Waste Heat Recovery in Military Applications

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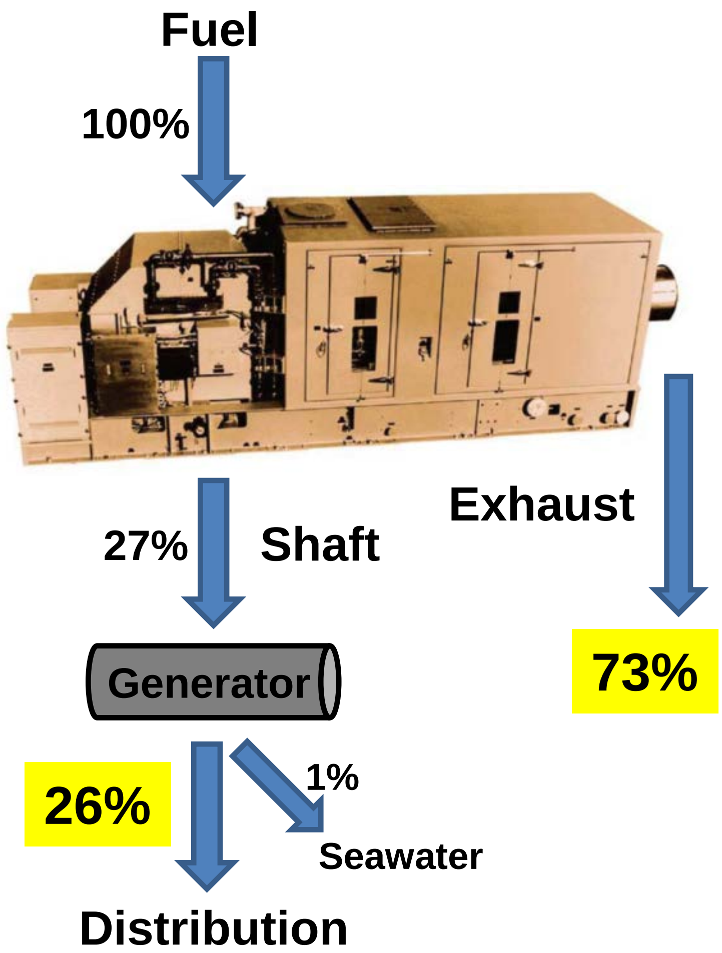
ACCELERATING TO THE NAVY & MARINE CORPS AFTER NEXT

Heat Recovery Benefit

- Two-thirds of the energy from DoD’s fuel is lost as waste heat.
- Capturing and converting that heat into useful energy could:
  - Increase mission endurance and operational reach through reduced fuel consumption
  - Enhance operational capabilities by providing additional power for electronic weapons and sensors
  - Reduce fuel consumption lightening logistic burden



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Heat Recovery Challenge

- **What form of energy recovery makes the most sense?**
  - Mechanical
    - Turbine recovery coupled directly to propulsion
  - Thermal
    - Provide space or hot water heating (cogeneration)
    - Heat driven cooling (absorption/adsorption)
  - Electrical
    - Power produced from turbine cycle or solid-state generator
- **How can energy recovered be integrated into platform to reduce fuel consumption and/or improve capability?**
  - Platform must be able to use additional energy to reduce fuel consumption
  - Thermodynamics dictates that bottoming cycles are less power dense than primary cycles

US Navy Experience

- USN has invested over $100M in waste heat recovery developments for shipboard gas turbines from 1960 to the present. The three major programs were:
  - 600 Hp Orenda gas turbine for minesweepers (two recuperators per engine)
  - Steam waste heat recovery for DDG-51 (RACER Boiler & Turbine using LM2500 exhaust heat)
  - 26,250 Hp Rolls Royce ICR gas turbine (Used intercooler and recuperator to recover heat from gas turbine exhaust)
- Each development program was successful in saving large amounts of fuel, but did not finish development or satisfy requirements for the following reasons.
  - Did not meet reliability expectations
  - Difficult to troubleshoot, maintain and repair
  - Thermal fatigue and expansion deformation

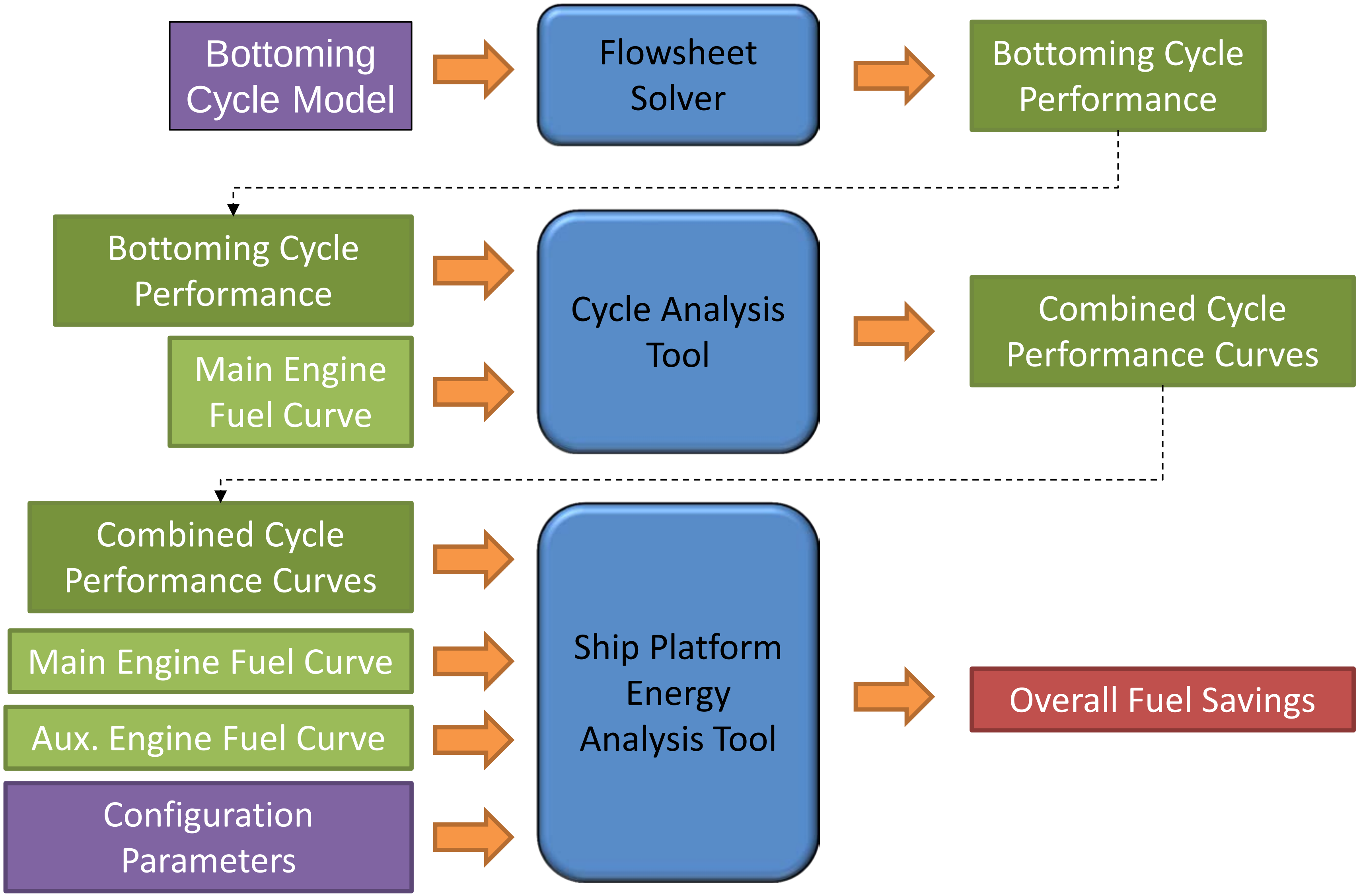
Lessons Learned

- The energy recovery heat exchanger presents the greatest technical challenge
  - Pressure drop on the prime mover
  - Fouling
  - Corrosion
  - Thermal stresses (induced by thermal transients)
  - Brazing during the manufacturing process
- Reliability cannot be sacrificed at the expense of performance

OECIF WHR Program

- Evaluate the efficacy of recovering waste heat to save fuel in various military systems
  - Application Analysis Tool
    - Simplify and standardize predictions of the fuel savings that can be achieved with the implementation of a WHR system.
  - Integration Study
    - Assess technical risks, estimate installation cost, and document impacts associated with integrating a WHR system into a Naval combatant.
  - System Demonstration
    - Assess reliability and effectiveness of exhaust gas heat exchanger and bottoming cycle.
- Metrics
  - Previous studies have shown potential to increase fuel efficiency by 10-15% for turbine generators
  - Power density cannot be neglected (50 lbs/kW)
- Period of Performance: Jul 2015 – Dec 2017

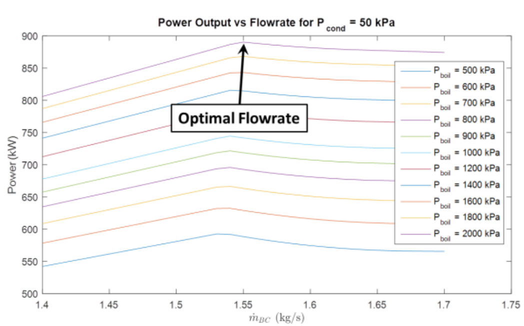
Analysis Tool

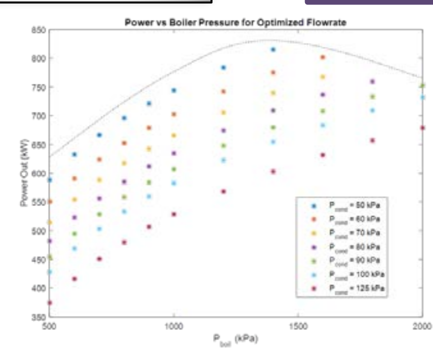


Cycle Applications

- **Bottoming cycles**
  - Steam Rankine
  - Organic Rankine
  - Supercritical CO_2
  - Air Brayton
  - Thermoelectric
- **Gas turbine cycles**
  - Multi-stage compressors/spools
  - Intercooling
  - Reheat cycles
  - Recuperators
  - Steam injection

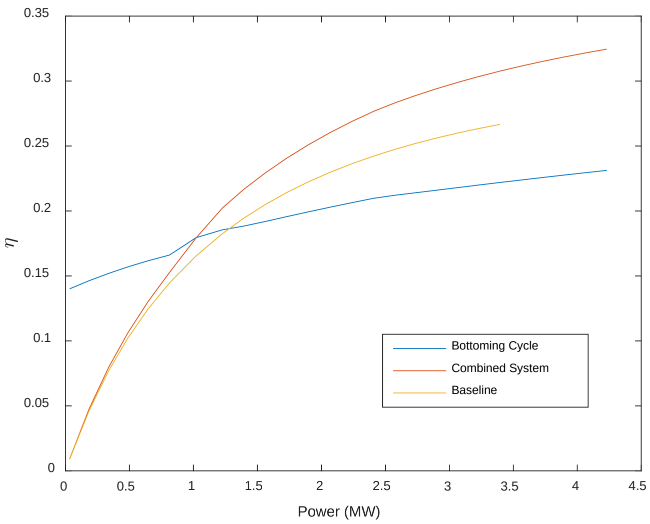
Model Results (i,j,k) → Determine Optimal BC Flowrate → $\dot{m}_{opt}(i,j)$ **Flow-optimized Model Results (i,j)** → Generate Plots of Trade Space Performance



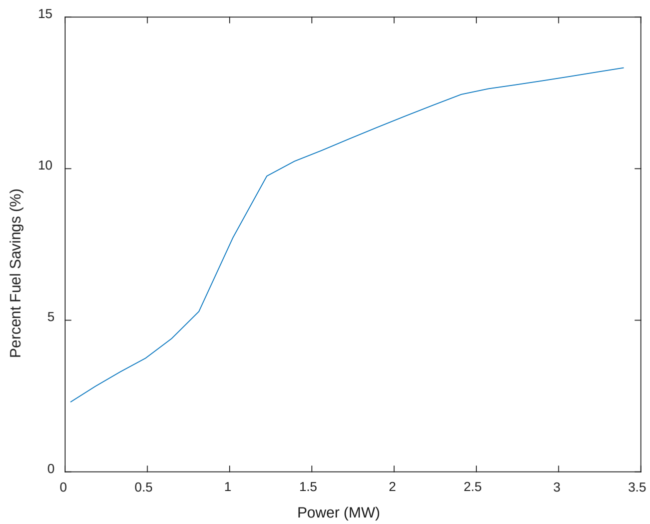


Cycle Analysis Tool

- **Performs power sweep of engine + bottoming cycle (BC) combinations**



- **Calculate performance data over full performance range**
  - **Fuel consumption vs. load**
  - **Fuel savings vs. engine only**



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Ship Integration Study

- The objective of the study is to inform decision-makers of the complexity, technical risks, and installation costs of back-fitting a waste heat recovery (WHR) system into a Navy surface combatant.
- Study focuses on integrating a WHR system with a Ship Service Gas Turbine Generator on a DDG 51 Flight IIA Platform
  - System being evaluated is the Echogen Power Systems EPS15M 800 kW model

Design Report

- **Major points to be covered:**
  - Notional locations and arrangements sketches
  - Optimized WHR system design including benefits, impacts, and maintainability
  - WHR system interfaces, integration plan, and ship system impacts
  - Itemized list of major equipment to be displaced and system departures from specification
  - Exhaust air interface study
  - Ship installation route/plan and impacts
  - Cost assessment
    - Describe cost assessment criteria and calculation methods
    - Determine installation costs
  - Notional ship availability and schedule
    - Develop a ROM installation schedule analysis
    - Work sequence estimate (notional ship availability installation estimate)
  - Qualification test parameters and cost

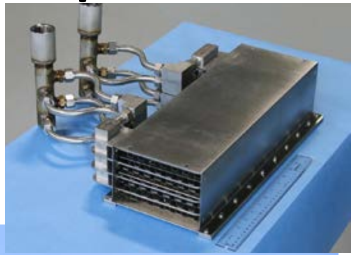
Exhaust Heat Recovery HEX

OBJECTIVE: Develop and demonstrate a durable, long-life heat exchanger suitable for recovering waste heat from highly transient exhaust combustion air ranging in temperature from 500 to 1200 °F.

- **Pressure drop across the combustion air side of the heat exchanger shall be less than 4 inches of water**
- **Capable of withstanding a thermal shock when a non-aqueous fluid at 60 °F enters a 1200 °F heat exchanger**

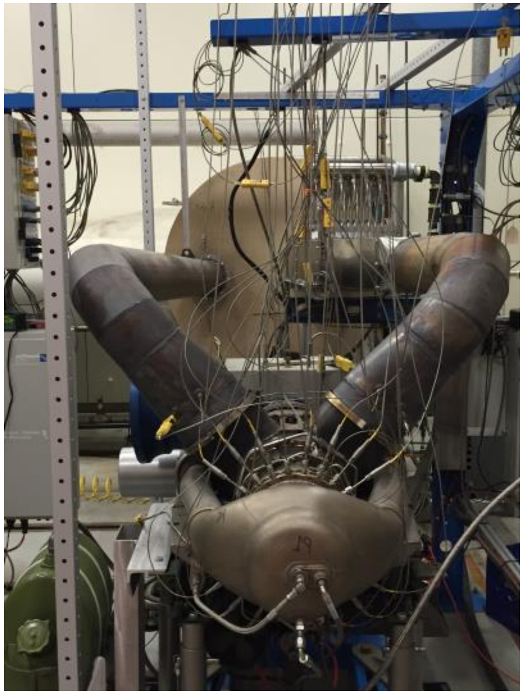
Creare Phase II SBIR (ONR)

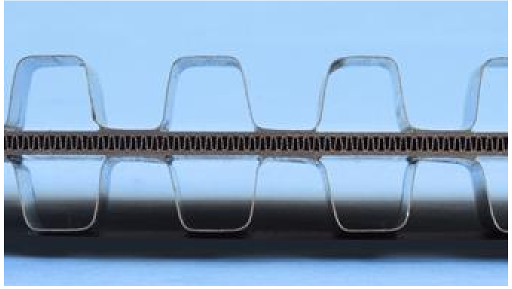
- **Designed and built a 1:18 scale prototype based on plate-fin design**
- **Performed effects tests (braze integrity, pressure testing, thermal shock)**
- **Testing with gas turbine engine at US Naval Academy**

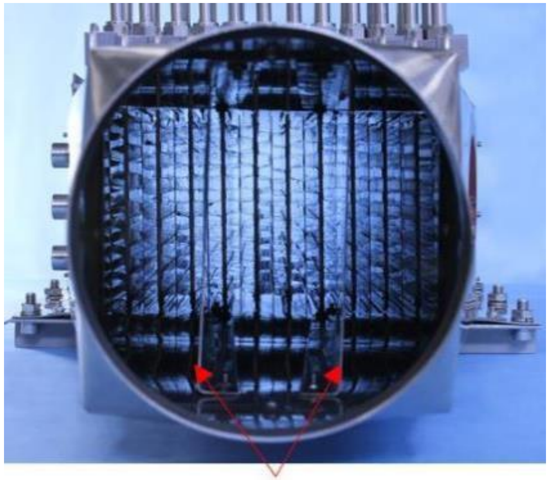


Exhaust Heat Recovery HEX

- **HEX installed and instrumented on a Rolls Royce T63 (250 hp) gas turbine at the USNA**
  - **Testing commenced Dec 2016**





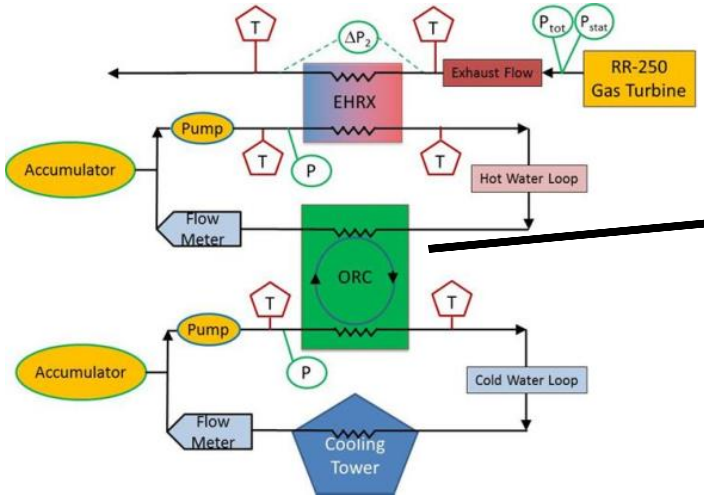


Adjustable Inlet Baffles

Exhaust Heat Recovery HEX

OBJECTIVE: Demonstrate effectiveness of energy recovery system suitable for recovering waste heat from highly transient exhaust combustion typical of military turbine.

- **Scale up heat exchanger panel to size needed for RR-501KB5 (3 MW) application**
  - **Approx 24” x 60” x 1” (vs 6” x 15” x 1”)**
- **Integrate with Rolls Royce T63 gas turbine and COTS Organic Rankine Cycle system**
- **Demonstrate HEX performance and power production with waste heat**



Path Forward

- Complete system demonstrations (early FY18)
  - Evaluate performance and reliability
  - Assess size and integration challenges
  - Validation of modeling work
- Coordinate with DOE sCO_2 Crosscut Team to leverage developments for military systems
- Coordinate service S&T investments in heat exchanger development
  - Univ of Maryland Workshop: ‘Innovative Designs, Materials, and Manufacturing of Heat Exchangers’
  - E&P COI study: ‘Additive Manufacturing Advances for Improved Thermal Management’


UNIVERSITY OF MARYLAND

S²TS SMALL AND SMART THERMAL SYSTEMS
ADVANCED HEAT AND MASS HEAT EXCHANGER LABORATORY

Innovative Designs, Materials, and Manufacturing of Heat Exchangers Workshop

October 21 and 22, 2015
University of Maryland, College Park, MD 20742

Sponsoring Organizations
Office of Naval Research (Dr. Mark Spector, Program Officer), the National Science Foundation (Dr. José L. Lage, Director), Advanced Heat Exchanger and Process Intensification at the University of Maryland

Workshop Advising Committee: Michael Ohadi (**Workshop Chair**, UMD, College Park), Mark Spector (ONR, **Workshop Co-Chair**), Arun Muley (Boeing Company); Hal Strumpf (Honeywell Aerospace); Tim Held (Echogen); Hal Stillman (International Copper Association)

Principal Investigator: Michael M. Ohadi

Other Key UMD Personnel assisting with the Workshop:
Veena Rao, Faculty Research Assistant
Farah Singer, Research Associate

This final report is submitted to Office of Naval Research ONR

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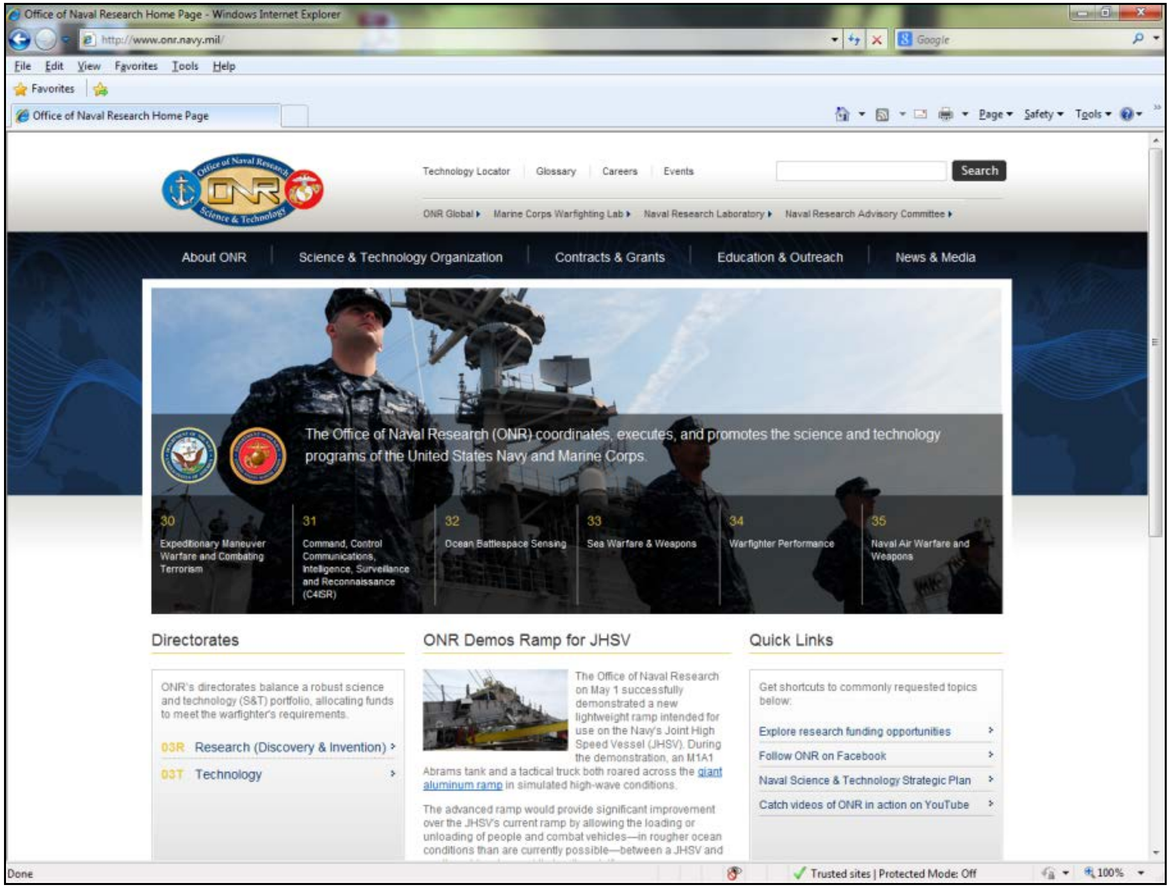
Where to Find Us



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