Mechanical Engineering Department

Professor Steven M. Miner
Chair

The faculty and midshipmen of the Mechanical Engineering Department have diverse interests in the fields of mechanics, materials and the thermo-fluid sciences. These interests are reflected in the types of research projects undertaken, which include sponsored faculty research, Trident Scholar projects and Midshipmen Independent Research projects. The focus of these projects runs the full spectrum from fundamental to pedagogical research.

This past year there were a total of 20 faculty members involved in 38 sponsored research projects. Sponsors included government agencies, academic institutions and industry. In addition to the sponsored faculty research there were 3 midshipmen involved in independent research projects with faculty and 3 midshipmen involved in Trident Scholar projects. Many of these projects were also funded by outside sponsors. The output for the past year included 69 publications, 3 books and 19 presentations; Midshipmen or recent graduates were involved in eight. Faculty in the department also sponsored two post-doctoral researchers.

The scholarly pursuits of the faculty allow them to remain current in their fields. This currency benefits the midshipmen both directly and indirectly. The midshipmen benefit directly because in many cases the midshipmen are involved in doing the research, which broadens and enhances their intellectual experience. Indirectly the midshipmen benefit because the results of the research find their way into the curriculum, which helps to maintain its currency.

Sponsored Research

Damage Mechanics in Ceramic Matrix Composites

Researcher: Associate Professor Oscar Barton, Jr.
Sponsor: Knolls Atomic Research Laboratory (KAPL)

Ceramic matrix composite materials (CMC's) are deemed essential for high temperature applications. Reinforcing these materials further increases the range of applications to include multi-axial loading conditions. However, the brittle nature of CMC's complicates the prediction of failure as well as a characterization of how the failure precipitated, or damage evolution. This research surveys the modeling of failure mechanism and damage mechanics for ceramic matrix composites. The motivation is to provide an assessment of the importance of modeling characteristics, material architecture, and solution methodologies on the development of the damage mechanics' methodology. Damage mechanics relate the development of damage mechanism within a material to their effect on the elastic properties, which are used to define the material's behavior. The approach can be undertaken on a micro-mechanic level in which geometric variables are incorporated to identify relationships between defects in the material, material properties and macroscopic behavior or through the introduction of internal variables suited to represent morphological changes on the mechanical response. These approaches are called continuum damage mechanics and provide the greatest interest.

Stability Analysis of Symmetric Angle-Ply Composite Laminates for Hygrothermal Effects using Eigensensitivity Methods

Researchers: Associate Professor Oscar Barton, Jr. and
Lieutenant Commander Marvin Campbell, USNR
Sponsor: Naval Academy Sabbatical Program (for OB)

Developing approximate closed-formed solutions for the mechanical responses of composite plates provide an alternative to traditional numerical approaches. In this research, eigensensitivity analysis, one that represents the eigenparameters in a Maclaurin series, is used to compute the critical buckling temperature for symmetric laminates. This method has been previously used to approximate the fundamental frequency of both symmetric and anti-symmetric angle-ply laminates. Results are presented for the S-1 boundary condition under a uniform temperature environment, and are compared with results computed using the Rayleigh-Ritz technique. Extension of this work to other boundary conditions and thermal environments is quite straightforward.

Ultrasonic Thermometer for High Temperature Materials Testing

Researcher: Associate Professor John A. Burkhardt
Sponsor: Knolls Atomic Power Laboratory (KAPL)

Ultrasonic thermometry offers the potential to measure temperature profiles in high temperature irradiation experiments. Standard thermocouples have reduced reliability in this environment. Ultrasonic thermometers offer the opportunity to measure temperature profiles within or adjacent to a test specimen with higher reliability. Feasibility demonstrations of such devices are reported in the literature but have not been taken to commercial use. Consequently, a project has been initiated to research and understand the principles of ultrasonic thermometry for the purpose of designing a thermometer to measure temperature profiles in the range of 1500F to 3000F in an inert radiation environment. To date theoretical models for the performance of ultrasonic transducers, a critical component of an ultrasonic thermometer, have been developed and validated experimentally.

Structural Testing of Missile Bodies and Surrogate

Researchers: Associate Professor John A. Burkhardt and Assistant Professor Peter J. Joyce
Sponsor: Naval Surface Warfare Center, Dahlgren Division (NSWC-DD)

Cantilever bend tests were performed on both partial missile bodies and missile surrogates. All tests were performed on a newly developed cantilever test rig specifically designed to allow free-end deflections in three orthogonal directions. This characteristic allowed for the testing of asymmetric, damaged structures without free –end constraints which would have induced spurious axial, bending or torsional loads. Strain, load and deflection data were recorded for each test. In total five tests were performed on two damaged missile sections, one undamaged missile section, one damaged missile surrogate and one undamaged missile surrogate. All test data were supplied to NSWC-DD as taken, with no analysis or post-processing provided.

NDE Signal Processing Analysis

Researchers: Assistant Professor John A. Burkhardt and
Visiting Research Professor Tony Mucciardi
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

Recent studies have shown that the location and size of subsurface flaws within thick sandwich composite panels can be located using laser vibrometry. Locating the depth of the flaw, however, was not possible. Consequently, this study has attempted to develop a methodology for determining flaw depth using previously acquired vibration data. Such a methodology has been developed that relies on recorded time domain thru transmission signals. In the presence of subsurface flaws anomalous features were observed in the recorded signals from which flaw depth can be estimated. Flaw size estimations were determined using an identical method coupled with a scanning laser vibrometer.

Experimental and Theoretical Study of Surface Tension Effects on Extended Surface Condensation

Researcher: Commander Matthew A. Carr, USNR
Sponsor: National Institutes of Standards and Technology (NIST), Materials & Equipment

The goal of this dissertation is to contribute to and build upon the existing knowledge and understanding of the effects of surface tension on the condensation of refrigerants on low-finned tubes. To this end, the project goals were to: (1) measure the heat transfer of a variety of refrigerants (R-123, R-245fa, and R-134a) on an early-model enhanced heat transfer surface (GEWA-K™); (2) measure the heat transfer of these same refrigerants on a more recently developed heat transfer surface (Turbo-CII™); (3) compare these experimental data to the heat transfer model of Rose (1994); and (4) extend the Rose model for these refrigerants and heat transfer surfaces through the selection/creation of appropriate empirical/analytical constants; and, (5) depending on the success or failure of item (4), propose a new model based on the Rose model that expands its validity to the Turbo-CII™ surface.

The significant contributions of this work are: (1) it provides experimental heat transfer data of R-245fa on two enhanced heat transfer surfaces (Note: there is very little prior data in the open literature for R-245fa on any type of heat transfer surface); (2) it provides experimental heat transfer data of several refrigerants on the Turbo-CII™ surface (Note: there is very little data in the open literature for any refrigerant on this enhanced surface); (3) it validates the Rose (1994) model for these refrigerants and heat transfer surfaces; and, (4) it develops a new heat transfer model for condensation of refrigerants on low-finned tubes.

This research constituted the PhD dissertation of the investigator.

An Investigation into the Effects of Perforations on the Heat Transfer Enhancement of Extended Surfaces

Researchers: Associate Professor Martin R. Cerza,
with Mr. Juan C. Adams and Dr. P. T. Ireland (Oxford University)
Sponsor: Oxford University

In the literature there has been a large discrepancy over the enhancement effects of hole perforations on the heat transfer enhancement of extended surfaces (thin fins). Some investigators have claimed the perforations do enhance heat transfer, and others have claimed there is no heat transfer effect on the use of perforated surfaces. The methods employed by past investigators were not well suited for resolving small length scales, hence their investigations were clouded by gross surface effects. Through the use of liquid crystal thermography and digital image processing employed in the current investigation, it has been conclusively shown that there is a heat transfer enhancement benefit through the use of perforated surfaces. Moreover, liquid crystal thermography aided by digital image processing proved to be a very good technique for resolving small heat transfer length scales. The investigation has concluded that perforations cause a surface heat transfer enhancement by partially restarting the thermal boundary layer. The partial thermal boundary layer restart allows for a heat transfer coefficient (or Nusselt number) increase or recovery over fully developed conditions in the surface region after the perforation. Since perforations also decrease the surface area of extended surfaces, the next step would be an optimization of the trade off between the enhanced heat transfer benefit and the loss of surface area. The investigation also lends itself to the fluid dynamic wall shear friction effects caused by perforations since many heat transfer-fluid mechanic analogies show that heat transfer coefficients and friction factors behave very similarly for many flow conditions.

Investigation into Thermosyphon Applications for the Cooling of Electronic Cabinets

Researcher: Associate Professor Martin R. Cerza and Assistant Professor Andrew N. Smith
Sponsors: Department of Energy (DOE) and Office of Naval Research (ONR)

Electronic cooling is quickly becoming a topic of paramount concern in the Naval Community. As computer chips and circuit boards get smaller while their power generation increases, very high heat fluxes have to be dealt with. Moreover, as power electronics becomes an important parameter in RF devices such as radar control units, IGBT devices

in propulsion switchgear, and increasing loads with regards to shipboard HVAC systems, the Navy will have to look at integrating all aspects of the thermal loads brought about by these components. One potential method of cooling electronic cabinets is the capillary pumped loop system (CPL). The CPL operates on a two-phase liquid-vapor thermodynamic system. Heat dissipated from electronics devices are conducted through the CPL evaporator walls and vaporize a working fluid. The vapor is then transported to a condenser where it condenses and releases heat to the ship's cooling water. This transport of heat is order of magnitudes more efficient than the forced air convection produced by fans, and with practically no noise produced.

The effectiveness of the resulting capillary-assisted thermosyphon (CAT) loop was then evaluated by investigating the effects of subcooling and orientation [tilt and pitch] on the thermal performance. The subcooling effects were studied for a range of heat loads by varying the chill water flowrate between .375 and 3.5 GPM, and varying the chill water temperature between 4 and 37 degrees Celsius. The heat inputs were also varied between 250 and 3200 W. Chill water temperatures were chosen that simulate the conditions of the sea that a warship would be operating in anywhere between the Artic and the Persian Gulf. Subcooling was shown to be dependent upon chill water sink temperature and not strongly dependent upon chill water flowrate. The influence of orientation on the thermal performance of the evaporator plate was also tested by pitching and tilting the plate up to forty-five degrees of inclination and observing the operating temperatures inside the plate. Results showed that the plate operated under all tilt angles, pitch angles, and pressure restrictions imposed. The most significant influence was observed during pitch angle testing due to the geometry of the plate.

Aircraft Electronics Cooling Modeling for the E6-B Aircraft

Researchers: Associate Professor Martin R. Cerza and Professor Steven M. Miner
Sponsor: Naval Air System Command

This project has just commenced and involves the development of an aircraft cabin cooling model for the E6-B (Boeing 707) aircraft. The model is to be a steady state model that predicts the various cabin temperatures when electronics cabinets are turned on. The model will encompass the air cooling source (APU) and work through the reverse Brayton cycle refrigeration machine, through the ducts and into the cabins where various electronic cabinets are generating heat.

Effects of Surface Roughness on Near-Surface Turbulence

Researchers: Associate Professor Karen A. Flack and
Assistant Professor Michael P. Schultz
Sponsor: Office of Naval Research (ONR)

The effect of surface preparation and surface coatings on the overall drag of a surface is investigated. Detailed measurements of near-surface velocity and turbulence parameters are obtained using laser Doppler anemometry in a recirculating water channel. The near-wall velocity profiles yield local skin-friction values, which can be integrated over the entire surface to determine overall drag on the plate. This drag measurement is compared to results from tow-tank test using plates with the similar surface coatings. Normalized turbulence profiles are compared to those of a smooth surface and sand-grain rough surfaces. The goal of the project is a better prediction of drag, using an empirical relationship of a roughness parameter, for any given surface roughness.

Hybrid Composite Joining and Characterization

Researcher: Assistant Professor Stephen M. Graham
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

This project is an investigation into novel concepts for joining of composite and metal structures. The objective is to develop integral joining methods that could be used in place of bolting or adhesive bonding. This research is being conducted in concert with the Marine Composites Branch of the Structures and Composites Department at the Naval Surface Warfare Center, Carderock Division. This investigation is being conducted using both analytical and experimental approaches. Novel joint designs will be developed, fabricated, instrumented and tested to evaluate the structural behavior in relation to commonly used joint configurations. Numerical analysis of the joints will be used to assist in design of the joints, and to interpret the test results. Particular attention will be paid to the initiation and evolution of damage, and how

the design of the joint influences the damage process. This project is a new-start and funds have been provided to NSWC by ONR. Some preliminary joint concepts have been fabricated and tested by NSWC. Numerical work is just beginning here at the Academy.

Investigation into the Relationship Between Fracture Behavior and Structural Integrity for Ship and Submarine Metallic Materials

Researcher: Assistant Professor Stephen M. Graham
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

Specific projects and effort covered under this project include the following:

1. CVNX-1 HSLA-100 Crack Arrestors - Provide assistance in project planning, test development, test execution, data analysis, data interpretation, reporting and presentation of results for a program to characterize the crack arrest performance of HSLA-100 steel as an alternative to HY-80 or HY-100 steels.

2. Fracture Toughness Review Process (FTRP) – Provide assistance in application and interpretation of the FTRP. Review structural or material assessments related to the FTRP. Develop material characterization plans according to Appendix C of the FTRP and provide assistance in the implementation of the plans, and the interpretation of the data. Conduct material screening or flaw assessments per the requirements of the FTRP. Conduct research on alternative criteria for evaluation of the fracture resistance of metallic materials. In particular, prepare criteria for evaluation of low tearing modulus materials with moderate toughness, and for very tough materials with high tearing modulus.

3. Metallic Materials Advanced Development and Certification Program (MMADCP) – Provide assistance on evaluation of fracture behavior of materials, including titanium alloys, nickel alloys, high-strength steels, and stainless steel alloys, and on the relationship between fracture behavior and structural performance for the various projects covered under MMADCP.

Elastic-Plastic Fracture Mechanics Technology for Light Water Reactor (LWR) Alloys

Researcher: Professor James A. Joyce
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

This research involved investigations of the fracture behavior of metallic alloys used in light water commercial nuclear reactor (LWR) systems. The primary 2003 goals of the proposed research were to develop and implement the fracture mechanics technology necessary for predicting the behavior of flawed LWR components within the ductile-to-brittle transition regime. Over the previous four years, a constraint-based cleavage fracture model (CCFM) has been developed and evaluated by the Naval Surface Warfare Center-U.S. Naval Academy group. Crack initiation was modeled in the CCFM using a probabilistic toughness-scaling model based on Weibull statistics. This model is similar to previous mechanics-based toughness scaling models. However, instead of requiring an "equivalently stressed volume" between the structure and specimen crack-tip at fracture, the Weibull stress, σ_w, serves as the critical transferability parameter between structures and specimens. The object of this effort was to continue this development and to calibrate and verify its applicability to life extension of LWR systems. Standard fracture toughness measurements, shallow crack fracture toughnesses, and bi-axial specimen fracture toughnesses were measured and compared within the context of the CCFM model. Results have shown that present assumptions that are the basis of ASTM fracture standards are inaccurate and that specimen geometry differences must be incorporated in ASTM standard E1921as soon as possible. The basic CCFM methodology, however, greatly improve the consistency of toughness measurements obtained from geometrics of widely varying crack tip constraint and should be incorporated in newly developed USNRC codes and regulations.

Continued ASTM and ASME standards support and development will also be provided as in past efforts. Near term objectives within this task are to rectify inconsistencies between ASTM standards E1820 and E1921. Revised standards documents are being developed and balloted to rectify these inconsistencies.

Mechanical Characterization of Al/PTFE Reactive Materials

Researchers: Assistant Professor Peter J. Joyce,
Professor James A. Joyce and Ensign H. Feigel, USNR
Sponsor: Office of Naval Research (ONR)

The objective of this research project is to conduct investigations of the mechanical response of Aluminum/Teflon (Al/PTFE) composites for use in enhanced warheads by the U.S. Navy. This work has demonstrated the successful application of fracture toughness testing methodologies, mature to the metals community, to both PTFE and Al/PTFE composites. Standard ASTM E1820 fracture toughness specimens (single-edge bend (Charpy scale SE(B)) and compact tension (1/2 T C(T)) of PTFE and Al/PTFE both pressed and sintered under like conditions were tested. In all cases the fracture toughness was quantified using the *J*-integral. Baseline fracture properties for both the PTFE and Al/PTFE composite (with 25% by volume 5 µm Aluminum spheres added) were obtained from room temperature quasi-static testing. These preliminary tests were used to investigate any spatial variation in the fracture toughness as well as any orientation dependence. The tests show good agreement between the fracture toughness results obtained from the SE(B) and C(T) specimens in which the cracks were oriented in an identical fashion. Since the SE(B) geometry cannot be used in all three desired crack orientations but is more conservative of material, for now both geometries will continue to be tested to allow comparison of all three crack orientations of interest. No difference in mechanical behavior was observed between tests run in three different orientations in the PTFE material but the Al/PTFE composite exhibited an interesting load shedding/fracture behavior unique to the thru-thickness splitting orientation.

Additional testing was performed for all three orientations over a range of test temperatures (–73 to +33ºC) and loading rates from 2.5×10^{-7} to 4.0 m/s to understand the visco-elastic/visco-plastic nature of the mechanical behavior. These results demonstrated a dramatic stiffening and decreased ductility with decreasing test temperature similar to that seen in tensile testing of the same material. The decreased ductility goes hand in hand with fracture initiation, which is assumed to account for the drop in load in the fracture toughness specimen load versus crack mouth opening displacement records. Decreasing the temperature by only 40ºC transitions the material toughness from crack tip blunting to extensive ductile crack growth. For temperatures slightly above ambient (33ºC), a creeping or viscous crack extension has been observed resulting in extensive crack growth. Fracture can clearly be a serious problem when this material is used at temperatures slightly above or below ambient no matter what loading rate is applied.

Similarly, both the PTFE and the Al/PTFE composite exhibited a subtle loss of ductility with modestly increasing loading rate, and a dramatic decrease in fracture toughness with larger increases in the applied loading rate. Brittle "pop-ins" were observed first, and then rapid crack growth which exhibits a very different morphology under scanning electron microscope observation. At the slowest loading rate both materials exhibited nothing but crack blunting, increasing the loading rate by an order of magnitude results in strong pop-ins (dynamic crack growth accompanied by a drop in load and resumed stable crack growth.) Increasing the loading rate to 25 mm/s and above results in smaller pop-ins (verified by observations in the scanning electron microscope), until at the highest loading rate shown (325 mm/s) the specimen has been pushed to a rate beyond pop-in behavior.

The major conclusions to date are that the normalization method is a valuable tool for obtaining fracture toughness measurements for structural polymers, even those that demonstrate considerable visco-elastic response. The normalization method allowed measurement of J_{Ic} and *J-R* curves over a wide range of test temperatures and loading rates using single specimen procedures. Both the neat PTFE material and filled PTFE material tested here transition from crack tip blunting behavior to low toughness *J* resistance curve behavior as the test rate is increased and/or the test temperature is decreased. The rate effects are significant at servo-hydraulic test rates and are thus important in many structural applications. Similarly, even small temperature changes, on the order of 20ºC, dramatically alter the fracture toughness properties of PTFE. Evaluation of the crack velocity shows it to be a nearly linear function of the applied *J*-integral rate for this polymer over more than seven orders of magnitude of loading rate applied in this work.

Evaluation of the Multi-component Resin Transfer Molding Process for Naval Aircraft Components

Researchers: Assistant Professor Peter J. Joyce and Mr. Neil Graf (NAWCAD/PAX)
Sponsor: Naval Air Systems Command (NAWCAD/PAX)

The objective of this research project is to evaluate the state of the art in resin transfer molding (RTM) process technology and examine the influence of controllable process parameters on the thermal and mechanical behavior of composites manufactured from multi-component resin systems. This information will help determine the requirements of a multi-component resin transfer molding process and its suitability for production implementation specifically for aircraft primary structural components.

One objective of this research included the design, demonstration, and evaluation of an automated, supervisory, computer controlled RTM process. A second objective involved the selection and characterization of candidate materials for multi-component RTM of primary structural composites, with a focus on two-part resin systems with textile reinforcement. The goal of this program of work was to evaluate the feasibility and process error tolerance of this intelligent RTM process applied to two candidate resin systems. A study was performed to examine the effects of major process parameters including: variations in the resin component mix ratio, injection temperature, cure cycle modifications, and "aeration." This involved flat panel fabrication and a wide array of testing including physical evaluation, thermal analysis, and mechanical testing.

Significant progress has been made toward each of these objectives. Tests to date have concluded that while the resin injection equipment designed by Northwestern University as part of the Center for Intelligent Processing of Composites (CIPC) program sponsored by ONR has great merit in terms of the concepts being attempted and the potential for improved manufacturing reliability, as yet the system does not perform satisfactorily. Improvements need to made in terms of system reliability and robustness as well as functionality, particularly with regard to extreme resin mix ratios. For the materials evaluation component of this research two different resin systems were selected, but only one resin system has been evaluated. The cure kinetics of the resin were first characterized using thermal analysis to determine the processability of the resin as well as the basic thermo-mechanical properties of the resin. The resin system studied showed excellent processability over a wide range (even unrealistic) of process variations studied, the development of three-parameter cure model (time, temperature, and mix-ratio) is still ongoing. Finally the effectiveness of the automated, supervisory, computer controlled RTM process with the selected material system was evaluated by fabricating aerospace quality panels over a wide range of process variations. Thermal analysis, ultrasonic non-destructive evaluation (NDE), and mechanical testing were used to determine composite panel quality. The results of this work have demonstrated the potential of the automated RTM process while allowing us to work out many of the problems, furthermore the results of our mechanical tests on the composite panels show that the material system chosen is in fact very robust and relatively insensitive to moderate variations in the processing parameters.

Response of Tapered Composite Structures to Torsional Loading

Researchers: Assistant Professor Peter J. Joyce, Paul Valsgaard (Aalborg University), and Dr. Anthony Vizzini (University of Maryland)
Sponsor: Office of Naval Research (ONR)

The objective of this research was to characterize the behavior of tapered composite structures under torsional loading. Tapered composite beams have been investigated extensively during the last two decades because of their wide application in rotorcraft but also in the burgeoning field of wind energy. Tapered composite beams can be tailored to have varying strength along the length of the beam by using to terminating plies, thereby optimizing strength and removing excess weight. This introduces a complicated problem of intralaminar stresses throughout the structure. While the problem of stress distribution in tapered composite beams under tension loading is well understood in terms of the induced transverse stress and strains, the torsional problem is not. This research aims to use experiments together with numerical analysis to understand the torsional problem. Then using the principle of superposition the two cases of tension and torsion can be summed to describe any combination of tension and torsion.

A series of tension/torsion experiments was performed on model tapered composite beams 254 mm long, 38 mm wide and 4.6 mm thick in the thick end and 2.6 mm thick in the thin end. All of the beam specimens were manufactured from Hexcel IM7/8552 prepreg (an intermediate modulus carbon fiber/toughened epoxy system). All of the specimens

consisted of 28 layers in the thick end and 16 layers in the thin end with plies dropped off in two pairs of two to maintain symmetry along the length. Three different layups were tested. Both ends of the specimen were clamped in a set of grips. The load was applied as a moment and a tensional load. In some tests the tensional load was negligible, in others the tension was up to 80% of the failure load in pure tension. In all cases the load, torsion and shear strain were recorded.

Corrosion Effects on Structural Integrity

Researcher: Assistant Professor Michelle G. Koul
Sponsor: Air Force Aging Aircraft Program Office (ASC/AAA)

This effort will help to provide tools to depot persons responsible for selecting environmentally benign corrosion maintenance procedures for aircraft. The evolving maintenance philosophy of "predict and manage" requires additional corrosion maintenance protocols for the depot maintainers. This philosophy is aimed at replacing the "find-and-fix" approach that requires the removal of all corrosion when detected during planned depot maintenance. The Air Force Research Laboratory (AFRL) and/or their contractors provided corroded specimens for evaluation at the Naval Academy. Prior to providing the specimens to USNA, the corrosion damage was evaluated using the NDE technology being developed as a separate part of this program. The primary objectives of the work to be performed at the Naval Academy were: (1) Characterize the types of corrosion damage observed in as a function of alloy, exposure environment and corrosion protection technology, (2) analyze the corrosion damage within the context of the provided sample history, previous corrosion damage evaluations and repairs, and the NDE results and (3) evaluate the incorporation of this data into structural integrity and lifetime predication models. Experimental data and analysis tools have been developed. Results are documented in a July 2003 *Corrosion* journal article.

A Comparison of Stress Corrosion Crack Growth Rates for AA7XXX Alloys as a Function of Aqueous Chloride Content

Researchers: Assistant Research Professor Brian J. Connolly (ONR Post-Doctoral Fellow),
Assistant Professor Michelle G. Koul, and Associate Professor Angela L. Moran
Sponsor: Office of Naval Research (ONR)

Various candidate alloys are being considered for drop-in replacement of corrosion-prone AA7075-T6 parts on aging military aircraft. The Service Life Assessment Program sponsored by NAVAIR is evaluating properties such as strength, toughness and high cycle fatigue life for comparison to specifications for AA7075-T6. The driving force for replacement, however, is the desire for improved corrosion resistance. Therefore, the resistance of the candidate alloys to corrosion damage such as intergranular corrosion, exfoliation and stress corrosion cracking (SCC) is also being evaluated. In order to contribute to this body of knowledge, this project is evaluating three aluminum alloys that meet mechanical property requirements and are thought to be superior to AA7075-T6 in terms of corrosion performance: AA7150-T7751, AA7249-T76511 and AA7040-T7651. Unlike the corrosion tests that are ongoing in the Service Life Assessment Program, this project will focus on SCC propagation rather than corrosion initiation. In order to minimize metallurgical differences due to processing, the alloys were obtained in similar product forms, with plate/extrusion thicknesses of 2.0-2.5-in. The SCC crack propagation rates are assessed as a function of applied stress intensity using displacement controlled double cantilever beam (DCB) specimens. The effects of bulk environment on crack propagation rates are assessed by conducting these tests in various aqueous solutions. DCB testing has been ongoing since April and the initial data was presented as part of an EM496 independent research project. A paper has been submitted and presented at NACE 2003 in the "Environmentally Assisted Cracking" symposium.

Diver Heater Using Hydrogen Fuel

Researchers: Professor Keith W. Lindler and
Professor Marshall L. Nuckols (Naval Architecture and Ocean Engineering Department)
Sponsor: Naval Surface Warfare Center, Coastal Systems Station

The properties and history of hydrogen fuel were reviewed in order to determine its suitability as a fuel source to provide the heating requirements of 6 divers in 0°C water for a period of 6 hours. It was determined that less than one pound of hydrogen combined with oxygen in a catalyst bed could meet the heating needs of the divers. Storing the hydrogen as

a metal hydride appears to be the safest method and would lead to the smallest storage volume. It was determined that the electric requirements of the pump used to circulate the heating water through the diver's suit could be provided by several thermoelectric generators which would use the heat released from the hydrogen as an energy source. The waste heat rejected from the thermoelectric generator would provide a large portion of the heating requirements for the divers.

The current research focuses on the testing of various metal hydrides to determine the best candidates to store the hydrogen for this application. Important parameters include the ability to recharge the storage at temperatures above $0^{o}C$, the ability to hold a large amount of hydrogen in a small volume ant the ability to release the hydrogen at 150 psia at temperatures below $100^{o}C$.

Fracture Mechanical Analysis of a Biaxially Loaded Cruciform Specimen

Researchers: Associate Professor Richard E. Link and Professor James A. Joyce
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

Traditional fracture toughness characterization of alloys uses standard fatigue cracked specimen geometries subjected to uniaxial loading normal to the crack plane. Some structures such as a pressure vessel subjected to thermal shock, may experience biaxial loading with significant stresses acting parallel to the crack plane. Recent experimental investigations using large cruciform specimens have demonstrated that biaxial loading may have an effect on the fracture toughness in the ductile-brittle region, resulting in an increase in the reference temperature, T_0. The large cruciform specimens are expensive and difficult to test, resulting in a sparse data base to support this observed effect. A smaller scale specimen has been developed that is more economical to fabricate and test. This investigation calculated the fracture driving force relationships for the new specimen. Elastic-plastic, three-dimensional finite element analysis was used to model the specimen and applied loading in order to determine the crack driving force as a function of applied loading. The results of the analysis will be presented together with experimental results at the Second International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics.

Determination of the Mass Properties for an STX SYNC Classic Putter

Researcher: Professor Steven M. Miner
Sponsor: STX Corporation

This study used the IDEAS™ software to construct a solid model of the STX SYNC Classic putter. The purpose was to determine the mass and the location of the center of mass for each component making up the putter, the mass and the location of the center of mass for the putter as a whole and the twist axis of the putter. In addition to modeling the standard putter, models were also completed for the putter with mass added to the top and bottom of the head. Location of the center of mass of the putter head assembly in relation to the impact location for the ball was also determined. Finally, a comparison between the ball impact location and the twist axis location of the putter was determined.

Multi-Functional Coatings for Military Applications

Researchers: Associate Professor Angela L. Moran and
Assistant Research Professor Brian J. Connolly (ONR Post-Doctoral Fellow)
Sponsor: Air Force MURI Program, Air Force Office of Sponsored Research (AFOSR)

This effort in support of MURI project headed by researchers at the University of Virginia seeks to identify the next generation military coating system that will provide a significant evolutionary advancement in performance from the standpoint of mission safety, corrosion protection, and environmental compatibility. The opportunity exists to create a metallic cladding that is easily field applied and has a range of functions to improve corrosion performance, coating adhesion, and provide active corrosion protection (i.e. self-healing). This can be accomplished through implementation of thermal spray technology and the use of nano-crystalline or amorphous matrix metallic glasses such as the Al-transition metal (TM)- rare earth (RE) glasses. A central characteristic of amorphous/ nano-crystalline materials is the ability to supersaturate desired alloying elements to produce a material with superior corrosion performance, as well as high strength, ductility, and wear resistance. Al-based metals have been thermally sprayed in air from wire, ribbon, or powder stock using several thermal spray techniques such as hand-held arc spraying and plasma spraying. Small panels have been produced

for materials characterization and corrosion testing. Control claddings have been compared to newer compositions aimed at multi-functionality. Fatigue life at several stress values have been determined for coated versus uncoated AA2024-T3 in a saltwater environment. Electrochemical inhibition of pitting and other forms of local corrosion, known to reduce fatigue lifetimes, will be distinguished from reductions in purely mechanically-driven fatigue processes by conducting tests in air, in benign solutions and in corrosive solutions. Mechanistic information on factors improving the fatigue resistance of high strength Al alloys will be obtained.

In FY-03, nearly pure aluminum coatings were deposited in air from powder stock to evaluate the corrosion/fatigue performance as a function of thermal spray coating process (i.e., powder flame spray, atmospheric plasma spray, and HVOF spray) and cold spray process such as Kinetic Metallization (KM). It has been the specific goal of the first stage of this program to select the process that optimizes the coating's physical, mechanical, and corrosion properties. Moreover, the testing performed on the near pure aluminum coatings has provided a suitable control for evaluating the inhibitive capability / performance of the exotic / glassy Al-TM-RE alloyed coating system presently under development at the University of Virginia. Evaluation of the physical/mechanical/corrosion properties of this coating system will constitute the bulk of the research activity during the next stage of this program. Additional objectives have been defined as a result of alloy development and process definition completed in the first stage. Specifically, questions concerning the viability of using a thermal spray technique to produce an amorphous or nano-crystalline coating need to be addressed as well as queries concerning the commercial availability of suitable feedstock in the chosen alloy composition for such a process.

Evaluation of the Environmentally Assisted Cracking Performance of Candidate Aluminum Alloys for Replacement of AA7075-T6 Aircraft Structures

Researchers: Associate Professor Angela L. Moran, Assistant Professor Michelle G. Koul and
Assistant Research Professor Brian J. Connolly (ONR Post-Doctoral Fellow)
Sponsor: Office of Naval Research (ONR)

The objective of this effort is to evaluate the environmentally assisted cracking (EAC) performance of two high strength candidate alloys (AA7249-T76511 and AA7150-T77511) that are being considered for replacement of corrosion-prone AA7075-T6 aircraft extrusions. Previous work has optimized the retrogression and re-aging (RRA) process for AA7249 extrusion with regard to strength and the RRA temper can be evaluated as part of this program. In addition, the crack propagation rate of these materials can be evaluated as a function of the aqueous chloride concentration in order to fully characterize the EAC performance.

The focus of this program is the evaluation of EAC propagation rates (da/dt) as a function of applied stress intensity (K_{app}) for pre-cracked specimens. The EAC resistance is evaluated in the short transverse direction with regard to the primary working direction, which commonly represents the lower bound of EAC resistance, as well as the type of orientation obtained in structurally significant locations such as rivet holes.

Two test methods are available to USNA for to assessing crack propagation rates. Fatigue pre-cracked double cantilever beam (DCB) specimens are bolt loaded at an initial value of applied stress intensity (K_{app}) and exposed to a NaCl solution, allowing the EAC crack to grow under a constant crack opening displacement and a decreasing K_{app}. The EAC crack propagation resistance is compared by plotting crack propagation rate (da/dt) versus $K_{app.}$ A value for the EAC threshold (K_{EAC}) is obtained from the K_{app} at which crack growth is arrested. The second technique is the rising step load (RSL) test. This test technique measures crack initiation (K_{EAC}) and propagation (da/dt) of immersed fatigue pre-cracked specimens under an increasing, stepwise K_{app}.

The effect of crack tip chemistry on EAC propagation rates will be evaluated indirectly by varying the bulk chloride concentration from approximately $3x10^{-4}$ to 3.5 wt.% in a buffered solution. The fracture modes will be evaluated using scanning electron microscopy (SEM) and metallographic sectioning. Quantitative electrochemical evaluation of selected alloys can also be conducted.

In FY-03, crack length versus time and environmentally assisted crack growth rate versus applied stress intensity (VK curves) for replicate double cantilever beam specimens of AA7040-T7651, AA7150-T7751 and AA7249-T76511 exposed to a drop-wise 0.6 M NaCl environment were conducted The AA7075-T6 alloy displayed the fastest average crack

growth rate (1.05 x 10^{-3} inches/hour (7.41 x 10^{-9} m/s)) in this environment while the AA7075-T73 displayed the slowest average crack growth rate (1.53 x 10^{-5} inches/hour (1.08 x 10^{-10} m/s)). The average crack growth rates of the AA7040-T7651, AA7150-T7751 and AA7249-T76511 alloys were observed at an intermediate level between the two AA7075 tempers, with rate of 1.7 x 10^{-4} inches/hour (1.20 x 10^{-9} m/s), 1.47 x 10^{-4} inches/hour (1.04 x 10^{-9} m/s), and 4.7 x 10^{-4} inches/hour (3.32 x 10^{-9} m/s) respectively. Crack length versus time and environmentally assisted crack growth rate versus applied stress intensity for replicate double cantilever beam specimens of AA7040-T7651 and AA7150-T7751 exposed to a chromate inhibited 0.6 M NaCl bulk environment (0.6 M NaCl + 0.02 M $Na_2Cr_2O_7$ + 0.07 M $NaC_2H_3O_2$ + HCH_3O_2 to pH=4) were also conducted. The SCC crack growth rates of the three alloys ranked in this chromate inhibited environment, from fastest to slowest, AA7075-T6, AA7040-T7651, and AA7150-T7751 with average crack growth rates of 4.0 x 10^{-4} inches/hour (2.82 x 10^{-9} m/s), 1.9 x 10^{-4} inches/hour (1.34 x 10^{-9} m/s), and 1.07 x 10^{-4} inches/hour (7.55 x 10^{-10} m/s), respectively. Additionally, EAC crack length versus time and EAC crack growth rate as a function of bulk solution chloride content was evaluated. The results indicate two plateaus of crack growth rates. Specimens exposed to bulk solutions containing 0.05 M NaCl and 0.1 M NaCl displayed low crack growth rates of approximately 1.0 x 10^{-4} inches/hour (7.06 x 10^{-10} m/s) for AA7040-T7651 and 6 x 10^{-5} inches/hour (4.23 x 10^{-10} m/s) for AA7150-T7751. The higher chloride concentrations (i.e., bulk solutions containing 0.6 M NaCl and 1.0 M NaCl) produce faster crack growth rates compared to the lower chloride concentrations by approximately a factor of two. No difference in crack growth rates was observed in the 0.05 M NaCl bulk solution compared to the 0.1 M NaCl bulk solution whereas a distinct increase in EAC crack growth rate was observed when comparing the results from the 0.05 M NaCl exposure with those obtained from the 1.0 M NaCl exposure. It should be noted that no significant difference can be inferred between the crack growth rates produced in the 0.6 M NaCl bulk solution compared to those produced in the 1.0 M NaCl bulk solution.

Evaluation of the Performance of Candidate Aluminum Alloys For Aging Aircraft Refurbishment and Replacement

Researchers: Associate Professor Angela L. Moran and
Assistant Professor Michelle G. Koul
Sponsor: Air Force Research Laboratory (AFRL)

AA7075-T6511 is used for the main structural components on a number of Naval and Air Force aircraft. T6511, or T6, describes the type of temper, which specifically is an artificial aging heat treatment. Although this temper results in high strength, it does not provide good resistance to environmentally assisted cracking (EAC). One heat treatment that can be applied to this alloy to enhance its EAC characteristics without sacrificing strength is called retrogression and re-aging (RRA). RRA consists of a short-time treatment of a T6 temper at an intermediate temperature followed by re-aging with a T6 aging treatment. The resultant aluminum has similar strength characteristics to a T6 temper, but it has improved resistance to EAC. Additionally, the Navy is currently considering the aluminum alloy AA7249 as a replacement for AA7075-T6511 extrusions. Initial testing has shown that the mechanical properties of AA7249-T76511 have met or exceeded the properties of AA7075-T6511 but the corrosion resistance characteristics of the final product form have not been documented.

The objective of this effort is to evaluate the environmentally assisted cracking (EAC) performance of AA7249-T76511 as compared to AA7075-T6 utilized in aircraft extrusions. Previous work has optimized the retrogression and re-aging (RRA) process for AA7249 extrusion with regard to strength and the mechanical properties of the optimal RRA tempers will be further evaluated as part of this program.

In FY-03, mechanical and metallurgical testing determined that AA7249 meets or exceeds all the properties of AA7075. Additionally, AA7249 performs better than AA7075 in environmental testing as seen in DCB tests where AA7249 exhibited a slower crack growth rate. Although AA7249 outperforms AA7075, it is not invulnerable to environmental attack. As seen in the double cantilever beam and slow strain rate testing, AA7249 is susceptible to both stress corrosion cracking initiation and propagation. These characteristics are dependent upon environment as determined by the DCB specimen in several different environments. The susceptibility of the alloy is also dependent on the microstructure. In general, when the specimens are more equiaxed, they are prone to more severe stress corrosion cracking. In addition, the wide panel extrusion is more susceptible to a faster crack growth rate once initiation has occurred. The effect of processing was particularly important in analyzing the wide panel data. The direction and orientation of the grain structure had an effect on the environmental response of the material. Those specimens with exposed microstructures exhibiting more equiaxed grains were more susceptible to intergranular crack propagation as compared to specimens whose grains were elongated parallel to the applied force.

Ceramic Matrix Composites and High Temperature Materials

Researcher: Associate Professor Angela L. Moran
Sponsor: Department of Energy (DoE), Knolls Atomic Power Lab (KAPL)

Materials for high temperature applications are required for the Department of Energy (DoE) as well as for the Navy. This project involves analyzing the validity of computer codes developed to predict the properties of ceramic composites. SiC/SiC composites are being experimentally tested to determine mechanical properties, density and uniformity. The test data is utilized to evaluate and compare the results of analytical codes developed by Rensselaer Polytechnic Institute (RPI), Virginia Tech, the National Aeronautics and Space Administration (NASA) and the Massachusetts Institute of Technology (MIT) to predict elastic stress states for different composite architectures. Materials have been acquired from commercial sources and have been fabricated in-house.

High Temperature Copper Alloys for the Automotive Industry

Researcher: Associate Professor Angela L. Moran
Sponsor: Ford Research Laboratory

Spot welding electrodes deteriorate very rapidly when used for welding of aluminum automotive components. This is due to the formation of a low melting point eutectic phase at the interface of the copper electrode and the aluminum, dissolving away the surface of the electrode. This project involves developing novel electrode compositions which suppress the formation of low melting point phases, thereby increasing electrode life. Advanced manufacturing methods such as laser cladding, ion implantation and spray deposition are being utilized.

Failures Analysis And Performance Evaluation Of Sprinkler Heads

Researcher: Associate Professor Angela L. Moran
Sponsor: Consumer Products Safety Commission (CPSC)

As a result of a CPSC ongoing investigation into the performance of sprinkler heads, the Naval Academy has been tasked with testing of sprinklers produced by a number of different manufacturers. Standardized test methods have been developed. Visual inspection and pressure testing have been conducted on samples provided to date. Metallurgical examination of samples has also been conducted as required to understand the mechanisms involved in the failure of certain heads.

Neutron Induced Charge Deposition: An Integral Part of Navy SLBM System Radiation Hardened Microelectronics Design

Researchers: Professor Martin E. Nelson and Lieutenant Commander Gene Canfield, USN
Sponsor: Strategic Systems Program Office (SSPO)

This research examines the need for the determination of neutron induced charge deposition in the design of radiation induced microelectronics utilized in Navy Submarine Launched Ballistic Missile (SLBM) systems. The research to date has examined trends in the commercial and radiation hardened microelectronic industries. Experimental data has been collected with both fission neutrons and 14 Mev neutrons on Charge Collection Devices (CCDs)to fast neutrons. The 14 MeV data was collected in September, 2002 using the Naval Academy's neutron generator and a data acquisition system developed by Draper labs. The fission data was collected in December 2001 at WSMR. It has been analyzed, and charge distributions have been developed as a function of neutron source, operational conditions, neutron fluence, and shielding materials. A meeting was held at the Naval Academy in November 2002 to discuss the next phase of data analysis.

Evaluation of Soft Error Rates in Silicon on Insulator (SOI) Based Microelectronic Devices Design

Researchers: Professor Martin E. Nelson
and Visiting Professor James F. Ziegler (Electrical Engineering Department)
Sponsor: Naval Research Laboratory (NRL)

The project had five specific tests (objectives), all of which involved the determination of the SEU rate of different microchips. The first test was to determine the radiation sensitivity of a 4Mb Honeywell SOI SRAM devices. Then the second experiment was to irradiate 256 Kb Honeywell SOI SRAM devices. The third radiation was to evaluate a commercial IBM 256 Kb SRAM device. The fourth test involved irradiating 1 Mb SOI Honeywell DRAM. Finally, the fifth test was to evaluate the redesigned 4 Mb Honeywell chip, which had been tested in the first.

In all experiments, the Naval Academy's 14 MeV neutron generator located in Rickover Hall was used. This source was calibrated as a function of beam current, accelerator voltage, and the distance each device was positioned from the generator's target head. In this way the neutron field bombarding each chip was well-known. Chip testers were used to readout changes in each chip's memory patterns during the radiation. By counting the number of "bit-flips" and knowing the neutron fluence, the SEU for each chip was established. In, the first test, the 4 Mb Honeywell SRAM was found to be radiation sensitive. This result was unexpected as the device tested was designed to be radiation hardened. These tests results are contained in an internal report listed below as publication A. As a result, the fifth test was added to the project. The second test was completed in July and as expected these chips had zero SEU sensitivity. The third test was in September 2002. The fourth test was delayed until a special chip socket board from Honeywell could be delivered to the Naval Academy. The fifth and final test was not scheduled, awaiting the chip redesign from Honeywell. This work complements a recent article accept for publication on the use of SEUs as a neutron detector.

Defect and Health Monitoring of a U.S. Navy Propulsion System Component

Researcher: Associate Professor Colin P. Ratcliffe
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

Propulsion systems have a rubber boot between the turbine and condenser. Each boot is inspected quarterly from the exterior and annually from the interior. For safety reasons the boot is replaced every seven years, irrespective or not of whether defects are located. The U.S. Navy is investigating different ways of testing these boots in order to have them replaced for cause, rather than time. This project investigated the feasibility of using the SIDER vibration procedure on the boot. SIDER assumed a planar, uniform mesh. The boots have 2-dimensional curvature. The investigation incorporated the curvature into the basic method, and verified the findings experimentally.

Damage Detection in Bridges

Researcher: Associate Professor Colin P. Ratcliffe
Sponsor: Naval Surface Warfare Center, Carderock Division (NSWC-CD)

There are hundreds of existing small road bridges that are close to the end of their life expectancy. The University of Delaware has designed a 100% composite bridge that was installed near Newark, Delaware. As part of this program, USNA has conducted an extensive experimental vibration analysis of the deck. The results of the modal analysis were used a) to verify finite element models; and b) to look for damage and other structural irregularities in the bridge. This year, the bridge was resurveyed and the vibration data obtained were used to extend the damage detection methods previously invented.

Thermal Management of GaN Power Electronic Devices

Researcher: Assistant Professor Andrew N. Smith
Sponsor: Office of Naval Research (ONR)

Solid-state transistors continue to have a wide array of applications that include power supplies, communications, electronic warfare, and multifunctional RF systems. The two most viable wide-bandgap semiconductor materials currently under investigation are Silicon Carbide (SiC) and Gallium Nitride (GaN). The thermal conductivity of the GaN samples

is being investigated using the 3ω technique in collaboration with the Electronic Materials Branch at NRL. The GaN samples are 3–5 μm thick deposited using metalorganic vapor phase epitaxy on 4H SiC, 6H SiC, and sapphire substrates. The 3ω technique requires the deposition of a metallic thin film microbridge. This microfabrication work was performed by NRL. The microbridge is used as both a modulated heat source and temperature sensor. Experimental apparatus has been assembled, and will be used to measure the conductivity of GaN as a function of temperature from 300 K to 500 K. The influence of the temperature dependent thermal conductivity on the operating temperature of actual devices will be modeled using CFDRC ACE+ software.

Thermal Analysis of a Naval Electromagnetic Railgun

Researcher: Assistant Professor Andrew N. Smith
Sponsor: Naval Surface Warfare Center, Dahlgren Division (NSWC-DD)

Electro-Magnetic (EM) Railguns are fired by sending electrical current down one conducting rail, through the projectile and then back down the opposite rail. The electrical pulse contains several million amps of current and lasts on the order of a few milliseconds. Due to the very short duration of the pulse, the electromagnetic field does not have sufficient time to diffuse into the conducting rail resulting in an uneven current distribution. The transient coupled thermal and electromagnetic equations were solved based on a quasi-1D approach. The quasi-1D approach was based on an initial surface current profile that was determined using a improved method. The results show a 400 C rise in temperature at the rail surface, and that an active cooling system is critical in order to operating an EM Railgun with a sustained rate of fire. The transient cooling was simulated for 6 and 12 shots per minute.

Intelligent Computer-Based Thermodynamics Instruction

Researchers: Associate Professor Kenneth L. Tuttle and Professor Chih Wu
Sponsor: Office of Naval Research (ONR)

Researchers received support to evaluate Intelligent Computer Assisted Instruction in thermodynamics including the textbook they wrote expressly for the course. The objectives were to teach thermodynamics using intelligent, computer-based instruction for thermodynamic-cycle analysis and other homework problems. Thermodynamic heat engine and heat pump cycles are the main thrust of most thermodynamics courses. The CyclePad software package meets this objective. This software is sophisticated, interactive and has some artificial intelligence capability. The students construct models of complex power plants and other heat engines and energy systems and then analyze those systems for capacity and efficiency. Students conduct experiments using the models they construct. The parametric analyses and graphical displays of results may be the strongest features.

Wu and Tuttle wrote a Proposal for Evaluative Study of Computer-Based Thermodynamics Instruction to ONR's Cognitive and Neural Science & Technology Division. They proposed an evaluative study of computer-based thermodynamics instruction for courses taught at the United States Naval Academy in furtherance of work already supported by the Office of Naval Research for several years. Several courses used computer-based approach on trial bases. Plans for an evaluation of the effectiveness of the computer-based approach are being developed at the Naval Academy. Evaluation makes it possible to achieve further progress in introducing intelligent computer assisted instruction in thermodynamics.

Boundary Layer Separation and Transition Control Under Low-Pressure Turbine

Researchers: Associate Professor Ralph J. Volino and
Assistant Research Professor Douglas Bohl (Post-Doctoral Fellow)
Sponsors: NASA Glenn Research Center and Office of Naval Research (ONR)

Boundary layer separation, reattachment, and laminar-turbulent transition are under experimental investigation. These phenomena are important in the flow over modern low-pressure turbine airfoils. The flow on the suction side of the airfoil is subject to an adverse pressure gradient, which tends to cause boundary layer separation. The adverse pressure gradient also tends to promote transition to turbulent flow. Transition often leads to reattachment of the boundary layer.

Boundary layer separation causes a degradation of performance, particularly if the boundary layer does not reattach. The interaction between separation and transition is complex, and the inability to accurately predict the flow is a limitation to designers. A detailed experimental database is needed to provide a better understanding of the flow, and a basis for new computational efforts and modeling. Experiments were initiated in 1998 at the NASA Glenn Research Center and continue at the Naval Academy in a single passage turbine cascade installed in a low speed wind tunnel. A series of experiments were completed using boundary layer trips of various heights to control the transition, separation and reattachment. These included measurements at five different Reynolds numbers and two different free-stream turbulence levels. Oscillating jets were used to control the flow in another set of experiments at a single operating condition. The jets proved very effective. Two papers have been written and accepted for conference presentation and journal publication. The work is ongoing.

Separated Flow Transition in a Low-Pressure Turbine Cascade: Mean Flow and Turbulence Spectra

Researcher: Associate Professor Ralph J. Volino
Sponsor: Air Force Research Laboratory (AFRL)

Data acquired in a low-pressure turbine cascade were analyzed. The facility was set up several years ago by the present investigator and researchers at Wright Laboratory. An Air Force researcher subsequently performed experiments under various conditions representative of the flow through a low-pressure turbine. Boundary layer data acquired with hot-wire probes in the flow and surface mounted hot-films were analyzed at USNA by the present investigator to document the boundary layer separation, transition and reattachment process on the suction side of an airfoil. Included was documentation of time averaged and spectral results. These results were then compared to results from the literature from similar facilities. A paper has been written and accepted for conference presentation and publication.

Thermocouple Response Measurements with Steam Injection

Researchers: Associate Professor Ralph J. Volino and
Dr. John Spyropolous (Naval Air Systems Command)
Sponsor: Naval Air Systems Command

The performance of fast responding thermocouples to steam injection was investigated in the large open return wind tunnel in the Fluids Laboratory at USNA. The thermocouples were placed in the wind tunnel along with a device for generating steam. Steam was generated and allowed to pass over the thermocouples while their temperature was monitored. In this way the temporal response of the thermocouples was determined at various flow speeds up to Mach 0.23. The results will be used in the evaluation of data from tests related to steam ingestion into aircraft engines during takeoff from aircraft carriers.

Independent Research

Surface Temperatures and Subsurface Velocities for Grid-Generated Turbulence

Researcher: Associate Professor Karen A. Flack

Evaporation at an air/water interface generates a surface layer that is colder than the bulk fluid. The situation of cold liquid over warm is unstable, resulting in turbulent convection. Recent studies have documented the surface temperature field and near surface velocity profiles for evaporative convection for varying hydrodynamic boundary conditions and a range of Rayleigh numbers. Additional studies using flow visualization and PIV measurements identified large scale turbulent motion including rising plumes, falling sheets and vortical structures. A detailed understanding of the surface temperature field during evaporation and the ability to obtain surface temperature statistics allows for the study of the response of this thin thermal boundary layer to other perturbations. The effect of isotropic turbulence on the surface layer is initially investigated before proceeding to the more complicated situations of shear and wave generated turbulence.

Determination of Clearance Requirements Around Obstructions in Finned Coldplates

Researcher: Professor Steven M. Miner

This study considers the subsystem level, specifically the transfer of heat from the component case through the coldplate to the coolant. In particular, the effect of bosses, used for mounting components, on the air flow distribution and temperature distribution in the coldplate is evaluated. The top and bottom plates spread the heat generated in the components to reduce the local heat flux. The fins substantially increase the heat transfer area, reducing the temperature rise from the coolant to the top and bottom plates. In this case a uniform distribution of flow across the coldplate can be achieved and there will be no localized hot spots. The presence of a boss has three effects on the coldplate performance. The boss disrupts the flow in its immediate vicinity, reducing the overall heat transfer coefficient. This causes an increase in operating temperature at that location. In addition, the boss will change the flow distribution in the coldplate. Locations both upstream and downstream of the boss may see reduced flow due to the obstruction, which in turn will cause an increase in operating temperature for these areas of the coldplate. The change in flow distribution will also increase the pressure drop through the entire coldplate, increasing the power required to operate the system. An initial evaluation of the flow around an unbounded and wall bounded cylinder was completed. This provides a starting point for the evaluation of clearance requirements for coldplates with fins.

Influence of Leading Edge Tubercles on Lifting Foil Performance

Researchers: Assistant Professor Mark M. Murray and
Assistant Professor David S. Miklosovic (Aerospace Engineering Department)

The reasons for the morphological adaptations evolved by animals are not always obvious. In an aquatic environment, turning performance of animals is constrained by morphology with the hydrodynamic characteristics of the animal's control surfaces being a major factor in determining level of performance. Humpback whales utilize extremely mobile, wing-like flippers with large rounded tubercles along the leading edge for banking and turning. This research effort experimentally explored the performance enhancement of leading edge proturbances or tubercles on a wing that is representative of a humpback whale flipper. Two model geometries were used for comparison: one without leading edge tubercles and one with representative tubercles (which give the leading edge a scalloped appearance). Wind tunnel force measurements were conducted at velocities up to 230 ft/sec and Reynolds of 5.5×10^5 based on mean chord length. The result of adding the tubercles showed significant improvements in the aerodynamic performance of the flipper, delaying the angle of attack at which stall develops by approximately 40%. Maximum lift coefficient and minimum drag coefficient did not change significantly. These results indicate that aerodynamic performance can be enhanced with tubercles present on the leading edge of a fin. The results of this work have been published in *Physics of Fluids,* Vol. 16, no. 5, pp L39-L42. The results were also reported on by a number of other publications including *Scientific American, Science, Science News, Natural History Magazine* and UPI (for publication in several news papers).

Pollution from Ship Stack Emissions

Researcher: Associate Professor Kenneth L. Tuttle

The purpose of this research was to determine whether stack emissions from ships can be reduced, either by modifications to the combustion process or by add-on end of pipe devices, and whether the exhaust emissions should be regulated either nationally or internationally. Written input submitted to the EPA is an attempt to convince the U.S. not to regulate ship exhaust emissions and especially not navy ships as they burn reasonably low sulfur fuel already and most have engines that produce low oxides of nitrogen. The results of this research were presented at annual and regional conventions of the Society of Naval Architects and Marine Engineers (SNAME).

Combustion of Shipboard Solid Wastes

Researcher: Associate Professor Kenneth L. Tuttle

The researcher was appointed to the Naval Studies Board of the National Research Council to study the disposal of solid wastes from ships because of his expertise in combustion of solid waste fuels. (The National Research Council is

the principal operating agency of the National Academy of Sciences and the National Academy of Engineering.)

Seventy percent of the combustible solid wastes generated on navy ships is generated on ships having incinerators that are being used. The questions are how to use the incinerators effectively and how to improve incinerator design to make it compatible with shipboard use as well as emissions regulations. Published data are on emissions from combustion of solid waste fuels. The data are from statistically designed, fractional factorial experiments that include seven independent variables and seven dependent variables. These experiments include both unsteady-state experiments as well as steady-state experiments. Three papers have been presented at the International Conference on Solid Waste Technology and Management. The Journal of Solid Waste Technology and Management published NOx emissions data from solid wastes. This is the first such data available in the literature. Two more are in progress.

Midshipman Research Course Projects

Analysis of Dehumidification Capabilities Onboard the Aquarius Undersea Habit

Researcher: Midshipman 1/C Richard W. Lang III, USN
Advisers: Professor Keith W. Lindler and
Professor Marshall L. Nuckols (Naval Architecture and Ocean Engineering Department)

The concept of saturation diving has allowed for the design and use of underwater habitats throughout the 20th century. These habitats have spanned various depths of the ocean and proved the concept that sustained life below the sea is possible. The need for improved environmental control systems onboard habitats was discovered after spending time with the crew of the Aquarius Underwater Habitat in Key Largo, Florida. Through conversation with the crew of Aquarius, and the concepts shown in this research, the environments within underwater habitats such as those operating today are narrowly bordering the accepted thresholds of human comfort. This relative discomfort comes from a combination of both improper internal temperature and high relative humidity within the habitat. In analyzing human comfort in warm water environments, humidity level becomes the dominating factor.

Improper interior temperatures and humidity levels within the habitat environment hamper mission effectiveness and can decrease the aquanauts desire to work within the habitat. The focus of this research has been on environmental control systems onboard underwater habitats in warm water environments. The goal of this research was to devise a means to provide a more comfortable living environment within the Aquarius while reducing the power requirement of the dehumidification system.

Parametric analysis of both the reverse Brayton and vapor compression air conditioning cycles was conducted and their effectiveness with respect to moisture removal, power consumption, and heat removal was compared. It is shown that an optimized vapor compression cycle with an evaporator temperature of 34 F combined with a thermostat set point of 80 F will result in a comfortable living environment while reducing the power requirement by 42%.

Temperature Stabilization of a Reference Light Source for Use in a TLD Reader

Researcher: Midshipman 1/C George Messner, USN
Advisers: Professor Martin E. Nelson and
Assistant Professor R. Brian Jenkins (Electrical Engineering Department)
Sponsor: Naval Dosimetry Center

Currently the US Navy uses scintillations from a radioactive C^{14} source for periodic calibration of its thermoluminescent dosimeter (TLD) readers. It would be preferable to use a non-radioactive reference light source. However, these sources currently produce unacceptable variations in the light output due to ambient temperature changes and the TLD heating process. To solve this problem, a temperature isolation box was designed and built to keep the output of the reference light source constant. The light source is stabilized by maintaining the box at a constant temperature by the use of a thermoelectric (TE) cooler. The TE cooler heats or cools the box based on a feedback signal provided by a thermistor. The system has been designed to maintain the temperature of the box to within one degree of 25 C for a period of one month.

The isolation box has been placed externally to a Bicron model 3500 TLD reader and employs a fiber optic cable to transmit the reference light source to the reader's photomultiplier tube. The system has been evaluated by varying the ambient temperature between 10 C and 40 C and using a data acquisition system, which simultaneously records both the isolation box temperature and ambient temperature with time. The conclusions of the project indicate that while the system meets most operational requirements, further improvements could be made by redesigning the instrumentation of the light source power output and by reducing system complexity.

Investigation into the Feasibility of Highly Enriched Uranium Detection by External Neutron Stimulation

Researcher: Midshipman 1/C Crystine M. Good, USN
Adviser: Professor Martin E. Nelson
Sponsor: Defense Threat Reduction Agency (DTRA)

The project was performed in order to help combat the illicit trafficking of special nuclear materials (SNM) into the United States, specifically through cargo containers. Highly enriched uranium (HEU) is difficult to detect because it emits low energy gammas that are easy to shield from a detector and also has almost no neutron signature because of its long spontaneous fission half-life.

This report studied the detectability of 1 kg of HEU in a cargo container, whose dimensions are 20 ft x 20 ft x 8 ft, by stimulating the HEU with a neutron source located external to the container and counting the above background neutron signature that would be produced due to fissioning. The neutron detector used in the project contained nine He^3 tubes moderated with polyethylene that had been designed for nuclear arms control applications. This project examined a wide variety of different energy sources, counting options, and the effect of different cargo materials present within the container. The study considered solution approaches using both deterministic and Monte Carlo techniques of which the latter solution approach was based on the MCNP4C2 transport code.

The major project conclusions are that this approach would be successful in all common environments except one, if a pulsed 14 MeV neutron source with a strength of 10^{12} neutrons/sec was used and the delayed neutrons from the fission products are counted when the source is between pulses. The study recommends a pulse and count time of 2.9 seconds, 48 cycles and a total examination time of 300 seconds for each container. The one environmental condition identified that would defeat this technique was the case of when the cargo had both a density of 1 gram/cm^3 or greater and a hydrogen atom content of 15% or greater. In order to succeed in this environment, the study concluded that the stimulation source strength would have to be increased several orders of magnitude to as high as 10^{15} n/sec, which is beyond current technical capabilities. A dose evaluation of the shielding requirements for a stimulation facility was also performed. For the case of a 14 MeV 10^{12} neutron/sec source, the study recommended a surrounding 7 foot thick concrete shield in order to meet current regulatory standards for facility operational personnel. The study noted that this technique could result in cargo activation that may require a post-irradiation decay time before the container could be released for public transportation to its final destination site. A recommendation is made for future study of this problem.

Trident Scholar Projects

Environmentally Assisted Cracking Properties of AA7249 Extrusions for Aerospace Applications (Trident Report # 304)

Researcher: Midshipman 1/C Kristen L. Deffenbaugh, USN
Advisers: Assistant Professor Michelle G. Koul and Associate Professor Angela L. Moran
Sponsors: Air Force Aging Aircraft Program Office (ASC/AAA)
and the Office of Naval Research (ONR)

Development of new military aerospace platforms is costly and time-consuming. Therefore, it is important that current platforms maximize their service lifetime. Exposure to environmental elements, particularly seawater, is especially troublesome to the Navy because it shortens required aircraft lifetime.

The P-3C is an example of a versatile aircraft whose lifetime has been extended to the point that environmental attack is now becoming a significant concern. Structural components in the P-3C are currently composed of aluminum alloy AA7075-T6, which has high strength but limited corrosion resistance. In particular, AA7075-T6 is susceptible to environmentally assisted cracking (EAC), which can cause catastrophic fracture of a stressed part. In 1999, Lockheed Martin Aeronautical Systems was granted funding to complete the Service Life Assessment Program (SLAP) for the P-3. One objective of this program was to identify a possible replacement for corrosion-prone AA7075-T6 extruded components that would help reach the goal service life of 2015. AA7249 is currently under development as a possible replacement material.

The objective of this project was to extend the ongoing evaluation of AA7249 extrusions to include corrosion testing, mechanical testing, and evaluations of the effects of processing on wide panel extrusions. The complete study was executed in three phases: (1) evaluation of local properties such as hardness, strength, and electrical conductivity as a function of position within the extrusions, (2) evaluation of the microstructure (i.e., grain size, shape, and orientation) as a function of position within the extrusions and (3) characterization and quantification of the EAC resistance as a function of the grain structure via a slow strain rate technique. The results of this study will contribute to the ongoing evaluation of these alloys for replacement of AA7075-T6 in aerospace structures. In addition, the results will provide an improvement in the basic understanding of the structure/property relationship obtained for these component parts, as well as the effect of processing on EAC behavior and material performance.

A paper on this work was presented at NACE 2003 in the "Corrosion and its Prevention in the Life Cycle of Military and Aerospace Equipment" symposium.

Optical Calibration of TLD Readers (Trident Report # 305)

Researcher: Midshipman 1/C Jeffrey H. Dormo, USN
Advisers: Associate Professor R. Brian Jenkins (Electrical Engineering Department)
and Professor Martin E. Nelson
Sponsor: Office of Naval Research (ONR)

The Navy uses thermoluminescent dosimeters (TLDs) on all of its nuclear warships. TLDs measure the amount of radiation a person receives through the use of a small internal crystal. Electrons in the crystal are excited to a higher energy state when they absorb radiation. If the crystal is later taken out of the TLD and heated to a high temperature, the electrons drop back to the lower energy state, emitting light. A TLD reader determines the radiation exposure by measuring the emitted optical energy.

Presently, TLD readers need to be calibrated frequently to ensure the measurements are accurate. A reference light source is used to calibrate the output of the reader. However, the power emitted by this light source is not stable over time, resulting in poor calibration. For this project, four light sources were compared as possible alternatives. The sources are a commercial light emitting diode, a commercial laser diode, a scintillating C-14 doped radioactive source, and a tritium source.

The first part of this project determined the cause of the instability in the output of the TLD reader. This included understanding the effects of environmental temperature variations on both the reader components and light sources. Consequently a temperature data acquisition system (DAQ) was developed to record the time variation of these temperatures. A second DAQ was then implemented to measure the optical power stability of each light source. After the power stability of each source was measured, the stability of the photomultiplier tube output in the reader was verified. Finally, since the Navy prefers to eliminate the use of unnecessary radioactive sources, various methods of guiding the light from the diode sources to the TLD reader using optical fiber were considered.

The research determined that the Ocean Optics LED and the C-14 source are relatively temperature independent. The C-14 operates within the ± 1% power stability criterion defined by the Naval Dosimetry Center.

A Capillary Assisted Thermosyphon for Shipboard Electronics Cooling (Trident Report # 312)

Researcher: Midshipman 1/C Eric Larsen, USN
Advisers: Associate Professor Martin R. Cerza and Assistant Professor Andrew N. Smith
Sponsors: Bechtel Bettis, Inc. and Office of Naval Research (ONR)

Recent advances in capillary pumped loop technology were incorporated into the design of a vertical flat plate evaporator for cooling high power electronics aboard naval vessels. This investigation included the design, fabrication, and experimentation of an evaporator plate configured for installation into a standard Navy electronics cabinet. Combining both the characteristics of a Capillary Pumped Loop (CPL) and a thermosyphon, this design integrated the wick from a CPL and the gravity head associated with a thermosyphon. The vertical evaporator plate was designed using AutoCAD, modeled in I-DEAS, and fabricated in a computer-numerically controlled (CNC) milling machine.

The effectiveness of the resulting capillary-assisted thermosyphon (CAT) loop was then evaluated by investigating the effects of subcooling and orientation [tilt and pitch] on the thermal performance. The subcooling effects were studied for a range of heat loads by varying the chill water flow rate between .375 and 3.5 GPM, and varying the chill water temperature between 4 and 37 degrees Celsius. Chill water temperatures were chosen that simulate the conditions of the sea that a warship would be operating in anywhere between the Artic and the Persian Gulf. Subcooling was shown to be dependent upon chill water sink temperature and not strongly dependent upon chill water flow rate. Pitching and tilting the plate up to forty-five degrees of inclination tested the influence of orientation on the thermal performance of the evaporator plate. Results showed that the plate operated under all tilt angles, pitch angles, and pressure restrictions imposed. The most significant influence was observed during pitch angle testing due to the geometry of the plate.

Publications

Journal (Refereed) Manuscripts

BURKHARDT, John A., Assistant Professor, Masri, R.M., Driscoll, C.F., von Fraunhofer, J.A. and Romberg, E., "Pressure Underneath Complete Dental Impressions," *Journal of Prosthodontists*, Vol. II, No. 2, September 2002.

The purpose of this work was to measure the pressure exerted under a maxillary edentulous impression utilizing four commonly used impression materials and four impression tray configurations. The study was performed using an oral analog that simulated an edentulous maxillary arch. Three pressure transducers were imbedded in the oral analog, one pressure transducer in the rugae area and the other two in the right and left ridge areas. Custom trays of four different configurations were fabricated. The four impression materials tested were: irreversible hydrocolloid, vinyl polysiloxane light body, vinyl polysiloxane medium body, and polysulfide. The custom tray and the oral analog were mounted using a reline jig and a Satec universal testing machine was used to apply a constant pressure of 2 kg over a period of five minutes on the loaded custom tray. The pressure was recorded every ten seconds. 128 impressions were made. Factorial ANOVA, and Tukey Multiple Comparison Test were used to analyze the results.. A significant difference in the pressure produced using different impression materials was found ($P<0.05$). Irreversible hydrocolloid and medium body vinyl polysiloxane produced a significantly higher pressure than light body vinyl polysiloxane and polysulfide impression materials. The presence of holes and/or relief did not significantly alter the magnitude of pressure.Impression materials can be grouped into two categories, high viscosity impression materials and low viscosity impression materials. The use of low viscosity impression materials (light body vinyl polysiloxane, polysulfide) is recommended when making complete denture impressions because they produce the least pressure thus recording the tissues more accurately. The use of holes and/or relief was not important clinically in changing the amount of pressure produced during maxillary complete denture impressions.

CARR, Matthew A., Commander, USNR, and Brown, J. Steven, "Container-Handling Crane: A First Year Engineering Student Project," *International Journal of Mechanical Engineering Education*, pp 298-306, Vol. 30, No. 4.

This paper describes a project suitable for first-year undergraduate engineering students, which integrates civil, electrical, and mechanical engineering concepts into an open-ended design and construction project. The project is a model crane, which simulates a shipping container handling system and is suitable for inter-team competi-

tion. The design criteria, materials, and competition rules are presented. As well, a series of short lecture topics, demonstrations, and facilitating homework assignments are outlined. This project and the associated supporting materials meet the goals of being relatively inexpensive while exposing the students to a broader perspective of the engineering profession and retaining their interest in engineering.

CERZA, Martin R., Associate Professor, Adams, J.C., Ireland, P.T., and Oswald, J., "Photographs on the Effect of Perforations on the Heat Transfer Due to Laminar Flow Over an Extended Surface," *The Journal of Heat Transfer*, Vol. 124, No. 4, pp. 593-600, August 2002.

In the past it has not been resolved as to whether perforated surfaces on a fin enhance heat transfer. In this photographic study which utilizes liquid crystal thermography, the evidence suggests that there is an increase in the local heat transfer coefficient in the vicinity of the downstream side of the perforations. The perforations appear to partially disrupt the thermal boundary layer and they appear to allow a partial restart of the boundary layer on the backside of the hole. For these series of photographs, a transient heating technique is employed. Helium at approximately 70ºC is allowed to flow through 5 perspex channels separated by 1 mm thick perforated fins. The channel cross sectional areas are 33 mm high by 13.1 mm wide. The channel length is 1 m. The initial temperature of the channels was 24ºC. A one degree, narrow band, liquid crystal (30ºC color change temperature) was painted over the black painted center channel fin. The time history of the color change of the painted fin was recorded on a standard CCD video camera. The peak intensity-time relationships were obtained from image processing the recorded video and the heat transfer coefficients were evaluated using a transient thin fin heat transfer model. The helium temperature was measured at 5 locations along the channel. As can be seen, there appears to be a local heat transfer enhancement near the backside of the perforations. Comparisons are made to non-perforated fins in the channel Reynolds number range of 750-2500.

CERZA, Martin R., Associate Professor and BOUGHEY, Britt W., (Trident Scholar, Class of 1999), "The Effects of Air Infiltration on a Large, Flat Heat Pipe at Horizontal and Vertical Orientations," *The Journal of Heat Transfer,* Vol. 125, No. 2, pp 349-355, April 2003.

In the satellite or energy conversion industries flat heat pipes may be utilized to transfer heat to the thermal sink. In this investigation, a large flat heat pipe, 1.22m x 0.305m x 0.0127m, fabricated from 50 mil Monel 400 metal sheets and Monel 400 screens was videographed at horizontal and vertical orientations with an infrared video camera. The heat pipe evaporator section consisted of a 0.305m x 0.305m area (one heated side only) while the side opposite the heated section was insulated. The remaining area of the heat pipe served as the condenser. In the horizontal orientation the heated section was on the bottom. In the vertical orientation the evaporator was aligned below the condenser. The sequence of photographs depicts heat inputs ranging from 200W to 800W, and the effect of air infiltration on heat pipe operation for both orientations. For the horizontal orientation, the air is seen to recede towards the small fill pipe as the heat input is increased. For the vertical orientation, the air and water vapor exhibit a buoyant interaction with the result that the air presence inhibits heat transfer by rendering sections of the condenser surface ineffective. The effects depicted in this paper set the stage for future analytical and experimental work in flat heat pipe operation for both normal and variable conductance modes.

FLACK, Karen A., Associate Professor, Saylor, J. R., Smith, G.B., and SCHULTZ, Michael P., Assistant Professor, "The Correlation Between Surface Temperature and Subsurface Velocity During Evaporative Convection," *Experiments in Fluids,* Vol. 32, pp. 570-579, 2002.

Correlation coefficients between measurements of temperature at a water surface and velocity at a location beneath the water surface undergoing evaporative convection are presented. The significance of these results and their implications for remote sensing of underwater objects via infrared imaging are discussed.

FLACK, Karen A., Associate Professor, and SCHULTZ, Michael P., Assistant Professor, "Turbulent Boundary Layers over Surfaces Smoothed by Sanding," *American Society of Mechanical Engineers (ASME) Journal of Fluids Engineering,* accepted for publication.

The effect of surface preparation and surface coatings on the overall drag of a surface is investigated. Detailed measurements of near-surface velocity and turbulence parameters were obtained using laser Doppler anemometry in a re-circulating water channel. Roughness parameter measurements are compared to results from tow-tank test using plates with the similar surface coatings.

JOYCE, James A., Professor, "Application of a T-Stress Based Constraint Correction to A533B Steel Fracture Toughness Data," *Fatigue and Fracture Mechanics: 33rd Volume, ASTM STP 1417*, ASTM International, pp. 307-327, 2003.

Over the past 18 months a large data set has been developed on an A533B plate material removed from the de-commissioned Shoreham nuclear power pressure vessel. The specimens in this data set were tested in the ductile-to-brittle transition regime using the procedures of the new "Master Curve" ASTM Standard E1921. Specimen geometries include SE(B) specimens from ½ thickness Charpy scale SE(B) specimens to Charpy geometries, and 1/2T and 1T SE(B) specimens with a/W ratios ranging from 0.1 to 0.55. Both BxB and Bx2B cross sections are included in the data set for both the shallow and deep crack SE(B) configurations. Also in the data set are C(T) specimens from 1/2T to 1T with a/W ratios from 0.5 to 0.75. Data sets of from 6 to 17 identical specimens of each geometry were tested at two to four different test temperatures in the ductile-to-brittle transition regime so that for each data set a reference temperature T_o and Master Curve could be developed according to E1921.

Results presented earlier showed that both crack length and specimen geometry (SE(B) versus C(T)) have strong effects on the T_o reference temperature. The geometry dependent shift of T_o was shown to persist even when the specimens were tested low in the transition where crack tip plasticity was very limited. The observation that the extent of plasticity had little effect on the observed specimen geometry shift led to an investigation of the use of the elastic T-stress as a useful measure of constraint for these results.

The effect of T-stress on specimen crack-tip constraint has been investigated recently by Gao and Dodds, who noticed the strong effect of the T-stress had on 3D finite element models under small scale yielding conditions. These authors proposed the use of a T-stress based constraint correction function based on a ratio of the fracture toughness for a specimen with a non-zero T-stress and the fracture toughness for the small scale yielding, T-stress = 0, reference configuration.

In this work the T-stress based constraint correction functions of Gao and Dodds are applied to the A533B data set of ductile-to-brittle fracture toughness tests using the procedure of ASTM E1921. The analysis shows that a Weibull modulus can be chosen that removes the observed constraint differences between the shallow and deep crack SE(B) data sets, resulting in what should be a geometry independent T_o value. A slightly different Weibull modulus is required when deep crack C(T) data sets are substituted for the deep crack SE(B) data sets, corresponding to an effective shift of the constraint corrected reference temperature T_o of approximately 10°C. The constraint correction procedure does not account for the difference observed in this data set between the deep crack SE(B) and C(T) data sets. Additional variability of the "geometry independent" T_o also results from the various T-stress analyses available in the literature. This "T-stress" uncertainty can result in an additional 2-3°C uncertainty in T_o.

KOUL, Michelle G., Assistant Professor, FERRER, Charles P. (Trident Scholar, Class of 2001), CONNOLLY, Brian J., Assistant Research Professor, and MORAN, Angela L., Associate Professor, "Improvements in Strength and Stress Corrosion Cracking Properties in Aluminum Alloy 7075 Via Low Temperature Retrogression and Re-Aging Heat Treatments", *Corrosion* Vol. 59, No.6, pp. 520-528, June 2003.

The susceptibility of aluminum alloy 7075 (AA7075) to intergranular stress-corrosion cracking (SCC) in the peak strength T6 temper is alleviated through the use of the T73, or overaged temper, which provides improved SCC resistance with a 10-15% strength loss compared to the T6 temper. Cina and Ranish indicated that retrogression and re-aging (RRA) heat treatments reduce the trade-off between T6 strength and T73 SCC resistance. The short time heat treatment they used, however, limited the applicability of RRA to thin sections of material. The primary goals of this research effort were to (1) determine if lower retrogression temperatures could be used in the RRA

process to extend the applicability of this heat treatment to thick section aircraft components and (2) to quantify any observed improvements. Alternate immersion (AI) and double-cantilever beam (DCB) tests were conducted in a 0.6 M NaCl solution to evaluate the SCC resistance of various tempers. Improvements in properties were demonstrated using RRA heat treatments at lower temperatures and longer times than those previously investigated. In general, the various RRA tempers below 200°C produced strengths similar to that of T6 with improved SCC properties. The RRA temper with retrogression at 160°C for 660 minutes produced the greatest improvement in SCC resistance, with only a 4% reduction in strength below T6.

KOUL, Michelle G., Assistant Professor, CONNOLLY, Brian J., Assistant Research Professor, DEFFENBAUGH, Kristen L., Midshipman 1/C (USN), and MORAN, Angela L., Associate Professor, "Environmentally Assisted Crack Growth Rates of High Strength Aluminum Alloys," *Journal of Metals,* Vol. 55, No. 1, pp. 49-52, 2003.

Aging aircraft have been known to experience corrosion related cracking problems that can be detrimental to the structural integrity, and entail significant economic loss due to cost of replacement of affected components and overall system down time. As the number of aging aircraft increase, the need for more environmentally assisted crack resistant aluminum alloys for component replacement and refurbishment as well as the need for quantitative measurements of the effects of corrosion on component lifetime prediction have become critical. The scope of this project is to evaluate the environmentally assisted long crack growth behavior of candidate high strength aluminum alloys/tempers, specifically AA7150-T7751 and AA7040-T7651, for consideration as viable replacements/refurbishment for stress corrosion cracking susceptible AA7075-T6 aircraft components found in aging aircraft systems.

NELSON, Martin, E., Professor, Phillips, G.W., August, R.A., Campbell, A.B., Price, J. L., Guardala, N.A., and Moscovitch, M., "Feasibility of a Neutron Detector-Dosimeter Based on Single-Event Upsets In Dynamic Random-Access Memories," *Radiation Protection Dosimetry*, Vol. 101., No. 1-4, pp 129-132, 2002.

The feasibility was investigated of a solid state neutron detector/dosimeter based on SEU effects in DRAMs commonly used in computer memories. Such a device, which uses a neutron converter material to produce a charge particle capable of causing an upset, would be light-weight, low power and could be read by simply polling the memory for bit flips. It would have significant advantages over standard solid-state neutron dosimeters which require off-line processing for track etching and analysis. Previous efforts at developing SEU dosimeters have suffered from poor response, which can be greatly enhanced by selecting a modern high density DRAM chip for SEU sensitivity and by using B-10 as a converter. Past attempts to use B-10 were not successful because the average alpha particle energy was insufficient to penetrate to the sensitive region of the memory. This can be overcome by removing the surface passivation layer before depositing the B-10 film or by implanting B-10 directly into the chip, previous experimental data shows a 1000 increase in neutron sensitivity by chips containing BSG, which could be used in an SEU detector. The results are presented as simulations showing that the absolute efficiency of an SEU neutron dosimeter can be increased by a factor of at least 1000 over earlier designs.

NELSON, Martin E., Professor, SARLESE, J.A. (Trident Scholar, Class of 2000), ZIEGLER, J.F., Visiting Professor (Electrical Engineering Department), Muhlfeld, H., Peterson, R.J., Campbell, A., Melinger, J.S., Clark, K., and Thompson, A.K., "Cosmic Ray Induced Soft Error Rates of Commercial 16 Mb and 64 Mb DRAMS at Aircraft Altitudes," *Journal of Radiation Effects*, Vol. 19-1, pp 100-106, 2003.

The soft error rate (SER) for commercial-off-the shelf (COTS) 16 Mb and 64 Mb memory devices has been estimated at different worldwide locations and altitudes from different commercial vendors. The chips were irradiated with neutrons, protons, and pions, whose energy ranged from thermal (.025 eV) to 280 MeV. The SER for these devices was then calculated at various altitudes for a given longitude and latitude using results from an atmospheric particle flux model. The results show that the 16 Mb chips have a much wider variation than the 64 Mb chips in their SER between vendors. In addition, the 64 Mb chips were found on average to have a smaller SER cross section (fails/unit particle fluence/bit) than the 16 Mb chips. A flight experiment needed to confirm these predictions is described

RATCLIFFE, Colin P., Associate Professor and ROGERS, David F., Professor (Aerospace Engineering Department), "Balanced Fuel Injector Effects on Inflight Aircraft Engine Vibration," *American Institute of Aeronautics and Astronautics (AIAA) Journal of Aircraft,* Vol. 39, No. 3, pp. 440-444, 2002.

Teledyne Continental Motors (TCM) large bore aircraft engines IO 520 and IO 550 are installed in a number of high performance single and twin engine general aviation aircraft. These flat horizontally opposed six cylinder engines are well known to have uneven air/fuels mixtures between cylinders. The uneven air/fuel mixture is a result of intake manifold design, comparatively loose tolerances on fuel injector nozzles, and back flow of fuel rich exhaust during intake/exhaust valve overlap. This uneven air/fuel distribution results in some cylinders running significantly rich of stoichiometric compared to others. Operationally, to avoid lean misfire and high cylinder head temperatures, the manufacturer recommends that the engine be leaned using exhaust gas temperature (EGT) until the first cylinder reaches peak EGT, and then to enrichen the mixture 25-50°F rich of peak. (The excess unburned fuel in an overly rich mixture reduces both the exhaust gas temperature and the cylinder head temperature.) The uneven fuel/air mixture between cylinders results in an uneven power production (BMEP) between cylinders which may lead to an increase in combustion induced vibration.

Recently, General Aviation Modification Inc. (GAMI) of Ada Oklahoma [1], has addressed the uneven combustion problem by careful selection of fuel injector flow rates to balance the fuel air mixture between cylinders. The net result of balancing the air/fuel mixture between cylinders is that the EGTs of all cylinders peak simultaneously. Thus, each of the cylinders receives the same air/fuel ratio. Hence, each cylinder produces the same power (BMEP) and uneven combustion induced vibration should be reduced.

GAMI has concentrated their research and marketing efforts on smooth lean-of-peak operation to reduce both fuel flow and cylinder head temperatures. To date, no other in flight vibration analysis of the effect of balanced flow injectors is known.

SMITH, Andrew N., Assistant Professor, Norris, Pamela M., Caffrey, Andrew P., Stevens, Robert J., Klopf, James M. and McLesky, James T., "Femtosecond Pump-Probe Nondestructive Evaluation of Materials," *Review of Scientific Instruments*, Vol. 74, pp. 400-406, Jan 2003.

Ultrashort-pulsed lasers have been demonstrated as effective tools for the non-destructive examination (NDE) of energy transport properties in thin films. After the instantaneous heating of the surface of a 100 nm metal film, it will take ~100 ps for the influence of the substrate to affect the surface temperature profile. Therefore, direct measurement of energy transport in a thin film sample requires a technique with picosecond temporal resolution. The pump-probe experimental technique is able to monitor the change in reflectance or transmittance of the sample surface as a function of time on a sub-picosecond timescale. Changes in reflectance and transmittance can then be used to determine properties of the film. In the case of metals, the change in reflectance is related to changes in temperature and strain. The transient temperature profile at the surface is then used to determine the rate of coupling between the electron and phonon systems as well as the thermal conductivity of the material. In the case of semiconductors, the change in reflectance and transmittance is related to changes in the local electronic states and temperature. Transient thermotransmission experiments have been used extensively to observe electron-hole recombination phenomena and thermalization of hot electrons.

Application of the Transient ThermoReflectance (TTR) and Transient ThermoTransmittance (TTT) technique to the study of picosecond phenomena in metals and semiconductors will be discussed. The pump-probe experimental setup will be described, along with the details of the experimental apparatus in use at the University of Virginia. The thermal model applicable to ultrashort-pulsed laser heating of metals will be presented along with a discussion of the limitations of this model. Details of the data acquisition and interpretation of the experimental results will be given, including a discussion of the reflectance models used to relate the measured changes in reflectance to calculated changes in temperature. Finally, experimental results will be presented that demonstrate the use of the TTR technique for measuring the electron-phonon coupling factor and the thermal conductivity of thin metallic films. The use of the TTT technique to distinguish between different levels of doping and alloying in thin film samples of hydrogenated amorphous silicon will also be discussed briefly.

TUTTLE, Kenneth L., Associate Professor and WU, C., Professor, "Computer-Based Thermodynamics," *Journal of Educational Technology Systems*, Volume 30, Number 4 – 2001-2002, pp. 427-436.

A new computer-based approach to teaching thermodynamics is being developed and tried by two mechanical engineering professors at the U.S. Naval Academy. The course uses sophisticated software, in this case CyclePad, to work all of the homework problems. A new text, written with traditional theory but computer-based problems, accommodates the new approach. The new course is scheduled for Fall Term 2001 at the Naval Academy. Computer-based thermodynamics courses teach the same theory as traditional thermodynamics courses as well as the same types of problems. However, traditional thermodynamic cycle hand calculations are replaced by cycle calculations using CyclePad. This new example of Intelligent Computer- Assisted Instruction, ICAI, switches emphasis from learning cycle calculations to learning cause and effect through parametric analysis. Parametric analysis is made feasible through experimentation using computer models. For this, CyclePad has artificial intelligence, sensitivity analysis and graphical presentation capabilities. Traditionally, thermodynamics culminates in analysis of the thermodynamic cycles. In this course, students will progress well beyond traditional thermodynamics courses by emphasizing cycle analysis.

VOLINO, Ralph J., Associate Professor, "Separated Flow Transition Under Low-Pressure Turbine Airfoil Conditions: Part 1. Mean Flow and Turbulence Statistics," *American Society of Mechanical Engineers (ASME) Journal of Turbomachineiry*, Vol. 124, pp. 645-655, October 2002.

Boundary layer separation, transition and reattachment have been studied experimentally under low-pressure turbine airfoil conditions. Cases with Reynolds numbers (*Re*) ranging from 25,000 to 300,000 (based on suction surface length and exit velocity) have been considered at low (0.5%) and high (9% inlet) free-stream turbulence levels. Mean and fluctuating velocity and intermittency profiles are presented for streamwise locations all along the airfoil, and turbulent shear stress profiles are provided for the downstream region where separation and transition occur. Higher *Re* or free-stream turbulence level moves transition upstream. Transition is initiated in the shear layer over the separation bubble and leads to rapid boundary layer reattachment. At the lowest *Re*, transition did not occur before the trailing edge, and the boundary layer did not reattach. Turbulent shear stress levels can remain low in spite of high free-stream turbulence and high fluctuating streamwise velocity in the shear layer. The beginning of a significant rise in the turbulent shear stress signals the beginning of transition. A slight rise in the turbulent shear stress near the trailing edge was noted even in those cases which did not undergo transition or reattachment. The present results provide detailed documentation of the boundary layer and extend the existing database to lower *Re*. The present results also serve as a baseline for an investigation of turbulence spectra in Part 2 of the present paper, and for ongoing work involving transition and separation control.

VOLINO, Ralph J., Associate Professor, "Separated Flow Transition Under Low-Pressure Turbine Airfoil Conditions: Part 2. Turbulence Spectra," *American Society of Mechanical Engineers (ASME) Journal of Fluids Engineering,* Vol. 124, pp. 656-664, October 2002.

Spectral analysis was used to investigate boundary layer separation, transition and reattachment under low-pressure turbine airfoil conditions. Cases with Reynolds numbers ranging from 25,000 to 300,000 (based on suction surface length and exit velocity) have been considered at low (0.5%) and high (9% inlet) free-stream turbulence levels. Spectra of the fluctuating streamwise velocity and the turbulent shear stress are presented. The spectra for the low free-stream turbulence cases are characterized by sharp peaks. The high free-stream turbulence case spectra exhibit more broadband peaks, but these peaks are centered at the same frequencies observed in the corresponding low turbulence cases. The frequencies of the peaks suggest that a Tollmien-Schlichting instability mechanism drives transition, even in the high turbulence cases. The Spectral analysis was used to investigate boundary layer separation, transition and reattachment under low-turbulent shear stress spectra proved particularly valuable for detection of the early growth of the instability. The predictable nature of the instability may prove useful for future flow control work.

VOLINO, Ralph J., Associate Professor, and SCHULTZ, Michael P., (Naval Architecture and Ocean Engineering Department), "Effects of Concave Curvature on Boundary Layer Transition Under High Free-Stream Turbulence Conditions," *American Society of Mechanical Engineers (ASME) Journal of Fluids Engineering,* Vol. 125, pp. 18-27, January 2003.

An experimental investigation has been carried out on a transitional boundary layer subject to high (initially 9%) free-stream turbulence, strong acceleration (K as high as $9x10^{-6}$), and strong concave curvature (boundary layer thickness between 2% and 5% of the wall radius of curvature). Mean and fluctuating velocity as well as turbulent shear stress are documented and compared to results from equivalent cases on a flat wall and a wall with milder concave curvature. The data show that curvature does have a significant effect, moving the transition location upstream, increasing turbulent transport, and causing skin friction to rise by as much as 40%. Conditional sampling results are presented which show that the curvature effect is present in both the turbulent and non-turbulent zones of the transitional flow.

VOLINO, Ralph J., Associate Professor, SCHULTZ, Michael P., (Naval Architecture and Ocean Engineering Department), and PRATT, Christopher M., Midshipman 1/C (USN), "Conditional Sampling in a Transitional Boundary Layer Under High Free-Stream Turbulence Conditions," *American Society of Mechanical Engineers (ASME) Journal of Fluids Engineering,* Vol. 125, pp. 28-37, January 2003.

Conditional sampling has been performed on data from a transitional boundary layer subject to high (initially 9%) free-stream turbulence and strong (K as high as $9x10^{-6}$) acceleration. Methods for separating the turbulent and non-turbulent zone data based on the instantaneous streamwise velocity and the turbulent shear stress were tested and found to agree. Mean velocity profiles were clearly different in the turbulent and non-turbulent zones, and skin friction coefficients were as much as 70% higher in the turbulent zone. The streamwise fluctuating velocity, in contrast, was only about 10% higher in the turbulent zone. Turbulent shear stress differed by an order of magnitude, and eddy viscosity was three to four times higher in the turbulent zone. Eddy transport in the non-turbulent zone was still significant, however, and the non-turbulent zone did not behave like a laminar boundary layer. Within each of the two zones there was considerable self-similarity from the beginning to the end of transition. This may prove useful for future modeling efforts.

VOLINO, Ralph J., Associate Professor, "Passive Flow Control on Low-Pressure Turbine Airfoils," *American Society of Mechanical Engineers (ASME) Journal of Turbomachinery*, October 2003. (CD-ROM)

Two-dimensional rectangular bars have been used in an experimental study to control boundary layer transition and reattachment under low-pressure turbine conditions. Cases with Reynolds numbers (*Re*) ranging from 25,000 to 300,000 (based on suction surface length and exit velocity) have been considered at low (0.5%) and high (8.5% inlet) free-stream turbulence levels. Three different bars were considered, with heights ranging from 0.2% to 0.7% of suction surface length. Mean and fluctuating velocity and intermittency profiles are presented and compared to results of baseline cases from a previous study. Bar performance depends on the bar height and the location of the bar trailing edge. Bars located near the suction surface velocity maximum are most effective. Large bars trip the boundary layer to turbulent and prevent separation, but create unnecessarily high losses. Somewhat smaller bars had no immediate detectable effect on the boundary layer, but introduced small disturbances which caused transition and reattachment to move upstream from their locations in the corresponding baseline case. The smaller bars were effective under both high and low free-stream turbulence conditions, indicating that the high free-stream turbulence transition is not simply a bypass transition induced by the free-stream. Losses appear to be minimized when a small separation bubble is present, so long as reattachment begins far enough upstream for the boundary layer to recover from the separation. Correlations for determining optimal bar height are presented. The bars appear to provide a simple and effective means of passive flow control. Bars which are large enough to induce reattachment at low *Re*, however, cause higher losses at the highest *Re*. Some compromise would, therefore, be needed when choosing a bar height for best overall performance.

VOLINO, Ralph J., Associate Professor, "Separation Control on Low-Pressure Turbine Airfoils Using Synthetic Vortex Generator Jets," *American Society of Mechanical Engineers (ASME) Journal of Turbomachinery,* October 2003. (CD-ROM)

Oscillating vortex generator jets have been used to control boundary layer separation from the suction side of a low-pressure turbine airfoil. A low Reynolds number (*Re*=25,000) case with low freestream turbulence has been

investigated with detailed measurements including profiles of mean and fluctuating velocity and turbulent shear stress. Ensemble averaged profiles are computed for times within the jet pulsing cycle, and integral parameters and local skin friction coefficients are computed from these profiles. The jets are injected into the mainflow at a compound angle through a spanwise row of holes in the suction surface. Preliminary tests showed that the jets were effective over a wide range of frequencies and amplitudes. Detailed tests were conducted with a maximum blowing ration of 4.7 and a dimensionless oscillation frequency of 0.65. The outward pulse from the jets in each oscillation cycle causes a disturbance to move down the airfoil surface. The leading and trailing edge celerities for the disturbance match those expected for a turbulent spot. The disturbance is followed by a calmed region. Following the calmed region, the boundary layer does separate, but the separation bubble remains very thin. Results are compared to an uncontrolled baseline case in which the boundary layer separated and did not reattach, and a case controlled passively with a rectangular bar on the suction surface. The comparison indicates that losses will be substantially lower with the jets than in the baseline or passively controlled cases.

WU, Chih, Professor, Bi, Y., and Chen, L., "Ground Heat Exchanger Temperature Distribution Analysis and its Experimental Verification," *Applied Thermal Engineering*, Vol. 22, No. 2, pp. 183-189, 2002.

The underground two-dimensional symmetry temperature field of a vertical double spiral coil ground heat exchanger designed for a ground source heat pump system was formulated using the volume control method. A heat transfer model of underground coil is made, and the underground temperature distribution of the coil was solved numerically. Experimental Temperature data are measured. The analytical results are compared thoroughly with the experimental data.

WU, Chih, Professor, PUZINAUSKAS, Paul V., Assistant Professor and Tsai, Y., "Performance Analysis and Optimization of a Supercharged Miller Cycle Otto Engine," *Applied Thermal Engineering*, Vol. 23, No. 5, pp 511-521, 2003.

One of the major alternatives of the Otto cycle has been examined to determine its potential for increased efficiency and net work power in the spark ignited internal combustion engine is to shorten the compression process relative to the expansion process by early close or late of intake valve. The modified Otto cycle is called Miller cycle. This paper deals with the analysis of a supercharged Otto engine adopted for Miller cycle operation. The Miller cycle shows no efficiency advantage and suffers a penalty in power output in the normally aspirated version. In the supercharged Otto engine adopted for Miller cycle version, it has no efficiency advantage but does provide increased net work output with reduced propensity to engine knock problem. Sensitivity analysis of cycle efficiency versus early close of intake valve and that of cycle net work versus early close of intake valve are performed. Optimization on the cycle efficiency is obtained.

WU, Chih, Professor, Chen, L., Zhou, S., and Sun, F., "Preliminary Design Optimization of a Steam Generator," *Energy Conversion and Management*, Vol. 43, No. 13, pp. 1651-1661, 2002.

A procedure for preliminary design optimization of a steam generator is developed with the objective of minimizing the weight of the generator. Some real engineering constraints are considered in the problem formulation. A method of evaluating the objective function and constraints of the problem is presented.

WU, Chih, Professor, Chen, L., Gong, J., and Sun, F., "Heat Transfer Effect on the Performance of a MHD Power Plant," *Energy Conversion and Management*, Vol. 43, No. 15, pp. 2085-2095, 2002.

The thermodynamic performance analysis of a MHD power plant is performed. The analytical expression for the power output and the efficiency are derived for the plant coupled to variable temperature heat reservoirs at constant gas velocity and constant Mach number conditions.

WU, Chih, Professor, He, J., and Chen J., "Ecological Optimization of a Multi-Stage Irreversible Combined Refrigeration System," *Energy Conversion and Management*, Vol. 43, No. 17, pp. 2379-2393, 2002.

A general cycle model of an irreversible Stirling heat engine using an ideal or Van der Waals gas as the working fluids is established. It includes three main sources of the irreversibility such as the heat transfer across the finite temperature differences in the isothermal processes, the regenerative loss resulting from the non-perfect regeneration in the regenerator, and the heat leak loss between the external heat reservoirs. The ecological function is taken as an objective function of the optimization. The performance characteristics of the Stirling heat engine at maximum ecological function are revealed.

WU, Chih, Professor, Chen, L., and Sun, F., "Performance Analysis for an Irreversible Variable Temperature Heat Reservoir Closed Intercooled Regenerated Brayton Cycle," *Energy Conversion and Management*, Vol. 44, No. 17, pp. 2713-2732, 2003.

The analytical formulae for dimensionless power and efficiency, as functions of the total pressure ratio, the intercooling pressure ratio, the component effectiveness, the compressor and turbine efficiencies and the thermal capacity rates of the working fluid and the heat reservoirs, the pressure recovery coefficients, the heat reservoir inlet temperature ratio, and the cooling fluid in the intercooler and the cold side heat reservoir inlet temperature ratio are derived for a closed intercooled regenerated Brayton cycle. The intercooling pressure ratio is optimized for optimal power and optimal efficiency, respectively. The effect of the component effectiveness, the compressor and turbine efficiencies, the pressure recovery coefficients, the heat reservoir inlet temperature ratio, and the cooling fluid in the intercooler and the cold side heat reservoir inlet temperature ratio on optimal power and its corresponding intercooling pressure ratio, as well as optimal efficiency and its corresponding intercooling pressure ratio are analyzed by detailed numerical examples.

WU, Chih, Professor, Chen, L., and Sun, F., "The Universal Power and Efficiency Characteristics for Irreversible Reciprocating Heat Engine Cycles," *European Journal of Physics*, Vol. 24, No. 4, pp. 359-366, 2003.

The performance of irreversible reciprocating heat engine cycles with heat transfer loss and friction-like term loss is analyzed using finite-time thermodynamics. The universal relations between the power output and the compression ratio, between the thermal efficiency and the compression ratio, and the optimal relation between the power output and the efficiency of the cycles are derived. Moreover, analysis and optimization of the model were carried out in order to investigate the effect of cycle processes on the performance of the cycle using numerical examples. The results obtained herein include the performance characteristics of irreversible reciprocating Diesel, Otto, Atkinson, and Brayton cycles.

WU, Chih, Professor, Chen, L., and Sun, F., "Optimal Performance of an Irreversible Absorption Refrigerator," *Exergy, an International Journal,* Vol. 2, No. 3, pp. 167-172, 2002.

An irreversible model of absorption refrigerator with heat transfer law is made. The relations between the optimum COP and the cooling load and the optimum distribution of the heat transfer surface areas of the heat exchangers are derived.

WU, Chih, Professor, Sun, F., and Chen, L., "Effect of Friction on the Performance of Dual Cycle," *Exergy, an International Journal*, Vol. 2, No. 4, pp 340-344, 2002.

An irreversible air standard Dual cycle model is proposed. The analytical formulas of power output versus compression ratio and efficiency versus compression ratio of the cycle are derived.

WU, Chih, Professor, Chen, L., and Sun, F., "Performance Comparison of an Irreversible Closed Brayton Cycle Under Maximum Power Density and Maximum Power Conditions," *Exergy, an International Journal*, Vol. 2, No. 4, pp 345-351, 2002.

In this paper, power density is taken as objective for performance analysis of an irreversible closed Brayton cycle coupled to constant-temperature heat reservoirs. The analytical formulas about the relations between power density and pressure ratio are derived with the heat resistance losses in the hot- and cold-side heat exchangers and irreversible compression and expansion losses in the compressor and turbine.

WU, Chih, Professor, "Power, Power Density and Efficiency Optimization of an Endorevrsible Braysson Cycle," *Exergy, an International Journal*, Vol. 2, No. 4, pp 380-386, 2002.

The performance optimization of an endoreversible Braysson cycle with heat resistance losses in the hot- and cold-side heat exchangers is performed. The analytical relations between the power output and the working fluid temperature ratio, between the power density and the working fluid temperature ratio, as well as between the efficiency and the working fluid temperature ratio of the cycle coupled to constant-temperature heat reservoirs are derived.

WU, Chih, Professor, Lin, G., Chen, J., and Hua, B., "The Equivalent Combined Cycle of an Irreversible Chemical Pump and its Performance Analysis," *International Journal of Ambient Energy*, Vol. 23, No. 2, pp. 97-102, 2002.

A chemical potential transformer operating among three reservoirs at different chemical potentials is analogous to a heat transformer operating among three heat reservoirs at different temperatures. When the influence of finite rate mass transfer between the working fluid and the reservoirs is taken into account, the chemical potential transformer may be conceived as a combined system having a chemical pump driven by a chemical engine. The fundamental optimal relations of the chemical engine and pump operating between two reservoirs are used to derive the fundamental optimal relations of the chemical potential transformer. Consequently, it is proved that such a combined cycle system is equivalent to the chemical potential transformer operating among three heat reservoirs at different chemical potentials.

WU, Chih, Professor, Chen, L., and Sun, F., "The Influence of Heat Transfer Laws on the Performance Characteristics of a Magnetic Stirling Refrigeration Cycle," *International Journal of Ambient Energy*, Vol. 24, No. 2, pp. 75-82, 2003.

The influence of irreversibilities of the finite-rate transfer between the working substance and the external heat reservoirs and the regenerative loss in the regenerative processes on the performance of a magnetic Stirling refrigerator is considered. Based on a general expression of the magnetization intensity of a ferromagnetic material and a class of heat transfer laws, the fundamental optimum relations between the cooling rate and the coefficient of performance and between the power input and the coefficient of performance are derived. The general characteristic curves of the cycle are presented. The influence of heat transfer laws on the performance of the cycle is discussed in detail. these results obtained here are very general. They include the optimal performance of not only a magnetic Stirling refrigeration cycle but also a magnetic Carnot refrigeration cycle.

WU, Chih, Professor and Nikulshin, V., "Exergy Efficiency Calculation of Energy Intensive Systems by Graphs," *International Journal of Applied Thermodynamics*, Vol. 5, No. 2, pp 67-74, 2002.

In the design and operation of energy intensive systems, the problem of improving its efficiency is very important. The main way to solve this problem is thermodynamic analysis. This paper describes the general approach for calculating the exergy efficiency of complex energy intensive systems with arbitrary structure. A novel general equation of systems exergy efficiency is provided. An example of the method applied to a nuclear power plant analysis is given.

WU, Chih, Professor, Chen, L., and Sun, F., "Cooling Load Density Characteristics of an Endoreversible Variable-Temperature Heat Reservoir Air Refrigerator," *International Journal of Energy Research*, Vol. 26, No. 10, pp. 881-892, 2002.

The performance optimization of an endoreversible air refrigerator with variable temperature heat reservoirs is carried out by taking the cooling load density as the optimization objective in this paper. The analytical relations of cooling load, cooling load density and COP are derived with the heat resistance losses in the hot-and cold-side heat exchangers.

WU, Chih, Professor, (co-author) "Friction Effect on the Characteristic Performance of Diesel Engines," *International Journal of Energy Research*, Vol. 26, No. 11, pp. 965-971, 2002.

An irreversible model for an air standard Diesel engine is presented. This model takes into account the finite time evolution of the cycle's compression and power strokes and it considers global losses lumped in a friction-like

term. The relationships between the power output and the compression ratio, as well as between the thermal efficiency and the compression ratio are derived.

WU, Chih, Professor and Wu, F., "Influence of Temperature Gradient on Acoustic Characteristic Parameters of Stacks in Thermoacoustic Engine," *International Journal of Engineering Science*. Vol. 24, No. 6, pp. 457-463, 2003.

Several acoustic characteristic parameters including propagation constants, impendence, and transmission loss are used to describe acoustic characteristics of a stack in thermoacoustic engine. The transfer matrix equation of the thermoacoustic stack and additional stacks are established. The expressions of important acoustic characteristic parameters of them are then derived. Theoretical calculation results show that the imposed temperature gradients have influence on the acoustic characteristic parameters of two kinds of stacks. For additional stacks, thermoacoustic source is zero due to lack of longitudinal temperature gradients. The expressions of propagation constant, characteristic impendence are special forms of those of the thermoacoustic stack. Theoretical calculation results of the acoustic characteristic parameters of the thermoacoustic stack are also presented to verify the application of the model built in this paper.

WU, Chih, Professor, Chen, L., and Sun, F., "Finite Time Thermodynamic Performance for a Class of Irreversible Refrigerators," *International Journal of Power and Energy Systems*, Vol. 22, No. 1, pp. 44-49, 2002.

The effect of heat resistance and heat leak on the performance of irreversible refrigerators using a generalized heat transfer law is analyzed. The relationship between the optimal cooling load and the COP for a steady state irreversible refrigerator is derived.

WU, Chih, Professor, Chen, L., and Sun, F., "Effect of Heat Transfer on the Performance of Thermoelectric Generator," *International Journal of Thermal Science*, Vol. 41, No. 1, pp 95-99, 2002.

The performance analysis of a thermoelectric heat pump is performed using the method of finite time thermodynamics and non-equilibrium thermodynamics. The heating load and coefficient of performance expressions of the heat pump are derived with consideration of heat transfer irreversibility in the heat exchangers between the heat pump and the external heat reservoirs as well as other internal irreversibility. Numerical examples are made.

WU, Chih, Professor, Chen, L., and Sun, F., "Power and Efficiency Performance of an Endoreversible Braysson Cycle," *International Journal of Thermal Science*, Vol. 41, No. 2, pp. 201-205, 2002.

The analytical formulas about the relations between power density and pressure ratio are derived with the heat resistance losses in the hot- and cold-side heat exchangers and the irreversible compression and expansion losses in the compressor and turbine of an endoreversible Braysson cycle. The maximum power density optimization is performed in order to search the optimum heat conductance distribution corresponding to the optimum power density of in the hot- and cold-side heat exchangers for the fixed heat exchanger inventory.

WU, Chih, Professor and TUTTLE, Kenneth, Associate Professor, "Computer-based Thermodynamics," *Journal of Educational Technology Systems*, Vol. 30, No. 4, pp. 427-436, 2002.

A new computer-based approach to teaching thermodynamics is being developed and tried by two mechanical engineering professors at the U.S. Naval Academy. The course uses sophisticated software to work all of the homework problems, accommodates the new approach. In this course, students will progress well beyond traditional thermodynamics courses by emphasizing cycle analysis.

WU, Chih, Professor, He, J., and Chen, J., "Heat Transfer Effect on the Performance of a Magnetic Ericsson Refrigerator," *Journal of Non-Equilibrium Thermodynamics,* Vol. 27, pp. 57-69, 2002.

Heat transfer effect on the performance of a magnetic Ericsson refrigerator is performed. Analytical relationships among the cooling load, COP and temperatures are derived based on a generalized heat transfer law.

WU, Chih, Professor, Chen, L., and Sun, F., "The Optimal Performance of a Carnot Heat Pump Under the Mixed Heat Resistance Condition," *Open Systems and Information Dynamics*, Vol. 9, No. 3, pp 252-256, 2002.

The optimal performance of an endoreversible Carnot heat pump under the condition of mixed heat resistance is investigated. The relationship between the optimal coefficient of performance and the heating load is derived.

WU, Chih, Professor, Zhou, S., Chen, L. and Sun, F., "Cooling Load Density Optimization of an Irreversible Simple Brayton Refrigerator," *Open Systems and Information Dynamics*, Vol. 9, No. 4, pp 3251-3370, 2002.

The performance analysis and optimization of an endoreversible air refrigerator is carried out by taking the cooling load density, which is defined as the ratio of cooling load to the maximum specific volume in the cycle, as the optimization objective in this paper. The results obtained are different from those with the cooling load objective. Numerical examples show the effects of pressure ratio and allocation of heat exchanger inventory on the cooling load density of the refrigerator.

WU, Chih, Professor, and CARR, Matthew, Commander, (USN), "Intelligent Computer-aided Design Optimization of heat Pumps, *Structural and Multi-Disciplinary Optimization*, Vol. 24, No. 6, pp. 457-463, 2003.

This paper describes the use of an intelligent computer aided software program in design and possible refinements of vapor heat pump technology. Several different arrangements of vapor heat pumps are demonstrated. Objectives for improvements, constraints, and design optimization are performed. Using the featured software increases the engineer's efficiency and abilities in analyzing vapor heat pump designs.

Conference Proceedings

CERZA, Martin R., Associate Professor, Adams, J.C., Ireland, P.T., and Oswald, J., "A Detailed Experimental Investigation of a Perforated Heat Transfer Surface Applied to Gas Turbine Recuperators," *American Society of Mechanical Engineers (ASME) Turbo Expo 2003 - Power for Land, Sea and Air*, Atlanta, GA, paper # GT2003-38740, 16-19 June 2003.

An effort is made to explain and improve the understanding of the mechanisms behind the thermo-hydraulic performance of perforated extended surfaces used in compact heat exchangers in the laminar flow regime (Re_D = 400-2500). A transient liquid crystal Technique, which uses Helium as operating fluid, together with digital image photographic processing have been used to provide measurements of local heat transfer coefficients for this geometry. This work has found that through the use of perforated surfaces there exists a local heat transfer enhancement benefit. It has also been found that although perforations cause a partial restart of the thermal boundary layer, a significant overall surface heat transfer enhancement may not be achieved over plain surfaces. It was also found that the distance between the fin's leading edge and the point of last significant enhancement resulting from a perforation, linearly depends on Reynolds number. Local heat transfer coefficient measurements were validated by single blow experimentation of similar geometries. The transient single blow technique used the curve-matching method to compare predicted and experimental temperatures.

DEFFENBAUGH, Kristen L., Midshipman 1/C (USN), KOUL, Michelle G., Assistant Professor, and MORAN, Angela L., Associate Professor, "Environmentally Assisted Cracking Properties of AA7249 Extrusions for Aerospace Applications," *NACE 2003 Conference Paper No. 03211*, San Diego, CA, March 2003.

Two candidate replacement alloys are being considered as possible drop-in replacements for A7075-T6 extruded components on the P-3C aircraft (AA7150 and AA7249). Preliminary evaluation indicates that these alloys exhibit improved corrosion resistance without a sacrifice in strength. This paper describes an experimental program that contributes to the body of knowledge required to safely employ AA7249 in lieu of AA7075-T6. This study examines three extrusions and compares the mechanical and EAC properties of each.

FLACK, Karen A., Associate Professor, and SCHULTZ, Michael P., Assistant Professor, (Naval Architecture and Ocean Engineering Department), "Mean and Turbulent Velocity Profiles for Sand-Grain Rough Surfaces," *Proceedings, Third International Symposium on Turbulence and Shear Flow Phenomena*, Sendai, Japan, 25-27 June 2003.

Comparisons of turbulent boundary layers developing over sand-grain walls as compared to smooth walls have been made. An increase in the physical growth of the boundary layer as well as an increase in the skin-friction was measured for the sand-grain surfaces. Normalized turbulence profiles for both the smooth and rough surfaces show good agreement.

JOYCE, James A., Professor, "Investigation of Specimen Geometry Effects and Material Inhomogeneity Effects in A533B Steel," *Proceedings of 14th European Conference on Fracture*, Crakow, Poland, September 2002. (CD-ROM)

The Master Curve method and the associated reference temperature, as defined in the new test standard ASTM E1921, is rapidly moving from the research laboratory to applications in the U.S. commercial nuclear power industry. The T_o reference temperature is very robust, and it has rapidly become a tool to investigate material inhomogeneity effects and constraint effects because it is capable of measuring differences imperceptible using earlier methods that have been used to define the ductile-to-brittle transition in structural ferritic steels. Previous work by the present authors[1-2] has shown that T_o is sensitive to the specimen geometry used in its evaluation. While this geometry sensitivity is expected if shallow crack specimens are compared with deep crack specimens, a significant difference also appears to exist between deep crack C(T) and SE(B) geometries. This difference causes concern in the application of ASTM E1921 to regulatory decisions facing the US Nuclear Regulatory Commission. In this work a study is made to separate the effects of material inhomogeneity and specimen geometry for the same A533B pressure vessel material studied extensively in the previous work. The results show that the T_o differences due to material inhomogeneity can be separated from that due to specimen geometry, at least if the data set utilized is extensive enough.

JOYCE, Peter J., Assistant Professor, MOURING, Sarah E., Associate Professor (Naval Architecture and Ocean Engineering Department) and BARTON, Oscar, Jr., Associate Professor, "Residual Strength of Impact Damaged Composite Sandwich Structures," *Proceedings of the 48th* International Society for the Advancement of Material and Process Engineering (*SAMPE) 2003 Symposium and Exhibition*, Long Beach, CA, 11-15 May 2003, pp. 1915-1925.

The compression strength of fiber placed quartz/epoxy honeycomb sandwich panels subjected to impact damage was determined as part of an ONR-sponsored program. A total of twenty-four specimens were tested including four undamaged control panels and twenty panels with varying levels of impact damage. Three impact energy levels were tested (8.1 N-m, 27 N-m, and 47 N-m) using two impactor sizes. Panel specimens were tested under edgewise compression in accordance with ASTM C-364. Experimental results show that impact energy level has a strong effect on both the compressive strength and failure mode. Specifically, the compressive strength decreases with an increase in impact energy level. Edgewise compressive failure of undamaged panels is by catastrophic fiber/matrix interfacial cracking of the face sheets combined with bending-induced fiber breaks. Low impact damage as characterized by visible matrix cracking results in an insignificant change in failure mode and load. An increase to 27 N-m of impact energy causes the failure to be progressive in nature and a 15% drop in the compressive strength. Even greater impact damage (47 N-m) leads to catastrophic skin/core interfacial failure due to initial impact damage of the skin/core interface and a 37% drop in the compressive strength.

JOYCE, Peter J., Assistant Professor and BURKHARDT, John A., Associate Professor, "Survivability Modeling and Validation in Complex Rib-skin Structures", *Proceedings of the 44th AIAA/ASME/ASCE/AHS/ACS Structures, Structural Dynamics, and Materials Conference*, 7-10 April 2003, Norfolk, VA., American Institute of Aeronautics and Astronautics (AIAA) Paper No. 2003-1470, (CD-ROM)

This paper presents a coordinated effort to model, test and validate the structural response of realistic aerospace rib-skin structures in both undamaged and damaged configurations. Coordinated experimental and finite element model results are presented for an approximately nine foot long, aluminum skinned cylinders thirty inches in diameter in both undamaged and damaged configurations. The structures considered are of riveted construction and include internal structural components including bulkheads and complex stiffeners. Experimental reproduction of the highly idealized loading conditions used in the finite element models required the development of a custom

loading rig that is described in detail. In summary, the finite element models were found to predict the structural stiffness of both the damaged and undamaged structures well. As expected the finite element models did not predict structural failure well as the primary failure mechanism were, for simplicity, intentionally not model.

JOYCE, Peter J., Assistant Professor and Graf, Neil A., "Automated RTM of a Multi-Component Resin System–A Parametric Evaluation," *Proceedings of the 34th International Society for the Advancement of Material and Process Engineering (SAMPE) Technical Conference – 2002 M&P Ideas to Reality*, Vol. 34, 4-7 November 2002, Baltimore, MD, pp. 222-235.

The Polymers and Composites Branch of the Naval Air Systems Command (NAVAIR), Patuxent River, Maryland, has teamed with fellow Navy, university, and industry partners to demonstrate the viability of resin transfer molding (RTM) for the manufacture of primary structural components for naval aviation applications. One objective of this research included the design, demonstration, and evaluation of an intelligent, supervisory, computer controlled RTM process. A second objective involved the selection and characterization of candidate materials, with a focus on two-part resin systems with textile reinforcement. The goal of this program of work was to evaluate the feasibility and process error tolerance of this intelligent RTM process applied to two candidate resin systems. A study was performed to examine the effects of major process parameters including: variations in the resin component mix ratio, injection temperature, cure cycle modifications, and "aeration." This involved flat panel fabrication and a wide array of testing including physical evaluation, thermal analysis, and mechanical testing. This paper will discuss the results of this parametric study and the associated recommendations regarding intelligent RTM with the candidate material systems.

JOYCE, Peter J., Assistant Professor, MOURING, Sarah E., Associate Professor (Naval Architecture and Ocean Engineering Department), and BARTON, Oscar, Jr., Associate Professor, "Mechanical Behavior of Composite Sandwich Structures Subjected to Impact Damage," *Proceedings of the 10th US-Japan Conference on Composite Materials*, 16-18 September 2002, Stanford, CA, pp. 91-100.

The compression strength of composite sandwich panels subjected to drop-weight impact damage was determined as part of an ONR-sponsored research program. A total of twenty-four specimens were tested including four control panels, which contained no impact damage. The remaining twenty specimens had varying levels of impact damage. Three impact energy levels were tested; 6 ft-lbs, 20 ft-lbs, and 35 ft-lbs, where 6 ft-lbs represents a low energy level and 20 and 35 ft-lbs both represent high energy levels in combination with two impactor sizes, 0.5 in and 1.0 in diameter. Each panel was manufactured using fiber placement technology and consisted AQII/977-3 Astroquartz/Epoxy upper and lower face sheets and HRP/F50-5.5 Flexcore core. Panel specimens were tested under edgewise compression in accordance with ASTM C-364 using a 50-kip SATEC universal testing machine. Results show that impact energy level has a strong effect on both the compressive strength and failure mode of the panel specimens while limited data for impactor size suggests that this factor is much less important. Specifically, the compressive strength decreases with an increase in impact energy level. Edgewise compressive failure of undamaged quartz/epoxy honeycomb sandwich panels is by catastrophic fiber/matrix interfacial cracking of the face sheets combined with bending-induced fiber breaks. Low impact damage as characterized by visible matrix cracking results in an insignificant change in failure mode and load. An increase to 20 ft-lbs of impact energy causes the failure to be progressive in nature and a 15% drop in the compressive strength. Even greater impact damage (35 ft-lbs) leads to catastrophic skin/core interfacial failure due to initial impact damage of the skin/core interface (unseen by visual inspection). Failure by face sheet separation (35 ft-lbs) leads to a 37% drop in the compressive strength.

KOUL, Michelle G., Assistant Professor, CONNOLLY, Brian J., Assistant Research Professor and MORAN, Angela, L., Associate Professor, "A Comparison Study of SCC Growth Rates for AA7XXX Alloys as a Function of Bulk Aqueous Chloride Concentration and Simulated Crack Tip Chemistries," Proceedings of the *NACE 2003 Conference,* Paper No. 03515, San Diego, CA, March 2003.

Various alloys are being considered for drop-in replacement and refurbishment of corrosion and stress corrosion cracking prone AA7075-T6 (UNS A97075) components on aging military aircraft. This project evaluates three candidate aluminum alloys that meet mechanical property requirements and are thought to be superior to AA7075-T6 in terms of corrosion performance. The three alloys tested include AA7150-T7751 (UNS A97150), AA7249-

T76511, and AA7040-T7651. Environmentally assisted crack growth rates for these alloys were documented and compared to those of AA7075-T6 and AA7075-T73 in various bulk aqueous chloride environments. A study was also performed to elucidate the mechanistic importance of critical crack tip chemistries on the stress corrosion cracking behavior of these 7XXX series alloys.

LINDLER, Keith W., Professor and NUCKOLS, Marshall L., Professor (Naval Architecture and Ocean Engineering Department), "Hydrogen Fuel Storage / Delivery for a Diver Heater Using Hydrogen Catalytic Reactions," *Proceedings of the Oceans '02 MTS/IEEE Conference*, Biloxi, MS, pp. 919-924, 28-31 October 2002.

The necessity for active diver heating during long duration, cold water, swimmer delivery vehicle (SDV) operations is well established. Alternative approaches to supply this active heating requirement have covered a wide range of technologies, including thermoelectric heaters, magnesium combustion, propane/catalytic heating, and direct electrical resistive heating. While all of these methods have been shown to be capable of producing sufficient quantities of heat, each has its own inherent restrictions and interface issues when applied to an SDV operation. These issues include heater power consumption requirements that compete and detract from the power requirements for SDV propulsion, and heater packaging requirements in an already space-limited environment.

A simple hydrogen catalytic combustion heater was tested as a breath heater for deep diving applications. The high heat production demonstrated during this testing suggested that this approach could also be used as a diver heater to potentially minimize package size and power requirements and yet meet all the diver heating requirements for long duration Spec War missions. Preliminary analysis has shown that less than 0.4 kg of hydrogen could supply the 2 kW of heat needed to sustain up to 6 divers in 0°C water for up to 6 hours. This paper investigates the various methods to store and supply the hydrogen fuel.

TUTTLE, Kenneth L., Associate Professor, "Effect of Load Swings on Particulate Emissions from Solid-Waste Boilers," *Proceedings of the 18th International Conference on Solid Waste Technology and Management,* Philadelphia, PA, pp. 729-737, March 2003.

Boilers often must take swings I the steam load. Although most types of boilers are able to follow load swings, operators worry about the effect this disruption may have on the combustion process. Engineers designed an experiment to determine the effect of load swings on particulate emissions from wood-fired boilers. The results apply to any grate-fired, solid-fuel boiler. This paper presents data and results and ties them to solid-waste fired boilers. This is an unsteady-state experiment. Data recorded during step changes in the fuel-feed rate reflect both increases and decreases. The related steady-state emissions data bracket both the step up and the step down. The analysis compares emissions during a step change in fuel-feed rate to emissions from bracketing steady-state test points.

VOLINO, Ralph J., Associate Professor, "Passive Flow Control on Low-Pressure Turbine Airfoils," *Proceedings of the 2003 American Society of Mechanical Engineers (ASME) International Gas Turbine Conference*, Atlanta, GA, June 2003. (CD-ROM)

Two-dimensional rectangular bars have been used in an experimental study to control boundary layer transition and reattachment under low-pressure turbine conditions. Cases with Reynolds numbers (*Re*) ranging from 25,000 to 300,000 (based on suction surface length and exit velocity) have been considered at low (0.5%) and high (8.5% inlet) free-stream turbulence levels. Three different bars were considered, with heights ranging from 0.2% to 0.7% of suction surface length. Mean and fluctuating velocity and intermittency profiles are presented and compared to results of baseline cases from a previous study. Bar performance depends on the bar height and the location of the bar trailing edge. Bars located near the suction surface velocity maximum are most effective. Large bars trip the boundary layer to turbulent and prevent separation, but create unnecessarily high losses. Somewhat smaller bars had no immediate detectable effect on the boundary layer, but introduced small disturbances which caused transition and reattachment to move upstream from their locations in the corresponding baseline case. The smaller bars were effective under both high and low free-stream turbulence conditions, indicating that the high free-stream turbulence transition is not simply a bypass transition induced by the free-stream. Losses appear to be minimized when a small separation bubble is present, so long as reattachment begins far enough upstream for the boundary layer to recover from the separation. Correlations for determining optimal bar height are presented. The bars appear to provide a simple and effective means of passive flow control. Bars which are large enough to induce

reattachment at low *Re*, however, cause higher losses at the highest *Re*. Some compromise would, therefore, be needed when choosing a bar height for best overall performance.

VOLINO, Ralph J., Associate Professor, "Separation Control on Low-Pressure Turbine Airfoils Using Synthetic Vortex Generator Jets," *Proceedings of the 2003 American Society of Mechanical Engineers (ASME) International Gas Turbine Conference*, Atlanta, GA, June 2003. (CD-ROM)

Oscillating vortex generator jets have been used to control boundary layer separation from the suction side of a low-pressure turbine airfoil. A low Reynolds number (*Re*=25,000) case with low freestream turbulence has been investigated with detailed measurements including profiles of mean and fluctuating velocity and turbulent shear stress. Ensemble averaged profiles are computed for times within the jet pulsing cycle, and integral parameters and local skin friction coefficients are computed from these profiles. The jets are injected into the mainflow at a compound angle through a spanwise row of holes in the suction surface. Preliminary tests showed that the jets were effective over a wide range of frequencies and amplitudes. Detailed tests were conducted with a maximum blowing ration of 4.7 and a dimensionless oscillation frequency of 0.65. The outward pulse from the jets in each oscillation cycle causes a disturbance to move down the airfoil surface. The leading and trailing edge celerities for the disturbance match those expected for a turbulent spot. The disturbance is followed by a calmed region. Following the calmed region, the boundary layer does separate, but the separation bubble remains very thin. Results are compared to an uncontrolled baseline case in which the boundary layer separated and did not reattach, and a case controlled passively with a rectangular bar on the suction surface. The comparison indicates that losses will be substantially lower with the jets than in the baseline or passively controlled cases.

VOLINO, Ralph J., Associate Professor, and Murawski, Christopher G., Separated Flow Transition in a Low-Pressure Turbine Cascade – Mean Flow and Turbulence Spectra," *Proceedings of the 2003 American Society of Mechanical Engineers (ASME) International Gas Turbine Conference*, Atlanta, GA, June 2003. (CD-ROM)

Boundary layer separation, transition and reattachment have been studied experimentally in a low-pressure turbine cascade. Cases with Reynolds numbers (*Re*) ranging from 50,000 to 200,000 (based on suction surface length and exit velocity) have been considered under low free-stream turbulence conditions. Mean and fluctuating velocity profiles and turbulence spectra are presented for streamwise locations along the suction side of one airfoil and in the wake downstream of the airfoils. Hot film gages on the suction side surface of the airfoil are used to measure the fluctuation level and the spectra of the fluctuations on the surface. Higher *Re* moves transition upstream. Transition is initiated in the shear layer over the separation bubble and leads to boundary layer reattachment. Peak frequencies in the boundary layer spectra match those found in similar cases in the literature, indicating that the important frequencies may be predictable. Spectra in the wake downstream of the airfoils were similar to the spectra in the boundary layer near the trailing edge of the airfoil. Comparisons to the literature indicate that small but measurable differences in the spectra of the low free-stream turbulence can have a significant effect on boundary layer reattachment.

Books

TUTTLE, Kenneth L., Associate Professor (co-author), "Thermodynamics: A Computer-Based Approach," Kendall/Hunt Publishing Co., Dubuque, Iowa, p 292, ISBN 0-7575-0494-9, 2002, (Updated and reprinted 2003).

The book is a full-immersion, intelligent computer-aided thermodynamics text. It includes basic thermodynamic concepts, working fluid properties, First Law and Second Law analysis for control mass and control volume systems. In addition, this textbook includes more sophisticated thermodynamic cycle analysis and related fuel and engine basics. This textbook is the first computer software manuscript of its kind in thermodynamics.

WU, Chih, Professor, "Intelligent Computer Based Elementary Applied Thermodynamics," Kendall/Hunt Publishing Co., ISBN 0-7872-9388-1, 2002.

The book is immersion intelligent computer aided thermodynamics for non-engineering major students. Included are basic concepts, finding properties, First law and Second law analysis for control mass and control volume systems, and thermodynamic cycle analysis.

WU, Chih, Professor, "Intelligent Computer Based Engineering Thermodynamics and Cycle Analysis," Nova Science Publishing Co., ISBN 1-59033-359-4, 2002.

The book is a fully immersion intelligent computer aided thermodynamics for engineering major students. Included are basic concepts, properties of thermodynamic substances, First law of thermodynamics for closed systems, First law of thermodynamics for open systems, Second law of thermodynamics, entropy, vapor cycles, gas closed system cycles, gas open system cycles, refrigeration and heat pump cycles, and finite-time thermodynamics.

Technical Reports

BURKHARDT, John A., Associate Professor and MUCCIARDI, T., Visiting Research Professor, "Sonic field map of acoustic transducer AT-0." Project Report, Naval Surface Warfare Center, Carderock Division, Code 623 (Reimbursable Order N6554002WR50385), March 2002.

The sound field of a spark driven acoustic source on an approximately 4' by 3' plane normal to the axis of the instrument is presented. As expected the sound field drops from a peak on the central axis towards the edges of the measurement plane. The rate of drop is found to be greater than expected, however.

BURKHARDT, John A., Associate Professor and MUCCIARDI, T., Visiting Research Professor, "Application of Signal Processing Techniques for Defect Detection and Depth Determination in Thick Foam Composite Plates," Project Report, Naval Surface Warfare Center, Carderock Division, Code 623 (Reimbursable Order N6554002WR50385), March 2002.

This report presents the results of a study to locate the position of subsurface flaws within thick sandwich composite panels time-domain signals measured using laser vibrometry. The technique explored uses an autocorrelation technique with the intent of locating interior reflectors by matching their shape and phase to the incident wave reflected from the surface. Initial results based on a limited set of data so the technique to be promising. Further work needs to be performed to determine the sensitivity and robustness of the technique.

GRAHAM, Stephen M., Assistant Professor, "Fracture Toughness of Alloy 718 Bar and Forging for ASDS Transit Latch Assembly," Naval Surface Warfare Center, Carderock Division, (TR-61-1999/06+CR), May 2003.

The fracture toughness and tensile properties of Alloy 718 were measured at quasi-static and dynamic loading rates for two different heat treatments and two product forms. The specimens were taken from a forging and rod stock intended for use in the ASDS Transit Latch Assembly. The forging material was scrap from one of four forgings used to fabricate the pawls for the vehicle hold-down, and the rod stock was material used to fabricate the clevices and other parts of the assembly. Consequently, the measured properties are representative of the actual material used in fabrication. The test temperature of 28°F and the loading rate were chosen to represent the worst-case in-service loading conditions. The tests showed that the heat treatment with the 1950°F solution anneal provides superior fracture toughness, tearing modulus and tensile properties when compared with the 1775°F solution anneal. Fracture toughness (K_{mat}) for the 1950°F anneal ranged from 166 to 210 ksi√in and the tearing modulus (T) ranged from 5 to 18 while the toughness for the 1775°F anneal ranged from 93 to 145 ksi√in and the tearing modulus from 1 to 6. These results are in good agreement with published data in the literature for these two heat treatments. There was no consistent effect of loading rate on fracture toughness for the range of loading rates considered (quasi-static to maximum load in about 3 milliseconds). The rod material generally showed higher

fracture toughness and tearing modulus than the forging for both heat treatments. Only the rod material in the 1950°F solution anneal meets the FTRP material screening requirements for toughness to yield ratio and tearing modulus ($K_{mat}/\sigma_{ys} \geq 1.15$ and $T \geq 10$).

GRAHAM, Stephen M., Assistant Professor, "Development of Structural Performance Based Material Screening Criteria for Metals in Transition," Naval Surface Warfare Center, Carderock Division, (TR-61-2002/02+CR), May 2003.

Certification of new welding systems for Naval ship construction involves demonstrating that the system will provide adequate structural performance under severe loading conditions. The standard certification test used by the Navy is the Explosion Bulge/Explosion Crack Starter test. This test is rather extreme in the level of plastic deformation developed in the plate, and can be very expensive. For certification purposes it would be desirable to develop relevant structural performance requirements and then use a simple, inexpensive test to determine if the welding system will meet the requirement. The objective of this study was to determine what combination of material properties the weld system must have to obtain the required performance. Scaling models are presented that compare a typical surface ship hull detail with the traditional Explosion Crack Starter specimen. Failure probabilities were calculated using the Weibull stress concept, the transition temperature and the Master Curve. The transition temperature and probability of failure are incorporated into criteria that the weld system must meet to ensure that the structure will have the desired performance. A series of tests on HSLA-65 welds was analyzed to validate the proposed approach.

SMITH, Russell, A., Professor Emeritus, MINER, Steven M., Professor, MORAN, Patrick J., Professor and BUCALO, Frank (Naval Academy technical support staff), "Effects of Center of Mass Location on Putter Performance," STX Report, March 2003.

Tests were conducted in which variables included the location of the center of mass and conditions in which the ball was struck in the swing plane and at two locations on the club face of the putter. The results for standard deviation about the mean for groups of 25 putts exhibited smaller values for lowered center of mass, balls struck at the center mark of the club and balls struck at the bottom of the pendulum swing. Measures of distance from the swing plane defined by means of the groups of 25 putts suggest that the distance between the putter face point of impact and the twist axis of the putter is an important variable influencing accuracy.

RATCLIFFE, Colin P., Associate Professor and Crane, Roger, "A Report on the Long-Term Health Monitoring of the Composite Road Bridge On Route 896, Delaware," Naval Surface Warfare Center, Carderock Division (65-TR-2003/09), March 2003.

This paper presents the results of an ongoing investigation that uses broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. More specifically, this paper presents results of the fourth inspection of the bridge I-131 on Business Route 896 located in Glasgow, Delaware. The bridge consists of two E-Glass/vinyl ester sections (each 13-ft x 32 ft) joined by a longitudinal joint in the traffic direction. Each section is a sandwich construction consisting of a 28-inch deep core and a 0.5-0.6 inch thick facesheets. The bridge deck configuration is representative of the deck for the JMLS and the LPD-17 masts that are currently under construction. This fourth vibration inspection was performed to establish the changes that are occurring during the service life of this civil structure. Demonstrating the ability to determine the structural health and any degradation in properties of the Route 896 bridge in its service environment would illustrate the utility of the broadband vibration technique for Navy structures. In addition to presenting a comparison of the modal results with those obtained from previous years, this fourth report in the bridge inspection series also presents the latest developments in the SIDER test method that includes an improved algorithm and an improved method of presentation. This improved SIDER analysis is also conducted on the prior years testing information, and the results are presented herein. Since the SIDER analysis has been substantially developed and modified since the third inspection effort on the bridge, this report details those changes. The SIDER results locate local variations in a structure, and how that variation is changing with time. This SIDER analysis is a further development to establish and create a vibration-based non-destructive evaluation method suitable for long-term inspection of large scale composite Naval structures.

RATCLIFFE, Colin P., Associate Professor and Crane, Roger, "SIDER Testing of the Half-Scale Composite Corvette Hull Section," Naval Surface Warfare Center, Carderock Division (65-TR-2002/18; 60 pages), September 2002.

The half-scale composite ship hull section was designed, manufactured and tested under joint US/Germany project agreement RTP-US-GE-N-95-0002. This report details the SIDER test of the hull section. The SIDER was conducted immediately prior to, and immediately after the UNDEX shock test that took place in May 2002. For the SIDER tests, the hull, shown in Figure 1, was located at the German Navy Base Olpenitz. The base is about half an hour's drive north of Eckernfoerde, Germany. The initial setup and preliminary SIDER data acquisition were conducted from May 8 through May 11, 2002. The follow-up SIDER data acquisition took place from June 1 through June 3, 2002.

RATCLIFFE, Colin P., Associate Professor and Wittig, Michael, (Office of Naval Research SEAP student), "Improvement in the SIDER Damage Detection Algorithm by Enabling a Variable Size Measurement Grid," U.S. Naval Academy Engineering and Weapons Division Technical Report EW-03-02, August, 2002.

Curvature approximation algorithms were developed that allow for variability in the spacing of the data points. The two algorithms developed use the second derivatives of interpolated polynomials, differing in the number of points used per interpolating polynomial. The development of a custom 4x4 matrix inversion routine is also covered. The completed algorithms were incorporated into SIDER and improved flexibility and precision when applied to real structures. This report also includes details of other activities undertaken during the SEAP summer period, including tests of the SIDER program.

TUTTLE, Kenneth L., Associate Professor and WU, Chih, Professor, "Using Articulate Virtual Laboratories in Teaching Engineering Thermodynamics and Energy Conversion," Report on Grant No. N0001402WR20280 to Office of Naval Research, Cognitive and Neural Science & Technology Division, July 2002.

The goal is to develop an evaluative study and perform evaluation studies of computer-based thermodynamics and energy conversion instruction for courses taught at U. S. Naval Academy. Progress for the period from 1Jul01 to 30Jun02 includes the following list of accomplishments in addition to developing an evaluative study:

- Wrote and published three thermodynamics textbooks dedicated to teaching computer-based thermodynamics using CyclePad.
- Wrote ten peer-reviewed papers related to this research including:
    - Three Journal Articles that have been published,
    - Two Journal Articles that are in press being published,
    - Two Journal Articles that have been accepted for publication, and
    - Two Proceeding Articles that have been presented at professional conferences.
- Attended two professional, technical conferences.
- Developed and taught EM485D, Thermodynamics: A Computer-Based Approach, with full immersion in computer-based instruction using CyclePad and a textbook written for the course.
- Developed and taught a special section of EM300, with partial immersion in computer-based instruction using CyclePad and the compatible textbook written for the course.
- Developed and taught EM443, an energy conversion elective for engineers, with partial immersion in computer-based instruction using CyclePad.
- Developed a proposal to evaluate computer-based thermodynamics at the U.S. Naval Academy.
- Determined ways to measure the effectiveness of teaching computer-based thermodynamics.
- Developed a plan for evaluating computer-based thermodynamics at the U.S. Naval Academy.
- Set goals for an assessment plan.
- Requested permission to conduct research involving human subjects at the U.S. Naval Academy.

- Scheduled two courses, one Fall Term 2002 and one Spring Term 2003, at the U.S. Naval Academy using computer-assisted instruction and textbooks produced during this period.

Book Chapters

SMITH, Andrew N., Assistant Professor and Norris, Pamela M., "Microscale Heat Transfer," Eds. A. Bejan and A.D. Kraus, Heat Transfer Handbook, chapter in book published by John Wiley & Sons, Inc., pp. 1309-1357, ISBN 0-471-39015-1, 2003.

Presentations at Professional Meetings and Conferences

BURKHARDT, John A., Associate Professor and JOYCE, Peter J., Assistant Professor, "Survivability Modeling and Validation in Complex Rib-skin Structures," 44th AIAA/ASME/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Norfolk, VA, April 2003.

BURKHARDT, John A., Associate Professor, "Inverse Radiative Transfer for the Determination of Acoustic Scattering Cross Section," NATO Advanced Study Institute on Wave Scattering in Complex Media. Cargese, Corsica, France, June 2002.

CERZA, Martin R., Associate Professor, Bar-Cohen, Avram Bar-Cohen (University of Maryland, College Park) and Joshi, Yogendra (Georgia Institute of Technology), Office of Naval Research Workshop to Assess Naval Thermal Management Needs, U.S. Naval Academy, Annapolis, MD, 8-9 April 2003.

CERZA, Martin R., Associate Professor, "Assessment of Navy Thermal Management Needs and Future Technologies for Next Generation Naval Systems," A Workshop on Thermal Packaging of High Flux Military and Commercial Electronics, University of Maryland, College Park, MD, 7 October 2002.

CONNOLLY, Brian J., Assistant Research Professor, KOUL, Michelle G., Assistant Professor, and MORAN, Angela L., Associate Professor, "A Comparison Study of SCC Growth Rates for AA7XXX Alloys as a Function of Bulk Aqueous Chloride Concentration and Simulated Crack Tip Chemistries," NACE 2003, San Diego, CA, March 2003.

CONNOLLY, Brian J., Assistant Research Professor, KOUL, Michelle G., Assistant Professor, and MORAN, Angela L., Associate Professor, "An Environmentally Assisted Long Crack Growth Study of 7XXX Series Aluminum Alloys in T7XXX Conditions," ICI-ORR: 43rd Corrosion Science Symposium, Cardiff, Wales, October 2002. (Invited presentation)

CONNOLLY, Brian J., Assistant Research Professor, KOUL, Michelle G., Assistant Professor, and MORAN, Angela L., Associate Professor, "Evaluation of Environmentally Assisted Crack Propagation Rates of Candidate Aluminum Alloys for Replacement of AA7075-T6 Aircraft Structures," Gordon Conference on Aqueous Corrosion, New London, NH, August 2002. (Poster presentation)

DEFFENBAUGH, Kristen L., Midshipman 1/C (USN), KOUL, Michelle G., Assistant Professor, and MORAN, Angela L., Associate Professor, "Environmentally Assisted Cracking Properties of AA7249 Extrusions for Aerospace Applications," NACE 2003, San Diego, CA, March 2003.

FLACK, Karen A., Associate Professor, and Smith, G. B., "Surface Temperature Field Statistics at an Air/Water Interface for Grid-Generated Sub-Surface Turbulence," American Society of Mechanical Engineers (ASME) Fluids Engineering Division Summer Meeting, Montreal, Canada, 14 -18 July 2002.

GRAHAM, Stephen M., Assistant Professor, "Fundamentals of Fracture Mechanics: Applications to Fracture Toughness Testing,," Short course presented to Electric Boat Corporation, Groton, CT, 9-10 June 2003.

KOUL, Michelle G., Assistant Professor, Cooper, K. R., Williams, J. M., Kelly, R. G. and Peeler, D. T., "Quantitative Analysis of Intergranular and Exfoliation Corrosion of Wingskin Materials," Aging Aircraft Conference, San Francisco, CA, September 2002. (Poster presentation)

KOUL, Michelle G., Assistant Professor, "Topographical Analysis of Corrosion Damage in AA775-T6 Using Laser Profilometry," Gordon Conference on Aqueous Corrosion, New London, NH, August 2002. (Poster presentation)

RATCLIFFE, Colin P., Associate Professor, "Bridge Evaluation Workshop: Field Load Testing & Long-Term Monitoring," University of Delaware, Newark DE, March 2002.

SMITH, Andrew N., Assistant Professor, "Thermal Analysis of EM Railgun," 19th Electromagnetic Launch Association Conference, Austin, TX, October 2002.

TUTTLE, Kenneth L., Associate Professor, "Effect of Load Swings on Particulate Emissions from Solid-Waste Boilers," 18th International Conference on Solid Waste Technology and Management, Philadelphia, PA, March 2003.

VOLINO, Ralph J., Associate Professor, "Passive and Active Flow Control on Low-Pressure Turbine Airfoils," National Aeronautics and Space Administration (NASA) Glenn Research Center, Cleveland, OH, 25 July 2002.

VOLINO, Ralph J., Associate Professor, "Passive and Active Flow Control on Low-Pressure Turbine Airfoils, Air Force Research Laboratory, Wright Patterson Air Force Base, Dayton, OH, 5 September 2002.

VOLINO, Ralph J., Associate Professor, "Separation Control Using Synthetic Vortex Generator Jets," 55th Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Dallas, TX, 25-26 November 2002.

WU, Chih, Professor, "Exergy Efficiency Calculation of Power Plant Based on Exergy Flow Graph," 13th International Symposium on Transport Phenomena, Victoria, British Columbia, Canada, 14 -18 July 2002.