NETL

the ENERGY lab

R&D FACTS

Turbines

Materials and Component Development for Advanced Turbine Systems

Background

Future hydrogen-fired or oxy-fuel turbines will likely experience an enormous level of thermal and mechanical loading, as the turbine inlet temperature (TIT) approaches 1700 °C (3092 °F) with pressures of ~40 bars (Table 1). For these systems, the estimated thermal loading or heat flux imposed on a turbine airfoil is projected to be about 10 times the level of current state-of-the-art (SOTA) gas turbines. Maintaining the structural integrity of future turbine components under these extreme conditions will require (1) durable thermal barrier coatings (TBCs), (2) high-temperature, creep-resistant metal substrates, and (3) effective cooling techniques. While advances in substrate materials have been limited for the past decades, thermal protection of turbine airfoils in future hydrogen-fired and oxy-fuel turbines will rely primarily on collective advances in the TBCs and aerothermal cooling.

Table 1. Advanced Turbine Operating Conditions

	Syngas Turbine 2010	Hydrogen Turbine 2015	Oxy-Fuel Turbine 2010	Oxy-Fuel Turbine 2015
Combustor Exhaust Temp, °C (°F)	~1480 (~2700)	~1480 (~2700)		
Turbine Inlet Temp, °C (°F)	~1370 (~2500)	~1425 (~2600)	~620 (~1150)	~760 (~1400) (HP) ~1760 (~3200) (IP)
Turbine Exhaust Temp, °C (°F)	~595 (~1100)	~595 (~1100)		
Turbine Inlet Pressure, psig	~265	~300	~450	~1500 (HP) ~625 (IP)
Combustor Exhaust Composition	9.27% CO_2 8.5% H_2O 72.8% N_2 0.8% Ar 8.6% O_2	1.4% CO_2 17.3% H_2O 72.2% N_2 0.9% Ar 8.2% O_2	82% H_2O 17% CO_2 0.1% O_2 1.1% N_2 1% Ar	75-90% H_2O 25-10% CO_2 1.7% O_2, N_2, Ar

This project supports a comprehensive effort conducted principally through NETL's Office of Research and Development (ORD) to generate a wrap-around, knowledge-based understanding of turbine materials and aerothermal systems for utilization in advanced land-based turbine applications as the hydrogen-fired and oxy-fuel turbines.

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This initiative, which began in Fiscal Year 2007, focuses on the efforts undertaken at NETL in Pittsburgh which:

- Combines the expertise of NETL, University of Pittsburgh (UPitt), and West Virginia University (WVU) researchers, working in conjunction with commercial metal and coating suppliers as Howmet International and Coatings for Industry (CFI) to develop advanced material systems, as well as non-destructive evaluation diagnostic techniques.

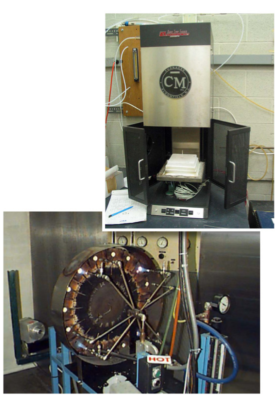
- Combines the expertise of UPitt and NETL to develop advanced aerothermal cooling and computational damage mechanics life prediction models, and to demonstrate the validity of advanced cooling concepts in bench-scale laboratory test facilities that have been designed and constructed on NETL's and UPitt's campuses.

- Utilizes test facilities at Westinghouse Plasma Corporation (WPC) for high temperature thermal flux testing, and Praxair's JETS testing for evaluation of newly developed material systems in conjunction with developing baseline reference performance characteristics for commercial state-of-the-art TBC-coated material systems.

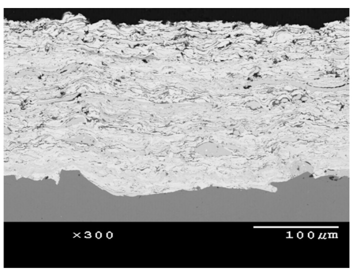
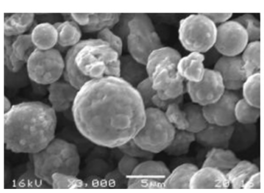
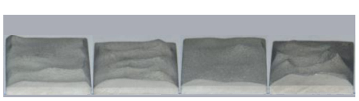
Project Objectives

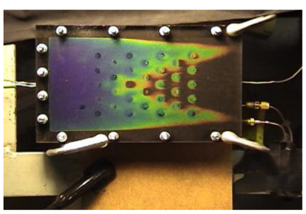
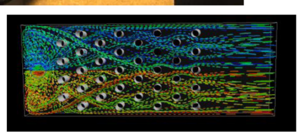
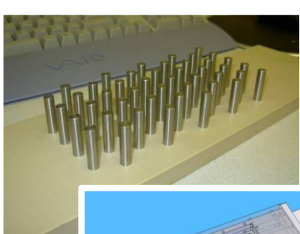
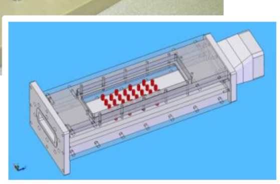
The Materials and Component Development for Advanced Turbine Systems project currently consists of multiple subtasks that focus on materials development, aerothermal heat transfer, and non-destructive evaluation techniques. Table 2 identifies the objectives of each subtask, as well as major accomplishments achieved since 2007. The Materials and Component Development for Advanced Turbine Systems project[1] is complemented by University efforts conducted under the IAES initiative for DOE NETL under Contract DE-AC26-41817.606.08.02.107—Advanced Plasma Sprayed Thermal Barrier Coating, and DE-AC26-41817.606.08.07.103—Turbine Aerothermal and Material Research for Oxy-Fuel and Hydrogen Cycles.

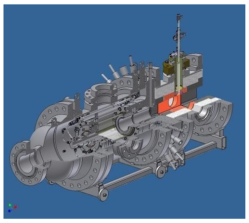
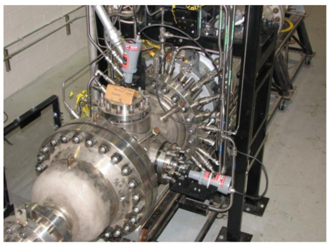
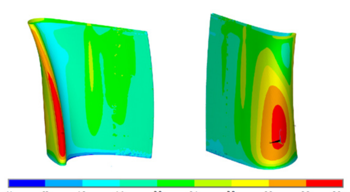
Table 2. Objectives and Major Accomplishments

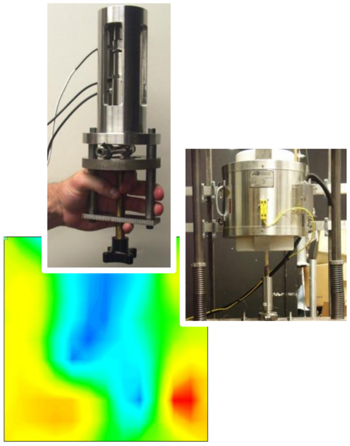
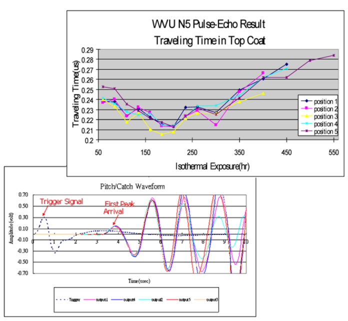
Subtask	Objectives	Accomplishments
Materials Development		
Bond Coat System Development  Substrates: René N5 and Haynes 230	• Modify a commercial spray coating technology to develop lower cost bond coat systems for nickel-based superalloys and single crystal substrates • Achieve performance and durability of state-of-the-art (SOTA) systems at >1100 °C • Integration of bond coat/TBC systems with higher temperature overlay systems, and internal diffusion barrier coatings	• Based on bench-scale weight change as a function of cyclic oxidation at 1100 °C, the NETL-A1D bond coat system ~tripled the oxidation life of René N5/Y (850 → 2,120 cycles). Cyclic oxidation life for SOTA PtAl systems on René N5 at 1100 °C is ~1,600 thermal cycles, and for Pt-Hf Mod γ+γ′ G2P ~1,100 thermal cycles. • Relatively smooth external NETL-A1D bond coat surface resulted; Detrimental internal secondary reaction zone was not observed • High temperature cyclic oxidation performance of NETL-A1 bond coat was shown to be alloy specific to alumina formers
Advanced Air Plasma Sprayed TBCs 	• Improve adherence, performance, and viability of thick APS-YSZ TBCs on Ni-based superalloys for turbine blades, vanes, and combustor components • Establish processing and microstructure/property interrelationships • Control 7YSZ-APS thickness, density, pore and crack morphology • Utilize conventional and high purity YSZ • Optimize NiCoCrAlY bond coat: Variation in Y content & surface roughness • Conduct cyclic oxidation & JETS testing • Define plasma sprayed TBC degradation mechanisms	• For IN 718 JETS testing, demonstrated viability of 375 µm APS after 2,000 cycles – TBC surface temp: 1300 °C–450 °C; through wall gradient: 1300 °C–1000 °C • Demonstrated TBC through-wall gradient (Δ °C): 350 °C/375 µm; 395 °C/750 µm; 550 °C/1125 µm • For high purity YSZ, demonstrated sintering resistance • Demonstrated failure in YSZ is primarily along splat boundaries. Two failure modes were identified based on APS coating thickness: - For >1 mm APS, cracks develop in lower 20% of the top coat (20 cycles @ 1100 °C) - For < 1mm APS, crack formation was associated with bond coat oxidation (140–220 cycles @ 1100 °C) • All TBCs exhibited edge cracking • The CTE mismatch between superalloy substrates and topcoats was found to have a dramatic effect on TBC cyclic life • For equivalent thickness, high purity-low density (HP-LD) APS TBCs are projected to have superior performance in comparison to SOTA EBPVD TBCs (1,200 vs 1,000 thermal cycles) • Deposition of a Zircoat (i.e., dense vertically cracked YSZ) inner layer (without an intermediate step in the deposition prior to deposition of the low density YSZ) did not produce an improvement in the life of the thin topcoats, but did for the thick topcoats

[1] DOE Contract DE-AC26-41817 and DE-AC26-41817.606.01.01

Subtask	Objectives	Accomplishments
Materials Development		
TBC Overlayer Coatings 	• Develop external coating overlayers capable of providing thermal protection at temperatures up to 1600-1700 °C • Identify appropriate rare earth zirconate overlayer composition(s) • Define overlayer thickness requirements • Develop processing techniques for manufacturing rare earth zirconate overlayers for ASP YSZ TBC systems • Conduct mechanical and thermal evaluation of processed overlayer/ TBC architectures	• $La_2Zr_2O_7$ was selected as an appropriate overlayer material due to its lower thermal conductivity and mechanical properties • For surface overlayer temperatures reaching 1680 ºC, an overlayer thickness of ~200 µm was estimated to be required to maintain the underlying YSZ at temperatures of $\leq$ 1300ºC • When 50-350 µm $La_2Zr_2O_7$ overlayers were manufactured, cracks were not visually observed either before or after Rockwell hardness indentation • After 1100 → 100 ºC thermal cyclic oxidation testing, mechanical failure resulted at the metal substrate interface for overlayer thicknesses of >100 µm that were deposited on 250 µm APS YSZ. This resulted due to high residual stress induced during overlayer processing.
Diffusion Barrier Coatings 	• Develop a viable and cost-effective processing route for deposition of oxidation resistant diffusion barrier coating (DBC) systems to limit/mitigate long-term coating/substrate interdiffusion at elevated process operating temperatures • Integrate the DBC systems with a reliable and durable Al_2O_3-scale forming metallic coating and, if necessary, an outermost thermal barrier coating (TBC) • Achieve operational performance of the DBC systems during both isothermal and thermal cycle exposures at 1100 ºC	• Rhenium (Re)-containing σ-phase was identified to be an excellent candidate for DBC systems • 40Re-40Cr-20Ni (at%) σ-phase powder was prepared by mechanically milling constituent powders followed by heat treatment at 1200 ºC for 6 hrs • Intact σ-coatings were deposited onto a Ni-base alloy via air plasma spraying (APS) • Assessment of thermal stability of the APS σ-coating demonstrated excellent diffusion barrier capabilities • Tungsten (W)-based σ-phase was also identified to be an excellent candidate for DBC systems. The advantage of using W instead of Re is cost reduction.
Oxide Dispersion Strengthened (ODS) Alloy Development  	• Investigate alloy effects on dispersion stability and oxidation resistance of ODS alloys utilizing a high throughput powder mixing technique (Hosokawa Mechano-Chemical Bonding (MCB) process) to produce ODS powders with reduced manufacturing cost • Develop suitable processing conditions to achieve a homogeneous ODS powder mixture comparable to that achieved with mechanical alloying • Evaluate the applicability of ODS coatings on superalloy substrates using cold spray technique with MCB-processed ODS powders • Assess ODS alloy mechanical behavior using micro-indentation	• Demonstrated via TEM that the MCB process forms a uniform ~25 µm Y_2O_3 layer along the surface of particles throughout the Ni-Cr powder matrix • A combined MCB and ball-milling ODS powder mixing procedure was developed - Results indicate similar ODS powder microstructural characteristics as compared to commercial ODS powders - Ball-milling time is significantly reduced (~15 hrs) • Using cold spray techniques and the MCB-ODS powders, Haynes 230 and René N5 coupons were successfully coated to thicknesses of 0.8 to 1.5 mm

Subtask	Objectives	Accomplishments
Aerothermal Heat Transfer		
Airfoil Heat Transfer Modeling 	• Develop 2D and 3D computer simulations identifying temperature and heat transfer distributions over generic airfoil configurations • Assess the impact of various cooling configurations on temperature, stress, strain characteristics under varying load conditions • Evaluate aerothermal effects of various working fluid compositions: Air (N_2), H_2O, H_2O/CO_2 • Identify optimal cooling configurations and guidelines to lower temperature magnitude and minimize the temperature gradient and associated stress	• Pressure and temperature distribution for hydrogen-fired and oxy-fuel airfoil exhibit similar trends to those under convection-dominated flow • External gas with higher steam content leads to higher heat transfer coefficient • Oxy-fuel is ~40% higher than hydrogen-fired • If complete TBC spallation occurs, a surface metal temperature increase of ~200–250 °C is projected • Internal cooling h_c significantly affects substrate metal temperature - 3-fold increase in internal h_c decreases metal surface temperature by ~150–200 °C for hydrogen-fired airfoil • Skin cooling reduces metal surface temperature by ~50–100 °C • Internal heat transfer coefficients are gradually reduced from leading edge towards trailing edge
Atmospheric Air Heat Transfer Unit  	• Demonstrate double wall internal cooling concepts to improve heat transfer using pin-fin vortex generators with cooling air • Investigate the effects of 90-degree jet inlet on internal cooling with staggered pin-fin arrays • Address effect of side blockages • Investigate heat transfer characteristics in tip turning region with various pin-fin arrangements • Address effect of pin-fin placement to side and tip endwalls • Acquire detailed distribution of local heat transfer coefficient, h, on both pin-fins and endwalls • Develop simulation approach to predict heat transfer within internal cooling channels	• Test unit designed and constructed • Jet impingement from 90-degree inlet demonstrated an increase in the overall average heat transfer coefficient throughout the entire cooling passage • Channels with blockages have up to 29% higher performance factor than those without blockages • Simulations predict heat transfer distribution and flow patterns, but are ~48% lower than experimental results • Pin-fins at tip turn regions alter flow field and enhance heat transfer in these regions
Atmospheric Steam/CO_2 Heat Transfer Unit  	• Develop test facility to explore novel concepts and technology for enhanced internal cooling with superheated steam and/or CO_2 with high aspect ratio enhancement features (i.e., vortex generators) • Develop flow and heat transfer correlations for air and steam cooling • Explore advanced cooling concepts. Characterize effects of partial pin-height on pin-fin array heat transfer • Explore flow field using FLUENT and compare numerical results with experimental data • Address material degradation near flow-solid interface and effects on cooling performance	• Test unit designed and constructed • Verified analysis approach and testing procedure using a smooth test plate. Results were compared against well-known Dittus-Boelter correlations • Conducted experiments with pin-fins using transient infrared thermal imaging technique for heat transfer characterization - Tests were conducted at Re_{Dh}=15,000–30,000 - Experiments were repeated with hot air • Superheated steam has significant contribution on heat transfer enhancement, 10-15% higher as compared to hot air • Completed 7 pin-fin test arrays at Re_{Dh}=10,000-25,000 - Presence of pin-to-endwall spacing promotes wall-flow interactions, generates additional separated shear layers, augments heat transfer - C/D=1 (staggered) exhibits the highest heat transfer enhancement - Pressure loss seems to increase with C/D

Subtask	Objectives	Accomplishments
Aerothermal Heat Transfer		
High Temperature, Pressurized Aerothermal Test Facility  	• Develop high temperature, pressurized aerothermal test module in conjunction with NETL Morgantown's combustion test facility • Experimentally characterize aerothermal heat transfer for advanced turbine applications using TBC-coated and uncoated nickel-based superalloy test coupons exposed to combustion gas temperatures & chemistries - $N_2/H_2O/O_2/CO_2$ - 1000 °C and 5-8 atm operating baseline - Back-side cooling • Computationally simulate and characterize heat transfer within the aerothermal test module section • Assess heat transfer; Address micro-scale cooling hole fabrication including stress reduction & high yield manufacturability; Optimize film hole/slot configurations; Identify proper coolant selection & flow distribution	• Completed design & construction of the experimental test module. Initiated shakedown phase • New 1-in cooling line with initial flow rate up to 8,000 scfh installed • Rebuilt compressor for 700 psi air compression • Test coupons machined with cylindrical holes and trench configurations
Airfoil Life Prediction Modeling 	• Develop 3D damage mechanics-based models for hydrogen-fired and oxy-fuel airfoil life prediction - Implement models within a commercial finite element analysis code - Determine evolution of stress and creep damage within a generic airfoil for hydrogen-fired and oxy-fuel turbine applications - Assess need for external film cooling - Determine evolution of fatigue damage for a variety of cyclic loading scenarios - Assess importance of creep/fatigue interaction - Predict airfoil life • Conduct isothermal, uniaxial constant-load, thermal-mechanical testing to validate damage mechanics variables pertaining to both the substrate and TBC • Develop damage mechanics models for fatigue crack initiation and growth, and assess the impact on the structural integrity of the TBC	• Creep and fatigue damage models integrated into finite element analysis (FEA) package (ANSYS) - Includes effect of stress relaxation - Centrifugal load (coating mass): 3,600 rpm with a base radius of 0.6 m - Aerothermal loading for hydrogen-fired and oxy-fuel applications from separate investigation - With and without film cooling - Internal cooling temperature of 527 °C with heat transfer coefficients from 1,000–3,000 W/m^2K - Coating: 250 µm YSZ; 10 µm TGO; 125 µm bond coat. CMSX4 substrate: 1,000 µm • Predicted extent of compact TGO growth, inward growth, and phase depletion • Current model predictions - Hydrogen-fired: After 1,000 hrs, limited creep damage projected along pressure surface of middle rib; After 4,000 hrs, extensive creep damage along pressure surface of middle rib, with damage along suction surface near trailing edge - Oxy-fuel: Extensive creep damage after 10 hrs, indicating need for external film cooling; Minimal creep damage after 800 hrs with film cooling - Creep damage dominates fatigue damage and the effects of creep/fatigue interaction are negligible

Subtask	Objectives	Accomplishments
Non-Destructive Evaluation Techniques		
Micro-Indentation Testing 	• Develop load-based, multiple loading/partial unloading micro-indentation technique for determining mechanical property degradation and debonding/spallation of TBC systems • Develop portable test unit for evaluating curved and flat TBC coupon geometries • Demonstrate feasibility of technique/equipment on as-manufactured and bench-scale tested commercial and NETL BC/TBC systems • Develop high temperature micro-indentation system capable of evaluating material mechanical properties (i.e., Young's Modulus, creep, hardness, etc.) at temperatures up to 1200 ºC. Validate determined material properties.	• Developed table-top and portable handheld micro-indentation units for determination of room temperature material mechanical properties. Developed high temperature system. - Validated accuracy of these systems in terms of reported literature data. For example, room temperature Young's Modulus of ~200–210 GPa for Haynes 230 and ~130–150 GPa for René N5. • SEM characterization of coupons after micro-indentation testing indicated no additional YSZ cracking or degradation near or around the indented region • Developed stiffness contour profiles for TBC-coated René N5 and Haynes 230 coupons - Within the initial 20 thermal cycles at 1100 °C, surface stiffness was reduced by ~2.8% for APS/MCrAlY, and ~15.1% for EBPVD/MCrAlY systems - Successfully predicted TBC spallation regions on four 1100 ºC exposed René N5/MCrAlY/APS YSZ TBC coupons • Demonstrated feasibility of the micro-indentation technique on an OEM TBC-coated first-stage blade
Non-Linear Acousto-Ultrasonic Diagnostics 	• Develop acousto-ultrasonic diagnostic techniques for early failure detection of commercial MCrAlY/EBPVD and MCrAlY/APS systems as a function of extended thermal cycling and static oxidation exposure at 1100 ºC • Explore finite element analysis (FEA) simulation of nonlinear acoustic effects to project detection of delamination and change of TBC material properties • Explore acousto-ultrasonic capability for NDE of industrial components coated with thermal barrier coatings	• Acousto-ultrasonic techniques successfully provided early warning of TBC delamination for 1100 ºC exposed coupons • Finite element analysis (FEA) simulation of ultrasonic wave propagation correlated well with experimental measurements and was used to estimate coating and substrate material properties - FEA showed nonlinear effects related to delamination between TGO and YSZ • Demonstrated feasibility of the acousto-ultrasonic technique on an OEM TBC-coated first-stage blade

Materials Development

Efforts in the *Materials Development* area are focused on (1) development of a wet spray bond coat system that can be applied to nickel-based superalloys and single crystal substrates and integrated with YSZ as either a discrete layer or as a functional gradient; (2) provision of higher thermal insulating capabilities of the external YSZ layer through development and application of low density, high purity APS YSZ layers with improved bond coatings; (3) development of overlayer coatings capable of providing thermal insulating properties up to temperatures approaching 1700º C, thus protecting the underlying YSZ; (4) diffusion barrier coating development for mitigating interdiffusion between the bond coat and underlying metal substrate; and (5) ODS powder and alloy development for potential generation of advanced high temperature substrate materials.

Aerothermal Heat Transfer

Efforts in the *Aerothermal Heat Transfer* area include development of three-dimensional computational simulations of external heat transfer and thermal loadings that are projected to be generated over a generic turbine airfoil for the hydrogen-fired and oxy-fuel turbine applications. Information from these simulations provides detailed local distributions of surface temperature and heat flux penetrating through the TBC layer. In conjunction with solid modeling, the metal substrate temperature, and local stress and strain over the entire airfoil are determined. Complementary to the aerothermal modeling effort is the development of a life prediction model for TBC-coated airfoils. This unique approach, based on damage mechanics for high temperature creep, fatigue, and crack formation and propagation, is capable of transforming a group of operating variables (i.e., temperature, stress, strain, and moisture) to quantify the durability and life of both the nickel-based superalloy or single crystal substrate matrix and the TBC.

In conjunction with the computational modeling efforts conducted at UPitt, bench-scale experimental test facilities were designed and constructed to address novel internal skin cooling concepts and reduced thermal load along flow passage tip turn regions within the airfoil. Additionally facilities were designed, constructed and are being used to explore the impact of superheated steam as an internal airfoil cooling media. UPitt's heat transfer expertise also supports NETL's high temperature, pressurized aerothermal test facility efforts in Morgantown, WV.

Non-Destructive Evaluation Techniques

Monitoring the stability or degradation of commercial TBCs or developmental material systems has been traditionally conducted via destructive analyses of numerous coupon samples. Frequently, however, destruction of coupons or full airfoils is not warranted since continued exposure or in-service use is required. Therefore development of *Non-Destructive Evaluation Techniques* is considered to be essential for assessment of extended component life. The objectives of this effort are to develop a micro-indentation methodology or technique, and prototype equipment to assess the residual stiffness of TBC coatings on flat, as well as curved surfaces (i.e., leading edge of the airfoil; tubular samples) to project material/component performance longevity and/or impending spallation of the applied protective coatings at room temperature, as well as at temperatures approaching 1200 °C. Non-linear acousto-ultrasonic diagnostics are similarly being developed to address material system and/or component life. Both techniques have recently been utilized to develop baseline materials property data for an as-manufactured, land-based, TBC-coated gas turbine blade.

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KEY:

* Advanced Materials Development

† Aerothermal Heat Transfer and Life Prediction Modeling

‡ Non-Destructive Evaluation

§ Aerothermal Test Facility