes for small sparse data sets, expanded model parameters including microstructure image; hybrid approaches

Session 5: High Temperature Behaviour		Chair: D. Thomson AFRL, USA
Paper and number	Lead, Collaboration	Contributions and Identified Needs
10 Microstructure-Sensitive Thermomechanical Forming Simulation Capability [16]	Raytheon, CWR U, U Michigan, American Lightweight Materials Manufacturing Innovation Institute, ONR	Simulation Model for large deformation processing (Forging) for microstructure, re-meshing and in service performance combining physics and experimental data for calibration, including dynamic recovery and recrystallization. CS: multistep, multiaxial forging including airfoil shape N: micro-scale test data; parallelize model- application to complex parts, image feature processing

11 Ceramic Matrix Composite behavior enhancement for Gas Turbines Hot Sections [17]	SAFRAN, (PW, RR, AFRL)	Ceramic matric composites experience for gas turbine hot sections including dual use CS: afterburner nozzle flaps, HPT shrouds, exhaust mixers, HPT blade, shroud exit cone: pilot evaluations and in service N: Roadmap/design criteria for development: margins, robust, cost effective for manufacture, certification; Technical: failure modes and damage tolerance, multi-scale behaviour, application to complex shapes, fiber reinforcement, fiber/matrix interface, dense matrix, environmental coatings, machining and NDT
12 Microstructure and mechanical properties of Inconel 718 and Inconel 625 produced through the wire + arc additive manufacturing process [21]	Cranfield U, DSTL	Process development for wire and arc additive manufacturing (IN718, 625) through to microstructure and performance (UTS, YS, Elongation, Hardness) CS: IN718 and 625 N: Optimization of process for performance- reduced cracking, precipitate secondary phases; assessment at operating temperatures

Session 6: Additive Materials		Chair: J. Brown, AFRL, USA
Paper and number	Lead, Collaboration	Contributions and Identified Needs
14 AM Design Tool for Rapid Structural Assessment of Aerospace Components [19]	USAF AFRL	Minimum design criteria and prediction of additive component life for fatigue from small crack growth models and defect observations including uncertainty quantification and reduced testing requirements CS: AM Superalloy 718 N: Minimum (mixed) data requirements, large scale validation, Optimum characterization build; Collaboration on short/long crack growth models.

13 Hybrid Energy-Based and Bayesian Statically Inference Fatigue Life Prediction of AM Components [20]	USAF AFRL	Rapid energy-based characterization of AM LCF and HCF fatigue behaviour in coupons with life model and uncertainty updates from observations CS: Aluminum 6061-T6, DMLS IN 718, and EBM Ti-6Al-4V N: Damage-energy mechanisms including thermodynamics, fatigue limit models, acoustic emission and thermal sensor inputs, repair applications
15 A High Cycle Fatigue Decision-Gate Assessment of Additive Repair for Fan Blades [18]	USAF AFRL, ARCTOS	Integrally Bladed Rotor (fan) component repair assessment tool for HCF with cost effectiveness tied to ENSIP decision gates with deviations from baselines CS: Ti 6Al-4V structural assessment for IBR blades, blown powder and wire feed N: Rule refinement for rules with microstructure, defect and porosity effects

Session 7: Nickel Super Alloys (Ni-SX)		Chair: M. Lunt, DSTL, GBR
Paper and number	Lead, Collaboration	Contributions and Identified Needs
16 Laser Surface Texturing to Improve EB-PVD Thermal Barrier Coating Adhesion [22]	Université de Bourgogne Franche-Comté, Institut Pprime, ISAE-ENSMA, SAFRAN TECH, CPER, FEDER	Thermal barrier coating fabrication durability improvements and damage mechanisms for HP blades including thermomechanical, cyclic oxidation, thermal gradient effects with spallation and recrystallization CS: CMSX4 Plus Ni super alloy tubular specimens N: Numerical simulation, component applications, characterize thermal conductivity, surface architecture design tools
17 Understanding premature blade failure in new ReRu-rich Ni-SX super alloys [24]	MTU Aero engines, Friedrich-Alexander-Universität	Turbine blade crack, LCF and HCF failure plasticity and thermodynamic physics for ReRu alloys especially lattice misfit and crack models compared with local microstructural data CS: model alloys N: Safe blade life design applications, Data on rare metal alloys, Recycling and repairability applications, Defect NDI

C. Questions and Answers

Note details of questions in the last three sessions are not complete because access to the recorded meeting files was lost. Text highlighted is to be confirmed with authors.

Paper No.	Question	Answer
A	Wu: What constitutive law are you using in CPFE- Hill's or linear/non-linear kinematic/isentropic hardening?	Hardy: Isentropic or Marots model, I think- C. Argyrakis can answer better. We tend to use our own codes but I believe it is more of the Marots type linear kinematic and we do add include isentropic hardening in there as well.
A	Cormier: Do you try to adjust the precipitate size at disk scale to try and reduce dwell crack growth? Or do you live with the precipitate size you get from processing?	Hardy: Up to now, we haven't tailored things but our new alloy will absolutely tailor the microstructure to have the best dwell crack growth resistance we can get. The stuff we have in-service not so much- with R1000 we don't cool particularly quickly. With new alloy absolutely we are tailoring.
1	Brown: For the large crack growth what life over prediction (non-conservatism) would you estimate (percentage) in a real application?	Amsterdam: More than 5% over-prediction. You should increase the stress by 25% or something to get similar lives. Sometimes factors are used in certain structures to get calculations to match the observed fatigue life. This could be a 20 to 80% difference.
B	Brown: What are the pressures for retiring/replacing old fleets versus maintaining them?	Keiver: This question we wrestle with every day. Sometimes it is easier to continue to put money into existing systems because it is harder to break away and move to something new. There is a risk attached to anything new- people get comfortable with even difficult older systems- a known risk versus the unknown of the new. Just completed this discussion on a (Bell 412) Digital Twin application: some saw the new approach to be risky cost-wise while others saw it as a technical de-risker. It is a dominant part of the discussion for cost benefit analysis.
B	Martin: What will digital transformation be able to provide- how much is worthwhile and what are the biggest cost savers to select specifically? {Look for the low hanging fruit and join up adjacent components for new benefits?}	Keiver: We have the same challenge in RCAF and the CF. Change needs to be supported by conclusive, deliberate analysis not following a 'fad'. We need cost savings and efficiencies but they must bring new levels of effectiveness. Seek to increase operational effectiveness and efficiencies- we agree that everything doesn't need to be digital. Otherwise stick with what is working. We think it will help understanding the asset throughout its life on all fronts. There are now some second and third order consequences being seen that argue against digitalization.

2	Hardy: Would the TMW model be appropriate for fine grain materials, which are known to contain oxide inclusions or carbides?	Wu: We haven't gone to that detail yet but we are working with Carleton U to address that. I believe it can be applicable, as long as the microstructural RVE is built to contain features and the modulus and surface energy of the inclusion/matrix interface energy are known. We may talk later xijia.wu@nrc-cnrc.gc.ca
3	Amsterdam: Is it fair to say that the crack propagation during resonance events is more related to constant amplitude fatigue crack growth and the in-flight growth is more related variable amplitude. Related to figures case study 1 with optical SEM, I know work by Simon Butter from DSTO AUS showing that during variable amplitude fatigue the crack path is smooth and for constant amplitude the crack starts to propagate on different planes causing vertical lines. Also differences in stress ratio can get slight crack deflection- optically seen. Could this help explain the optical graphs and differences in fracture surfaces?	Chapman: I think it may. One of the things we attempted that may have helped (not successful) was to try to observe how the oxygen content was different in colour bands- blue to white. At the time we didn't have the technology available. We would like to do some sectioning through the bands to see if we have a different oxygen profile. This would help corroborate the colour-oxide correlation related to amplitude modes and amplitudes. We agree and want to do more work to confirm this postulation.
4	Cormier: Re CS 1, have you tried to section just below the crack path (100-200 nm) because your stress ratio is not too high? If you are in a resonant mode you should have a very pronounced microstructure evolution in this material. At perhaps 1-10 kHz where you have a very pronounced microstructural evolution/ deformation: solution of precipitates, shearing, crystographic model (?). It is really interesting to know if you are really in the resonance or not? There is evidence in the literature of these effects.	Chapman: Are you asking about subsurface? We haven't done the sectioning because of time during the investigation. It is something interesting to do. We were able to verify the crack origin microstructure and see the gamma - gamma prime microstructure beneath. We did see one case of crystographic mode but not in all.
4	Wu: What about grain boundary precipitate and possible sliding which can also influence the creep performance? (Cormier- do you try to take in account grain size effect for IN718)	Lancelot: Our QuesTek colleague did this part. I don't think it has grain boundary slide but does include grain size for hardening. For the precipitate I mentioned already the delta which destroys properties in time. It was difficult to model and so we need more effort to include that effect. The empirical TTT diagrams shows the grain boundary delta (high temp.) and bulk (at low temp only). Difficult to model both types- bulk depends on the gamma double prime distributions to select out. The microstructure evolution simulation only considers the two gamma types.

4	Cormier: This alloy and other 718 class (IN625) are known to have highly sensitive precipitate kinetics depending on processing routes (dislocations, density). Is there any way to account for these to modify TTT diagrams, e.g., your IN718?	Yes, this can be done in software. Complex processing routes and functional curves of temperature can be done. You can also try to predict continuous cooling diagrams but good luck. You can also vary the initial dislocation density and elastic properties of the matrix phase and some others. Here I tried to keep many parameters constant to simplify the calculation and only modify the interfacial energy and the nucleation site density
4	Cormier: Concerning the fast M54 steel design, you assume that you can reach the maximum properties but in real life only reduced properties might be achieved. Is this something that you are working on or you want only the maximum properties?	Lancelot: QuesTek could answer better but I feel confident that they use a probabilistic approach to find property distributions.
5	Cormier: Do you try to use model reduction to simplify physics models from the rich models for microstructure including boundary conditions or RUL?	Tinga: It is always finding the balance. Microstructure could give accurate result but you need a lot of data for the parameters. Balancing accuracy and unavailable data tends to reduced order models.
6	Cormier: What really is cold creep in Ti alloys? At room temperature- Viscous or time independent plasticity process?	Pilchak: Time dependent plasticity and stress redistribution among neighbouring grains. Each of the slip systems has a different rate sensitivities dependent. Combination of both.
6	Wu: Is there a way to mitigate the dwell effect?	Pilchak: The common thread among failures is the microtexture region. If you can process them away through TM processing then you can reduce the effective slip length and eliminate the highway for cracks as they form. >10x dwells have really large microtexture regions at the initiation sites.
7	Fishersworring-Bunk: What are your recommendations based the vast amount of experience? For future R&D activities?	Kumar: As a structural person, great focus is needed on ceramic materials for future applications- more ductility, toughness.
8	Fishersworring-Bunk: Digital Twin capabilities- descriptive, diagnostics, predictive, needing to lead to prescriptive action. How to get there with a black box approach? What is the plan?	Heron: A white box approach is easier to see the application. We started there but we think the black box Neural Network model will help support the decision making process. The data have a lot of noise and engine operations have complex variations. Adding diversity to the decision making process, start with the White Box model and add the Black Box model diversity for greater confidence in the final result.

8	Ten Hoeve: Can you explain how the data is collected from the vehicle to the digital twin? Wirelessly?	Heron: During development and testing of the digital twin, data must be collected from each unit and transferred to a central database for validation. This is gathered from each vehicle wirelessly using cellular connection, and is possible since most testing occurs in the UK. We have other similar systems in harder to reach corners of the globe that can communicate back using satellite, so that’s an option too. However, the end goal is to embed the digital twin within each vehicle to perform autonomously, so no communication with the outside world is required.
9	Fishersworring-Bunk: Your use of PCA as a starting point- how many components and what were the eigenvectors (linear components for prediction) associated with them? The most important parameters from PCA?	Chen: Not sure whether we used the linear combination and expect a non-linear function is required.
9	Wu: Are those TBCs, e.g. APS-TBC produced by the same deposition process? If not process parameters could be a variable in ML.	Chen: Even for that type, there could be different processes parameters (T, cooling rate, technology level) and properties. It was a challenge to identify them and categorize into the data set. There is a risk to aggregating the data but it is needed for ML approaches.
9	Brown: How did you choose the training data population versus the test population?	Chen: Not answered in the session
10	Brown: Can you highlight where DEFORM is unable to solve this type of problem?	Borkowski: PW colleagues asked for an alternative because it can’t parallelize over more than maybe 8 cores and also has a loose coupling between re-meshing and the MS prediction. DEFORM can do crystal plasticity sim with re-meshing but with only one way coupling- run the sim with a phenomenological plasticity model (isentropic or kinetic hardening), then take the deformation history of each element and feed into crystal plasticity model to predict the texture. The problem is that you break the connection between the texture and deformation which are linked (only deformation to texture is used). Author M. Anahid helped with this aspect. LSDYNA helped with this and this capability is available in their commercial package.
11	None	

12	Brown: What types of applications are being considered with WAAM? It is capable of large builds so there may be many opportunities?	James: Size is limited by robot positioning. The DSTL-sponsored application is for a high speed environment and large components are possible in our centre.
12	Cormier: Are you processing in domain CMT or closer to GMAW processing conditions which might explain Laves cracking?	James: GMAW- plasma with tungsten electrode. Agree that CMT could be better.
12	Cormier: Don't you feel inter-pass rolling, solution and aging would be really expensive compared to a forged part? All of the processing loses some benefits of an AM technique?	James: We want find out how to increase tensile properties of the WAAM process. Equipment already exists but it is likely quite expensive.
12	Cormier: Surprised by the high amount of carbon in the EDS measurements and might bias your assessment of the phases actually occurring?	James: Carbon result is unreliable because it should have been removed during the analysis procedure before imaging. Thank you.
14	Wu: Can you explain more about the KN approach and the threshold fatigue limit?	Sheridan: It depends on the crack growth method. The threshold was determined from the data.
13	Brown: Could you use more than 2 points for the prediction algorithm?	Celli: Yes and also add more information like entropy degradation.
15	Martin: Can you comment on the porosity effects and distribution across the repair?	Scott-Emuakpor: The effects are partially a function of the shape of the sample near the wall and the fact that the repair process was not optimized for this demonstration.
16	Brown: Can you give some more detail on the genesis of laser texturing?	Cormier: Early proven applications were in bio-prosthesis where earlier applications only considered surface chemistry.
16	Martin: What would be the trade-off in this type of approach in a CMAS environment?	Cormier: Maybe it would be better for thermally sprayed. Gaps in patterns caused porosity. There may be information from the AVT TBC work that could be available next year.
17	Cormier: Is the 250 µm threshold critical for design?	Kirzinger: Yes
17	Lunt: Comment more of the rafting behaviour.	Kirzinger: It is different by alloy. It is important for the first creep mechanisms to have temperatures above 700 C.
17	Wu: What are the defect types that you consider? Cast pores?	Kirzinger: Internal defects, yes casting pores and others like residual cracks.

17	Goehler: Does the audience have other experiences in this domain?	None offered.

D. Plenary Session Comments

Comments
1. Areas not covered: environment, hot corrosion, user/operator experience (to prioritize failure modes), low cost vehicles, repair integrity, and collaboration mechanisms.
2. Certification by analysis needs uncertainty and risk incorporated.
3. There are challenges in getting support for technology developments but a game changer is rapid deployment of a repair versus general contributions to sustainment. Fatigue work is still needed but funding for the second 60 years is difficult. Especially hard to get support for low TRL materials work which does not have the visibility (and novelty) of enterprise effects like big data. Generic applications versus proprietary concerns.
4. How do we exploit civil applications and identify what industry is not doing?
5. References to other groups: Confidence Assurance Group (Wu); Spring 2022 symposium of damage and deterioration of high temperature alloys in USA (Hardy?), Public-Private Partnership Industry 2016-2019 project called “Prediction of fatigue in engineering alloys” (PROF). Financial contributions from the Netherlands Ministry of Economic Affairs and Climate Policy, through TKI-HTSM and the Materials Transition Programme, the Netherlands Ministry of Defence, GKN Fokker, Embraer, Airbus, Wärtsilä and Lloyd’s Register (Amsterdam see paper 1)