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High Energy Laser
for next generation ships

Turbomachinery for Man-Portable Power

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14. ABSTRACT
This issue of the WSTIAC Quarterly features an article on Ar-Xe Laser: The Path to a Robust All-Electric Shipboard Directed Energy Weapon and Turbomachinery for Man-Portable Military Power Application. Included the WSTIAC Calendar of Events and the Directors Corner. Details on several Training Courses sponsored by WSTIAC are also included in this issue.

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The feature article in this issue of the *WSTIAC Quarterly* presents the results of a basic research program that focused on a high energy laser (HEL) system for naval applications. High energy lasers, and more generally, the directed energy (DE) class of weapons, have great potential for changing the current and future battlefield. In a 2007 report, the Defense Science Board called directed energy a "transformational" capability for "facing increasingly sophisticated traditional challenges" as well as "new asymmetric and disruptive threats."[1]

Director's Corner

While the development of some forms of directed energy weapons (DEWs) has been more successful than others, the transition of DEWs as a whole from research, development, testing and evaluation, to their integration on military platforms has faced its fair share of challenges. For example, high power microwave DE systems have received significant attention primarily because of the highly successful demonstrations of the Active Denial System (ADS). This system, however, has not yet been deployed.

Similarly, the transition of high energy lasers from the laboratory to military platforms has been challenging. For instance, despite anticipation that the Airborne Laser (ABL) might be the first HEL to achieve operational capability, it has faced technical and logistical limitations and issues, thus causing program delays. Other HEL programs have faced similar challenges and there is still no operational high energy laser capability.

In the aforementioned report, the Defense Science Board noted that interest in HELs for DEW applications has declined over the past decade due to a "lack of progress." The task force that developed the report, however, did cite some promising applications of HEL systems, among other DE technologies. One such promising application is the use of HELs for "ship defense against maneuvering cruise missiles and tactical ballistic missiles."

While the Air Force must deal with the reality of gravity and thus the implications of added weight aboard an aircraft, the Navy has a little more flexibility. The authors of the feature article in this issue, Dr. Apruzese and his colleagues at the Naval Research Laboratory (NRL), have demonstrated that an argon-xenon (Ar-Xe) chemical laser system has the potential to meet the Navy's requirements for a shipboard HEL system. The Ar-Xe chemical laser is a departure from traditional chemical lasers, such as the chemical oxygen iodine laser (COIL) used for the ABL, the hydrogen fluoride (HF) laser, and the deuterium fluoride (DF) laser. This article gives an excellent, detailed synopsis of the research program as well as a recommendation for the path forward to a shipboard directed energy weapon for anti-missile defense.

I hope this article and the rest of the issue prove to be useful in your continued efforts to support our warfighters. For more information on directed energy and other weapon systems technology, please contact us at wstiac@alionscience.com or 877.978.8737. The Defense Science Board report on directed energy weapons can be found online at http://www.acq.osd.mil/dsb/reports/2007-12-Directed_Energy_Report.pdf.

In the next edition of the *WSTIAC Quarterly* we will introduce our two new technical focus areas: Cyber Warfare and Maritime Surveillance Systems.

John Weed, WSTIAC Director

[1] "Defense Science Board Task Force on Directed Energy Weapons," Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, December 2007.

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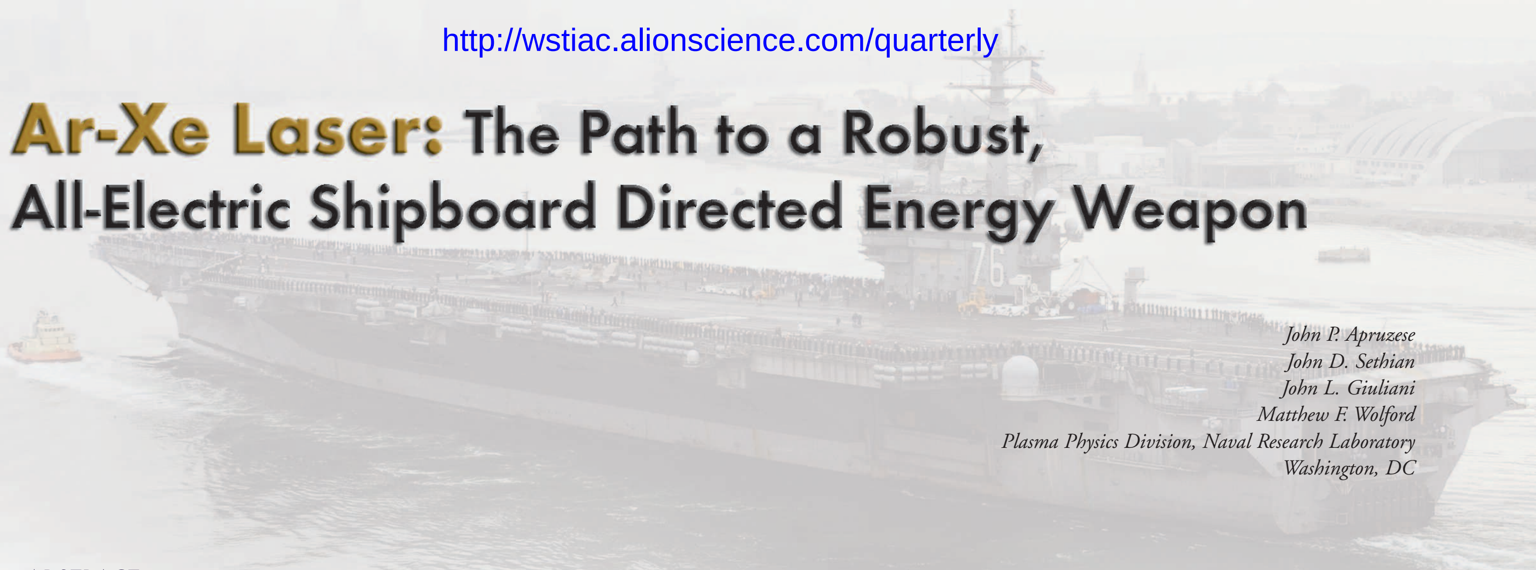

Ar-Xe Laser: The Path to a Robust, All-Electric Shipboard Directed Energy Weapon

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ABSTRACT

High energy lasers (HELs) long ago demonstrated their potential to destroy missiles in flight, a capability which could significantly reduce the threat to the fleet arising from anti-ship cruise missiles. However, no HELs have been deployed to date. Until recently, no laser had credible prospects of meeting the Navy's requirements for safety, power, size, beam quality, electrical drive, and atmospheric propagation. The electron beam pumped argon-xenon (Ar-Xe) laser has been investigated in an Office of Naval Research (ONR)-sponsored 6.1 program at the Naval Research Laboratory (NRL). The results of this program, summarized in this article, indicate that the Ar-Xe laser has a strong potential to meet these requirements. A technical road map which scales the present parameters of the Ar-Xe laser to a deployable system is presented.

INTRODUCTION

In 1978, the US Navy accomplished one of the most important milestones in the search for a directed energy weapon (DEW) with the first shootdown of a missile in flight by the Navy-ARPA Chemical Laser (NACL). Despite three decades of subsequent effort, there is still no operational shipboard directed energy laser weapon. This is primarily due to the fact that, until recently, no suitable laser candidate existed. "Suitable" means good maritime atmospheric propagation, durability to withstand the rigors of a shipboard environment, adequate power, electrical drive, efficiency, beam quality, and safe operation. NRL's Plasma Physics Division has conducted a 5-year 6.1 program (October 2003 – September 2008) which investigated the electron beam pumped Ar-Xe laser. This program met all of its scientific and technical objectives, and the authors believe that the Ar-Xe laser can meet the Navy's requirements:

(1) The wavelength is 1.733 microns, which has an absorption of only 2.2% per km in a maritime atmosphere.

(2) The laser uses rugged pulsed power technology, which is ideally suited for the all-electric warship of the transformed Navy.

(3) The laser medium is an inert gas that is recycled through a closed loop without combustion or exhaust.

(4) The laser operates at an "eyesafe" wavelength which greatly reduces operational safety risks associated with reflection and scattering of the primary beam.

This integrated theoretical/experimental program used the NRL Electra laser.[1] Electra is being developed as a krypton fluoride (KrF) laser for fusion energy, and it is sponsored by the Department of Energy's (DOE) High Average Power Laser (HAPL) program. DOE investment well exceeds $50M to date, a factor of at least 30 times greater than the $1.8M total 5-year cost of the 6.1 program itself. The 6.1 Ar-Xe research using Electra has enabled the identification of a credible path to a DEW class laser. The following sections describe the basic features of the Ar-Xe laser, summarize the achievements of the 6.1 program, and delineate the technical roadmap for carrying this research to fruition as a practical shipboard DEW.

BASIC PROPERTIES OF THE AR-XE LASER

When a high energy (approximately hundreds of keV) electron beam is launched into a mixture of the inert gases argon and xenon, the gas becomes partly ionized. The ionized species interact through complex atomic and molecular ionic processes and lead to the preferential population of an upper excited state in neutral xenon (see Figure 1). This results in a population inversion and lasing at 1.733 microns. Even in a maritime tropical atmosphere with 70% relative humidity at 80°F, the absorption at this wavelength is only 2.2% per km.[2] Within a microsecond or so after passage of the pulsed electron beam, full relaxation of the gas has occurred, and it returns to its quiescent, neutral, chemically inert state. Thus, not only does this laser propagate well at sea, it recycles its lasing medium, and there is no hazard to the crew arising from the materials needed to make it work. Furthermore, the electron beams which pump the laser medium are readily producible by rugged, industrial pulsed power generators well-suited to the all-electric warship of the future. The electron beam quality and kinetic energy requirements are substantially less stressing than those needed for a free electron laser (FEL), and the radiation shielding requirements are also significantly reduced. Clearly, this laser has the potential to be an attractive DEW option for the Navy.

In order to produce a uniform gas laser medium of large volume, two counter-propagating electron beams have been employed in gas lasers such as the Electra KrF laser at NRL. This strategy is also applicable to the Ar-Xe laser. The critical components in the vicinity of the laser cell are illustrated in Figure 2. This figure portrays the implementation of the Ar-Xe laser at NRL on the Electra facility. Each electron beam draws its energy from a separate capacitor bank, which is discharged through a pulse-forming line into a vacuum diode. Peak voltage pulses of approximately 500 kV at each diode launch electron beams from a cathode surface into the gas from opposite sides of the rectangular laser cell. To isolate each vacuum diode from the laser gas, a

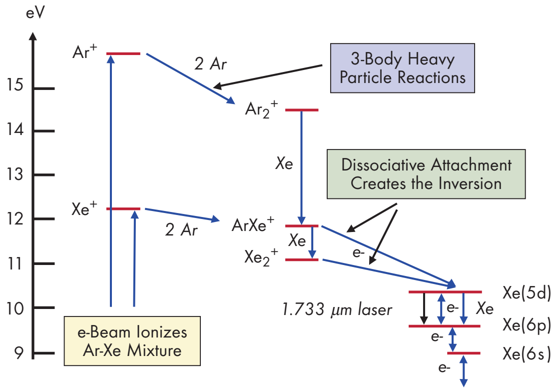

Figure 1. **Reaction kinetics, as presently understood, which produce population inversion in the Ar-Xe laser.**

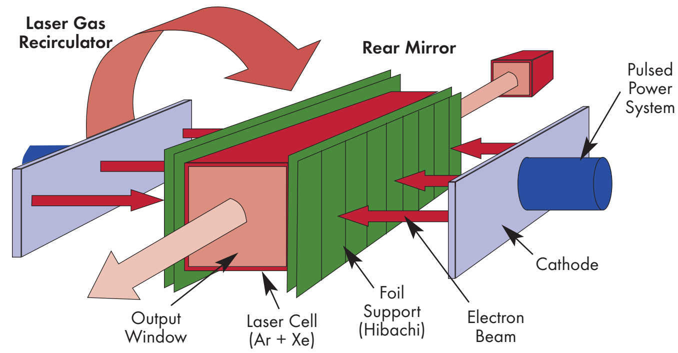

Figure 2. **Diagram of Ar-Xe laser components as realized on NRL's Electra facility.**

grill-shaped structure, known as a hibachi, supports a pressure foil and a separate anode foil. Typically, these foils are composed of stainless steel or titanium. The laser gas flows between the two foils within a recirculator, which serves to cool and quiet the laser gas. Figure 3 is a photograph of the Electra facility showing the identical capacitor banks that power the diodes. The pulse forming lines are visible (blue tubes) in the photo as are the racetrack-shaped magnets (black) which guide the electron beams. The rectangular laser cell is in the central core between the magnets.

Though it is not optimized for Ar-Xe, Electra was an excellent platform to study the physics of this laser and to identify the issues needed to scale Ar-Xe to DEW-class power levels. Furthermore, many of the technologies developed by Electra for DOE's laser fusion program are applicable to an Ar-Xe HEL DEW. The main relevant technologies are: rep-rated pulsed power, development of a gas recirculator, durable cathodes, and an efficient, cooled hibachi which can last for tens of thousands of individual pulses. In addition, an advanced, all solid-state 250 kV pulsed power demonstration system with efficiencies exceeding 80% has been developed which has operated continuously for 1,000,000 shots at rep rates up to 10 Hz. Thus, the Navy stands to benefit greatly from the 30-to-1 cost leverage described above.

OBJECTIVES AND ACCOMPLISHMENTS

The essential goals of the NRL Ar-Xe laser 6.1 program were: (a) demonstrate the Ar-Xe laser on NRL's Electra facility, (b) determine (within Electra's capabilities) the optimal operating conditions, coupled with an understanding of the basic kinetics and reaction channels that affect gain and efficiency, and, (c) based on the authors' studies, produce a concept design of a high power Ar-Xe laser system. A typical Ar-Xe laser experiment on Electra employed a diagnostics suite schematically shown in Figure 4. There is a time-integrating calorimeter to measure the total laser energy output, time resolving photodiodes to examine the laser pulse shape and its spatial variation, a pressure transducer which is used to unfold the beam deposition into the laser cell, and an interferometer to follow the electron density.

The comprehensive suite of diagnostics diagrammed in Figure 4 resulted in the collection of a large quantity of data over 4 Electra Ar-Xe campaigns totaling 935 shots. Of course, not every instrument shown was deployed on every shot. An example of some of the most detailed data is shown in Figure 5, where the

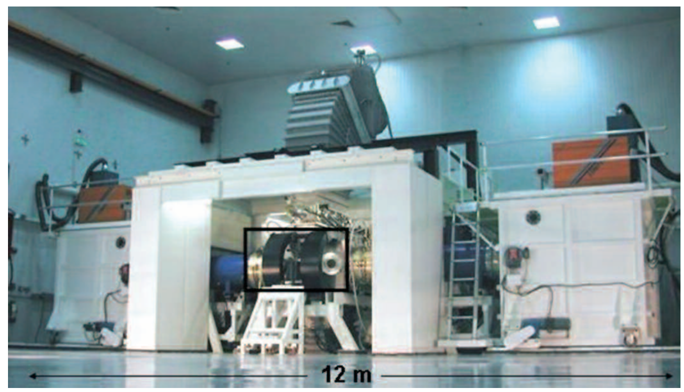

Figure 3. **Photograph of NRL's Electra laser. Rectangular region outlined in black indicates the area diagrammed in more detail in Figure 2.**

experimentally measured intensity of the 1.733 μm laser light is depicted as a function of space and time. Such data was employed in conjunction with a model of the Ar-Xe laser kinetics to guide the choice of experiments and to deduce the underlying physics that are needed to optimize the laser.

The scientific data and reasoning that justifies the following conclusions has been presented in detail [3-7], to which the interested reader is referred. Also, in its final year the program's advances in the science of the Ar-Xe laser resulted in three invited talks [8-10] at national and international conferences.

- Repetitively pulsed lasing at 1.733 μm was demonstrated at 5 Hz, 45 W average power at 9 J per pulse. This was accomplished with only one side of the diode pumping the laser gas. With two-sided pumping and further fine adjustment of the voltage and foils, the authors are confident that powers of at least 100 W could have been achieved, if resources and time had permitted.
- The electron beam power deposition density that maximizes the efficiency of the laser is 50-100 kW/cm^3. Note, this is an order of magnitude smaller than Electra's capability of 700 kW/cm^3. Since Electra's pulse width is fixed at 140 ns, the only way to obtain the optimum power deposition density was to reduce the diode voltage and to use thick anode and pressure foils, in effect throwing away much of the available energy. This would not be necessary with an optimum pulsed power design, which

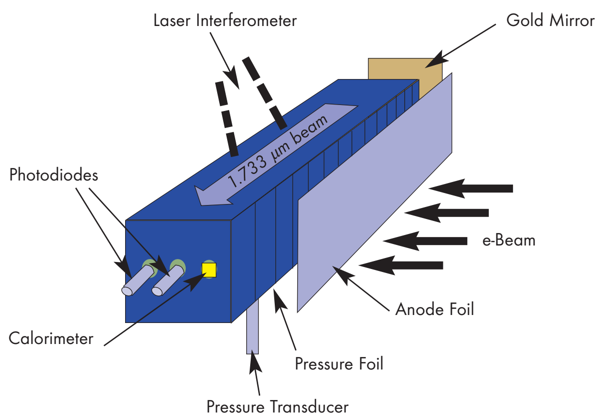

Figure 4. **Typical diagnostic setup for Ar-Xe experiments on NRL's Electra facility.**

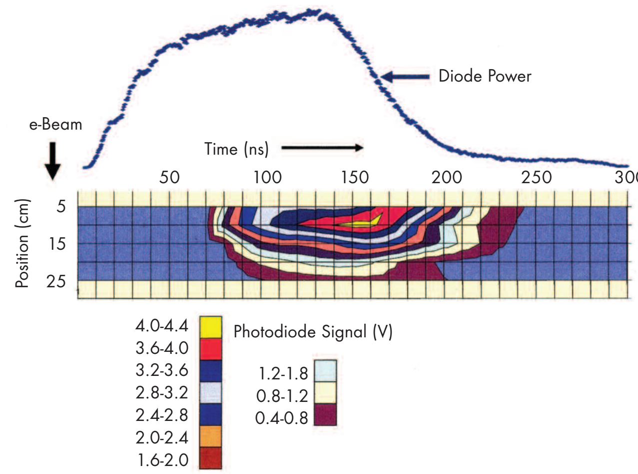

Figure 5. **Laser power at 1.733 μm is shown as a function of time and distance from the e-beam entrance foil (the pressure foil) for a one-sided pumping experiment. In this Electra shot, the total energy deposited was 577 J, the Xe fraction 1%, and the total pressure 2.0 atm. The photodiodes were arrayed along the direction of e-beam propagation, as shown in Figure 4. The diode power is depicted in the curve shown above the power contours on the same time scale.**

would spread the energy over a much longer pulse and thereby achieve larger laser energy output.

- The ionization fraction during lasing was found by interferometry to be 10^{-5} to 10^{-4}. These data are the first measurements anywhere of the electron density during Ar-Xe lasing, and they exceed by an order of magnitude the estimates of previous workers.
- This high ionization fraction, unexpected and unexplained by other laboratories' previous modeling of the Ar-Xe system, is in generally good agreement with our model, which employed modern atomic physics codes to calculate key rates. The single most significant limitation on our model is the uncertainty in key *molecular* rates which greatly influence the inversion kinetics. Some are not known even to within a factor of 2.
- Gain was measured and found to vary from 0.04 cm^{-1} at a Xe mixing ratio of 0.5% to 0.22 cm^{-1} at 2.5%.
- A 20-year-old debate was settled by demonstrating that the ion Xe_2^+, in addition to $ArXe^+$, is responsible for creating the population inversion.[4] This demonstration also led to an understanding of the laser's behavior as a function of gas temperature.
- The intrinsic efficiency of the laser, defined as the emitted energy of the laser beam divided by the energy deposited by the electron beam, maximizes at a Xe mixing ratio of 1%. This efficiency increases rapidly with pressure and reached 3% at a pressure of 2.5 atm. *Electra cannot safely access pressures higher than 2.5 atm.* Figure 6 shows the rapid improvement in laser performance with pressure. Each half atmosphere pressure increase has brought a 40% increase in laser yield.

THE PATH TO A PRACTICAL SHIPBOARD DEW

The results of this 6.1 program to investigate the Ar-Xe laser suggest a path that could lead to a naval directed energy weapon. It consists of 5 principal steps, as illustrated in Table 1.

It is generally believed that power somewhere in the vicinity of 1 MW is needed for an effective laser DEW.[11] The third column of Figure 7 gives a factor which is the power enhancement that would result from successful implementation of the corresponding phase of the overall program. Multiplying the factors together, and by the presently achieved 45 W, gives a power near 1 MW. The first phase, using two-sided pumping and further improvement of the foils with fine tuning of the optimum voltage, could have been done on Electra had time and resources permitted. It is the lowest risk of all of the steps presented, since pumping from both sides would have energized both halves of the laser cell, likely giving at least a factor of 2 power enhancement. The second phase would be aimed at taking advantage of the observed increase in efficiency and power with laser gas pressure, shown in Figure 6. This phase cannot be implemented on Electra, since its safe pressure limit is 2.5 atm. Recall also that the only way to obtain the optimum power deposition density of 50-100 kW/cm^3 on Electra was to discard some of its available energy, since its pulse width is fixed at 140 ns. In principle, the best use of the stored energy in a pulsed power generator to drive the Ar-Xe laser would be to modify the

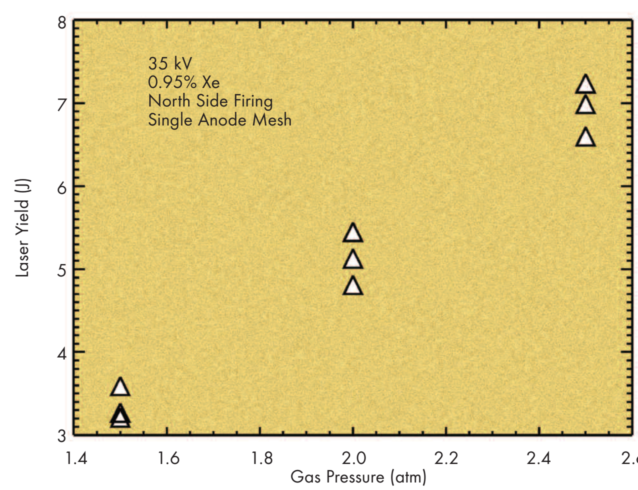

Figure 6. **Measured laser yield vs. gas pressure. As shown, generally 3 shots were taken for each distinct set of experimental conditions on Electra. Subsequent use and adjustment of an anode foil increased the laser yield at 2.5 atm to 9 J.**

Table 1. **Suggested road ahead from the NRL Electra experiments, resulting in a 1 MW Ar-Xe laser, suitable for use as a shipboard DEW.**

R&D Goal	Approach	Improvement Factor Relative to Electra's 45 W	Facility / Technical Issues
Maximize the efficiency across entire cell	Optimize foils, hibachi, and voltage	2 - 3	Electra / electron transport, beam stopping in gas
Increase intrinsic laser efficiency	Test different kinetics (e.g., pressure, output coupler)	1.3 - 2	HAWK or similar / test on laser cell with a pressure limit >2.5 atm
Longer pulse width	Extend to 2 µsec, instead of 140 nsec on Electra	15	HAWK or similar / sustain optimal lasing conditions over the longer pulse
Higher rep rate	50 Hz instead of 5 Hz	10	**Future:** 25 kW system / foil and cathode durability, thermal management
DEW-class High Energy Laser ~ 1 MW	50 Hz, 2 µsec: Larger laser cell (1 x 1 x 3 meters)	33	**Future:** Full-scale prototype / uniform e-beam deposition and extraction

e-beam pulse width to optimize both the deposited energy and power. As mentioned above, this also cannot be done on Electra. However, there are existing long-pulse pulsed power systems which are well suited to optimizing the single-shot Ar-Xe laser performance. An example is the HAWK facility, which is also within NRL's Plasma Physics Division. HAWK is an integral part of the experimental facilities of the Pulsed Power Physics Branch, Code 6770. HAWK was built in 1990 at a cost of $500,000 and paid for by the Defense Nuclear Agency. It has been employed to investigate and develop high power X-ray sources, such as plasma Z pinches and bremsstrahlung diodes. It is pictured in Figure 7. The authors envision the construction of a dedicated laser cell built to safely withstand pressures as high as 4 atm. The front end of HAWK could be mated to this new laser cell, as shown in Figure 8. Pulse widths at least as long as 800 ns, possibly longer, could be sustained on HAWK, thus enabling the testing of the Ar-Xe laser in promising regimes of higher power and longer e-beam pulse widths. There are also repetitively pulsed e-beam systems being developed elsewhere for microwave weapons (see, for instance, Reference 12, page 29). The final two phases of the overall concept for creating a 1 MW Ar-Xe laser would require investments in new dedicated systems. The fourth phase envisions a further increase in power of a factor of 10, brought about by increasing the e-beam pulse rep rate by that factor, from 5 to 50 pulses per second. Existing pulsed power gas switches can accommodate such a rep rate; the main questions surrounding this phase are of durability and thermal management. Two of the key engineering issues which arise in the design and implementation of such a system are the following: First, based upon the gas temperature dependence of the laser kinetics, the gas will need to be recirculated to keep it cool; this would also avoid any problems that might arise from turbulence. To completely replace the gas prior to each pulse at 50 Hz requires a flow velocity of about 30 cm/0.02 sec or 15 m/sec. Electra's recirculator typically operates with flow velocities of approximately 6-8 m/sec. The second key issue is thermal management of the hibachi foil. The system

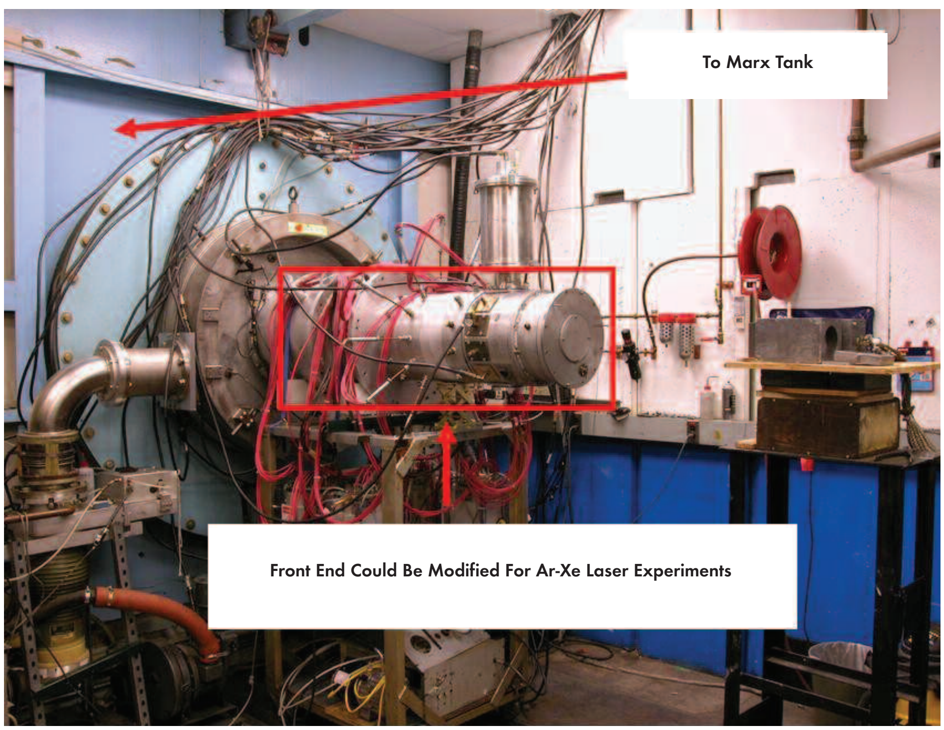

Figure 7. **The HAWK pulsed power generator, one of the experimental facilities of NRL's Pulsed Power Physics Branch, Code 6770.**

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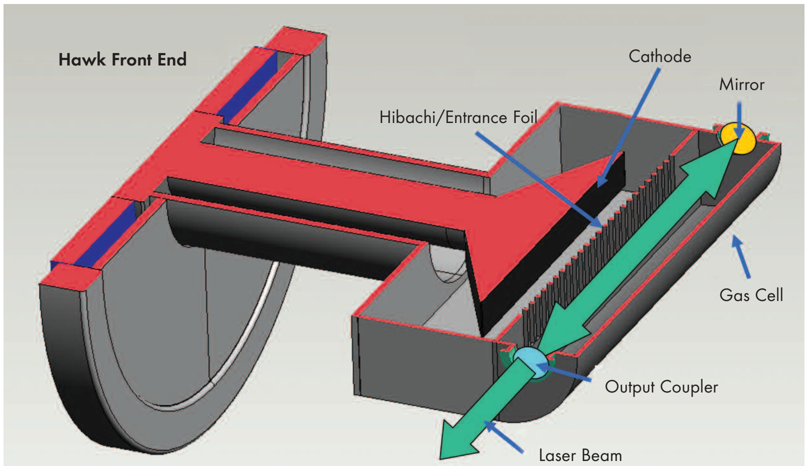

Figure 8. **A new, high-pressure laser gas cell could be mated to HAWK by flaring its inner conductor to form the cathode.**

envisioned in the fourth phase will require about an order of magnitude more heat removal than has been demonstrated on Electra. This phase will either resolve these issues, paving the way to a practical shipboard Directed Energy Weapon, or lead to a program off-ramp. The fifth and final step to a 1 MW system is to build and energize a laser cell of dimension 1 x 1 x 3 m, which is 33 times the volume of Electra's. Table 1 is not intended to be a dogmatic or rigid technical path to an Ar-Xe laser DEW; many reasonable variants can be contemplated in developing the laser to meet the critical naval need of shipboard anti-missile defense.

SUMMARY

Three decades ago, US Navy tests demonstrated the promise of high energy lasers in defending the fleet against sea-skimming missiles. No HELs have yet been deployed because, until recently, no candidate laser appeared capable of simultaneously meeting the requirements for power, ruggedness to withstand a shipboard environment, atmospheric propagation, electrical drive, efficiency, beam quality, and safety. Present-day candidates which are under investigation include the free electron laser (FEL), incoherently combined fiber lasers, and the electron beam pumped Ar-Xe laser. In this report, the major results have been presented and the implications of a 5-year 6.1 program at NRL to investigate the Ar-Xe laser have been discussed.

The experiments were conducted at the Plasma Physics Division's Electra facility, which was designed as a rep-rated krypton fluoride laser for fusion applications. Though not ideally suited for the Ar-Xe laser, using Electra leveraged more than $50M investment to date by the US Department of Energy and also led to significant advances in understanding the physics of this important and powerful infrared laser. Efficiency of 3% was demonstrated on Electra, whose laser gas pressure is limited to 2.5 atm. The efficiency increased at a rate of about 40% per half-atmosphere increase in pressure (Figure 6). Other experimental facilities exist, some within NRL, in which the Ar-Xe laser could be tested at higher pressures and longer e-beam pulsewidths, which are the most promising avenues for further improvement in efficiency. The 6.1 program demonstrated that the Ar-Xe laser is a promising candidate, from both a practical and a scientific standpoint, for shipboard anti-missile defense.

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Kirtland AFB, NM

The Directed Energy Engineering Analysis Center (DE^{2}AC) has been given approval by the Defense Technical Information Center (DTIC) to operate as an information-sharing Information Analysis Center (IAC) entity. One of the primary goals of the DE^{2}AC is to support the research and development of advanced concepts in directed energy (DE) and optical systems for a variety of military applications. Directed energy weapons will provide military commanders a near-instantaneous capability to deliver scalable levels of force from strategic and tactical platforms in the air, on land, at sea, and from space. DE is the next generation weapon for the warfighter of today and the future. It provides a speed of light response with a potentially unlimited magazine of ammunition, which is a force multiplier to any of the services.

During this next quarter, active users of the Total Electronic Migration System (TEMS) will find the DE^{2}AC logo alongside the other IACs' logos. Thus, users will be able to gain access to a wealth of DE related scientific and technical information (STI). The DE^{2}AC is co-located with the Air Force Research Laboratory Directed Energy Directorate (AFRL/RD) at Kirtland Air Force Base (AFB), New Mexico. Kirtland AFB has a storied history dating back to the 1970s with the development of the Chemical Oxygen Iodine Laser (COIL) and most recently with the Airborne Laser Program, the Active Denial System, and the Air Tactical Laser Program. AFRL/RD provides the DE^{2}AC with needed support to build momentum for the growth and sustainment of a valuable resource for all scientists, researchers, and engineers in the DE community.

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Turbomachinery for Man-Portable Military Power Applications

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INTRODUCTION

Within various military environments, there is a critical need for portable power sources for applications ranging from auxiliary vehicle power to battery charging. For maximum portability in the battlefield environment, the power sources must provide high power density and operate with available logistics fuel for long duration missions. For example, to provide a high level of situational awareness, today's soldier carries into the field a vast array of equipment, including GPS navigation, communications, computers, sensors, multi-function lasers, and many other devices. It is not unusual for a soldier to require over 30 pounds of non-rechargeable batteries to support a 72-hour mission.

Recognizing the ever increasing demand for portable power by the dismounted soldier, further improvements must be made in energy management and storage in order to keep this power demand under control. In this regard, as evidenced in Figure 1, significant advances have been made in battery storage, some technologies already reaching near theoretical limits. Non-rechargeable batteries, such as lithium-magnesium/manganese batteries, have achieved energy densities of approximately 250 W-hr/kg, whereas rechargeable lithium-ion batteries have a lower energy density of approximately 150 W-hr/kg, but can be recharged in 3-5 hours hundreds of times. However, fossil fuels such as No. 2 diesel oil have significantly higher energy densities, approximately 12,000 W-hr/kg. For a 35% energy conversion efficiency, this equates to 4,200 W-hr/kg (fuel only), close to a factor of 17 greater in energy density than current state-of-the-art battery technology. For a typical 72-hr mission requiring 3,600 W-hr of energy storage, only 1.9 lb of fuel, or 1 quart, is required to carry out the mission, compared to 30 pounds of batteries. This results in a substantial margin in weight for the power generation hardware; the longer the operation, the more significant the weight benefit. In this example application, the use of rechargeable batteries and a highly portable, lightweight, efficient, multi-purpose generator can meet the needs of tactical soldier deployments, providing a significant reduction in the need to carry hundreds of pounds of batteries into and out of the field of operation.

A very enticing approach for a lightweight, man-portable generator is based on a highly recuperative, Brayton cycle microturbine-generator. The air-standard Brayton cycle has long been recognized as an inherently compact power source, making it the predominant power plant of choice in aircraft applications, and increasingly, in land-based utility power applications. A typical large simple cycle gas turbine may produce upwards of 300 megawatts of power and have 35–40% thermal efficiency. The most efficient gas turbine engines have reached 46% thermal efficiency.

Beyond a certain power rating (approximately 25 kW), direct scaling of the gas turbine engine structure becomes impractical due to fabrication limitations and dominance of certain physical phenomena such as heat transfer. This makes it difficult to design components for high efficiency at low power levels. Current technology, recuperated, open Brayton cycle micro gas turbines (MGTs) that operate off available logistics fuels have serious specific mass, thermal efficiency, and cost challenges. In particular, MGTs less than 10 kW suffer significantly in performance, resulting in unimpressive thermal efficiencies, often less than 15%. Through recent technological advancements in compressor and turbine aerodynamic designs and manufacturing techniques, materials technology, thermal recuperation, and bearing technology, the potential to improve thermal efficiencies to over 35% is very promising. Detailed cycle analyses and advanced turbomachinery technology developments have established the basis for significant enhancements in man-portable MGTs that promise to make it superior to both advanced diesel and fuel cells for numerous military applications. The following discussion illustrates the thermodynamic performance potential that can be achieved with a basic recuperative Brayton cycle microturbine-generator and the primary areas of technology development that must be focused on to meet this objective.

THE AIR-STANDARD BRAYTON CYCLE

The basic Brayton cycle utilizes an internal combustion process. The major components consist of the compressor, turbine, combustor, and generator. The compressor, turbine, and generator all rotate on a single shaft. The compressor provides the necessary pressure rise to

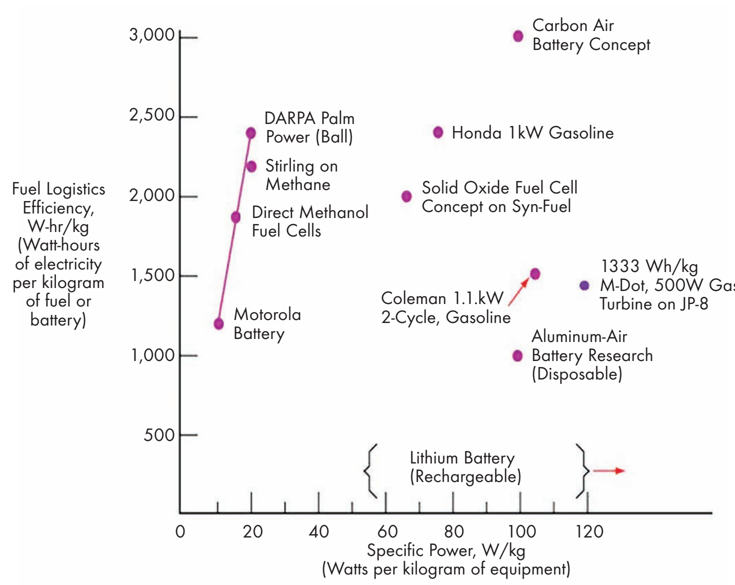

Figure 1. Efficiency and power density for various man-portable power systems.

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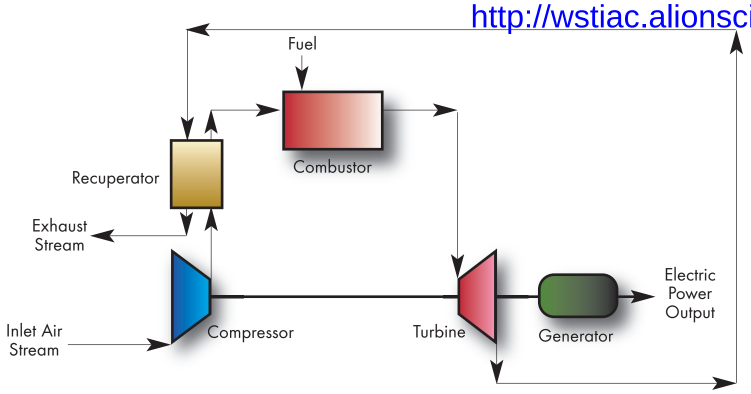

Figure 2. **Recuperative Air-Standard Brayton Cycle.**

the air stream. The pressurized air enters the combustor where fuel is added and burned to increase the temperature to the required turbine inlet condition. The hot, high-pressure gas then expands through the turbine, driving both the compressor and generator to provide the required output electrical power. The ideal cycle efficiency is a function of overall pressure ratio: the higher the pressure ratio, the greater the efficiency. In an actual gas turbine engine, the maximum temperature and pressure ratio are determined by material properties.

The recuperated cycle shown in Figure 2 permits a much higher efficiency than the simple Brayton cycle at a low compression ratio, and thus it is clearly the preferred cycle at low power. Recuperation increases the overall cycle efficiency by recovering a portion of the waste heat from the turbine exhaust stream, thereby reducing the amount of fuel which must be burned in the combustor for a given power output and mission duration. The potential drawback is that the recuperator adds weight and pressure losses to the system. Consequently, the optimum system design requires a careful tradeoff of efficiency and net size and weight. An important added benefit is the reduction in the exhaust temperature. Consequently, the recuperative cycle is a very promising approach for the successful implementation of the gas turbine as a power source for portable, low-power applications, offering the potential of providing power density levels an order of magnitude higher than batteries or other power storage devices.

Thermodynamic Cycle Analysis – Basic Cycle

A first step in the feasibility study for a gas turbine engine system is to specify a thermodynamic cycle and perform the requisite analysis to determine if this cycle can meet the desired threshold of component performance. Thus, it is necessary to specify a target cycle, followed by substantiation of required performance levels for each component. Shown in Figures 3 and 4 are performance characteristics of a simple cycle without a recuperator for various compressor and turbine efficiencies, and turbine inlet temperatures of 1800°F and 2400°F. The lower temperature represents a reasonable upper temperature limit for an uncooled turbine, while the higher temperature requires the use of a ceramic or cooled metallic turbine. For the 10 kW microturbine being considered in this example, advances in the field of high-temperature ceramic turbine wheels are becoming more practical in low-power applications and offer a viable method of extending the limit on allowable turbine inlet temperature.

At an inlet turbine temperature of 1800°F and compressor/turbine efficiencies of 80%, compressor pressure ratios of over 10 are required to achieve a thermal efficiency of approximately 27%. Increasing the turbine inlet temperature to 2400°F improves the efficiency to 32%. However, in both cases, multistage compressors and turbines, which significantly complicate the design and are not practical at this low power level, would be required. The impact of lower compressor and turbine efficiencies of 65% is quite significant. Since the net power output is the difference in the compressor power input and the turbine power output, the reduction in these efficiencies results in rather low thermal efficiencies in the range of 8% to 16%. Under this circumstance, single-stage compressors and turbines would be possible, although the low efficiencies would not be considered very attractive. As such, the use of a simple Brayton cycle turbine is not considered a viable approach for low power microturbines.

Thermodynamic Cycle Analysis – Recuperative Cycle

A significant improvement in the overall cycle can be achieved by incorporating a recuperator into the system. The recuperator recovers the turbine exhaust heat to preheat the compressed air, thereby reducing the input fuel requirement. In the counterflow recuperator, the maximum amount of heat that can be recovered is determined by the effectiveness of the recuperator and discharge temperature of the compressor. Because of this, as the compressor pressure ratio and associated discharge temperature increase, an optimum thermal efficiency is reached.

Shown in Figures 5, 6, and 7 are the operating characteristics of the system for various design and operating conditions. For the variable turbine inlet temperatures shown in Figure 5, the recuperator effectiveness was specified at 90%, with compressor and turbine efficiencies of 80%. This design assumes a 5% pressure loss through the combustor and recuperator and a combined mechanical efficiency (bearings, seals, and generator losses) of 90%. These are reasonable maximum values that can be achieved with current high temperature metallic materials capable of operating at 1800°F and

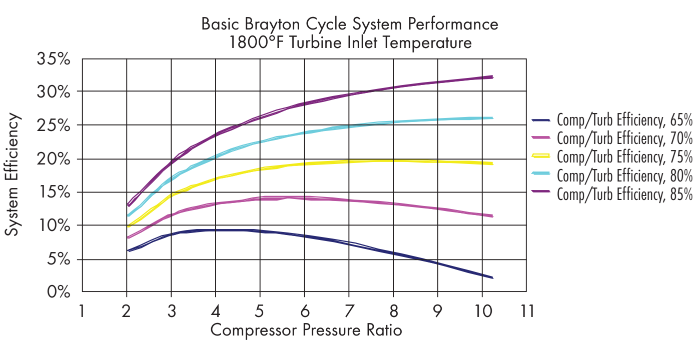

Figure 3. **Simple cycle, 1800°F turbine inlet, variable compressor/turbine efficiency.**

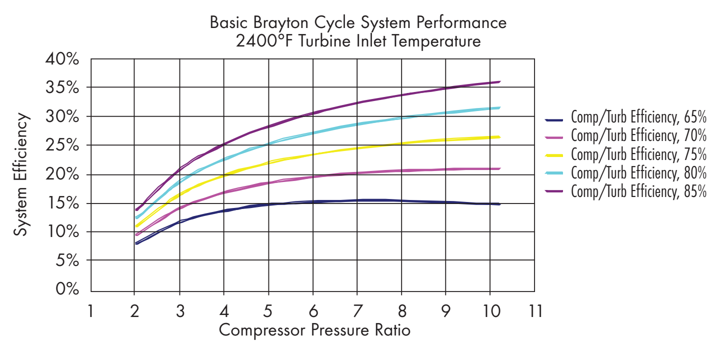

Figure 4. **Simple cycle, 2400°F turbine inlet, variable compressor/turbine efficiency.**

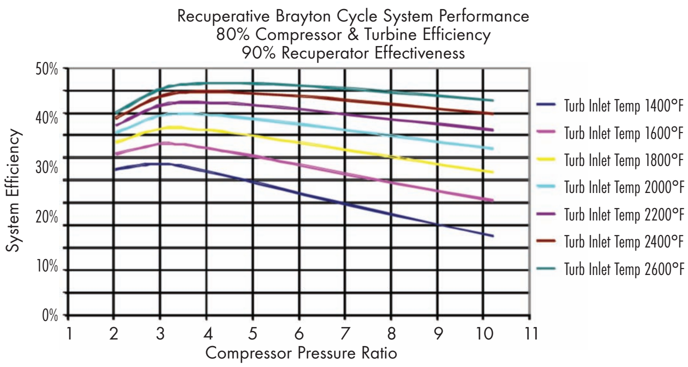

Figure 5. Recuperative cycle performance with varying turbine inlet temperatures.

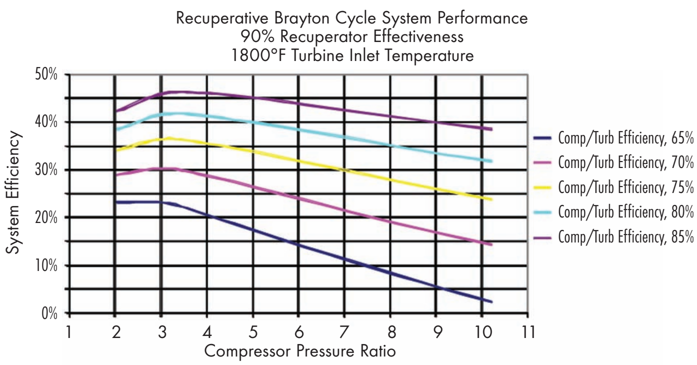

Figure 6. Recuperative cycle performance with varying compressor/ turbine efficiencies.

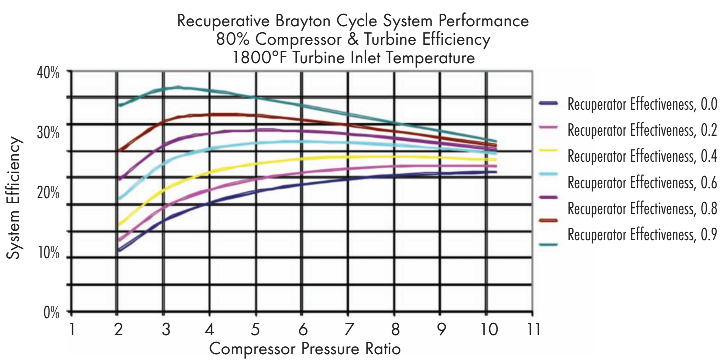

Figure 7. Recuperative cycle performance with varying recuperator effectiveness.

advanced compressor and turbine designs. Turbine inlet temperatures above 1800°F assume the use of advanced ceramic materials, and are shown to illustrate the future capability of this technology. At a turbine inlet temperature of 1800°F, a thermal efficiency of 42% (lower heating value) can be expected. Utilizing advanced ceramic materials, and a turbine inlet temperature of 2200°F, a thermal efficiency of 48% could be achieved. In particular, it can be seen that the optimal thermal efficiency tends to be reached at a pressure ratio of 3 to 4. This is very significant in that a single-stage radial compressor and turbine can be used to deliver the net power to the generator.

The impact of the compressor and turbine efficiencies for this design is shown in Figure 6. In the ranges specified, the peak thermal efficiencies occur at a pressure ratio of 3 to 4. However, the impact of going from 65% to 85% efficiency is quite dramatic, increasing the thermal efficiency by a factor of two, from 24% to 47%. In this regard, a very critical design factor is associated with using the most advanced aerodynamic technology to design these components. This implies integrated state-of-the-art blade, diffuser, and volute concepts.

Figure 7 illustrates the impact of the recuperator effectiveness on the thermal performance. The heat exchanger effectiveness is the ratio of the actual heat transfer rate to the thermodynamically limited maximum possible rate which can be realized in a counterflow heat exchanger of infinite heat transfer area. Recuperator effectiveness is a function of the heat transfer coefficients and surface areas associated with the air and gas streams. For a given flow passage geometry (pressure drop may change), effectiveness basically translates into heat exchanger volume. Conventional design approaches strive to achieve an effectiveness of approximately 0.7. However, the effectiveness is not a linear function of the volume, and increasing the effectiveness from 0.7 to 0.8 results in an increase in volume by a factor of 1.7. Further, increasing the effectiveness from 0.7 to 0.9 results in an increase in volume by a factor of 3.9. For an effectiveness of 0.7, a thermal efficiency of 34% can be achieved, increasing to 37% and 42% for an effectiveness of 0.8 and 0.9 respectively. Therefore, in the design of the system, the size of the recuperator must be carefully considered in terms of the overall thermal efficiency.

DESCRIPTION OF MICROTURBINE-GENERATOR

The basic function of a microturbine-generator is to convert the thermal energy provided by the combustion of the fuel into electrical power. In operation, ambient air enters through the high-speed generator to cool the windings and into the centrifugal compressor. The compressed air then flows into the combustor where fuel is added, and the temperature increases to the inlet value for the radial inflow turbine. The partially cooled combustion gas then flows into the counterflow recuperator, giving up its heat to the compressed air. All the components rotate on the same shaft. To minimize the size of the system, the recuperator is wrapped around the combustion chamber. The recuperator also serves to help attenuate any noise generated from the rotating equipment. Since the generator is well above synchronous speed of 3,600 rpm, the output power is rectified from high frequency alternating current (AC) to direct current (DC) and then back to 60 Hz AC power.

Shown in Table 1 are the thermodynamic requirements for a 10 kW microturbine generator. The assumed turbomachinery efficiencies are based on utilizing state-of-the-art aerodynamic and materials technology, with reasonable design margins. The overall weight of the system is estimated to be less than 75 pounds.

In comparison to the proposed microturbine, is a 2.6 kW, single-shaft regenerative microturbine-generator. The turbine rotates at

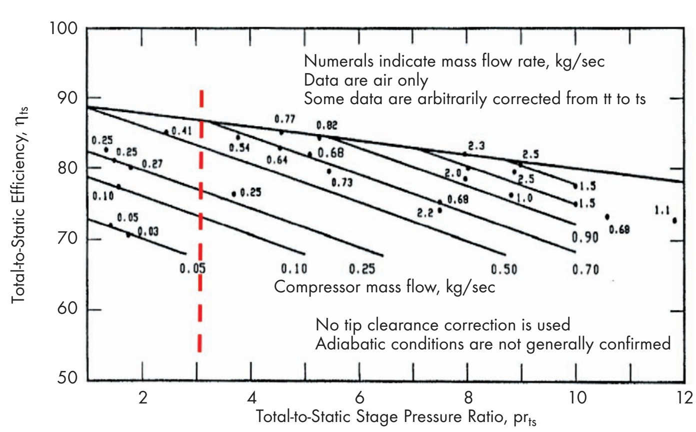

Figure 8. Centrifugal compressor design-point performance trends.

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Table 1. **Thermodynamic cycle requirements for 10 kW microturbine-generator.**

Input Design Parameters	Calculated Output Conditions and Performance
Inlet Air Flow Rate = 650 lb/hr	Compressor Air Outlet Temperature = 330°F
Fuel Input = 5.06 lb/hr, No. 2 fuel oil	Recuperator Air Outlet Temperature = 1253°F
Compressor Inlet Pressure = 14.7 psia	Turbine Outlet Temperature = 1356°F
Compressor Discharge Pressure = 44.1 psia	Exhaust Gas Temperature = 449°F
Pressure Loss Across Combustor = 1.5 psi	Operating Speed = 110,000 rpm
Pressure Loss Across Recuperator = 1.0 psia	Compressor Impeller Diameter = 3.1 inches
Compressor Air Inlet Temperature = 70°F	Turbine Rotor Diameter = 3.5 inches
Turbine Inlet Temperature = 1800°F	Compressor Efficiency = 75%
Regenerator Effectiveness = 0.9	Turbine Efficiency = 80%
Overall Mechanical/Electrical Efficiency = 85%	Overall System Thermal Efficiency = 37%

100,000 rpm and incorporates a permanent magnet generator. The dimensions are 32.5x16.5x18 inches, and the unit weighs 150 pounds. The thermal efficiency is estimated to be approximately 6-10%. A 10.5 kW commercial reciprocating engine-generator has dimensions of 37.5x24.3x24.5 inches, weighs 403 pounds, and has a thermal efficiency of 18%. Both of these conventional units are significantly larger and much less efficient than that projected for the advanced microturbine-generator.

DESCRIPTION OF MAJOR COMPONENTS

Compressor and Turbine Aerodynamics

Conservation of thermodynamic cycle characteristics is a first requirement when scaling down a gas turbine engine. This implies similar energy exchange between fluid and rotating components, but at a smaller mass flow. A consequence of maintaining the same levels of pressure and velocities is that mass flow and power depend on cross-sectional area and scales with diameter squared. The principal condition for maintaining similar levels of turbomachinery performance is the preservation of velocity triangles, Reynolds number, and Mach number. Maintaining similar Mach numbers usually does not create any problems. A reduction of Reynolds number with adverse performance effects while decreasing dimensions is unavoidable unless the viscosity and/or pressure levels are also modified. The impact of reducing dimensions on centrifugal compressor performance can be estimated from Figure 8, where the change in efficiency with decreasing mass flow is indicated by the vertical dashed line [12]. At the design flow rate of 0.08 kg/s flow, an isentropic efficiency of 75% represents a practical maximum performance based on current technologies.

A useful similarity parameter that is often used for selecting turbomachinery architecture for a required duty is the specific speed, Ns, which can also be used to estimate achievable performance levels. Experience has shown that peak efficiencies are associated with Ns in the range of 0.6 to 0.8. Optimum Ns values result in a higher rotational speed for a required mass flow. Designing for a lower Ns value allows a lower rotational speed for the same mass flow or power but penalizes efficiency. The higher values of Ns lead to rotational speeds that may not be reachable (rotordynamic and bearing problems), and a lower value of Ns may be a design option to alleviate the bearing problems. The corresponding penalty on efficiency can be gauged from Figure 9.

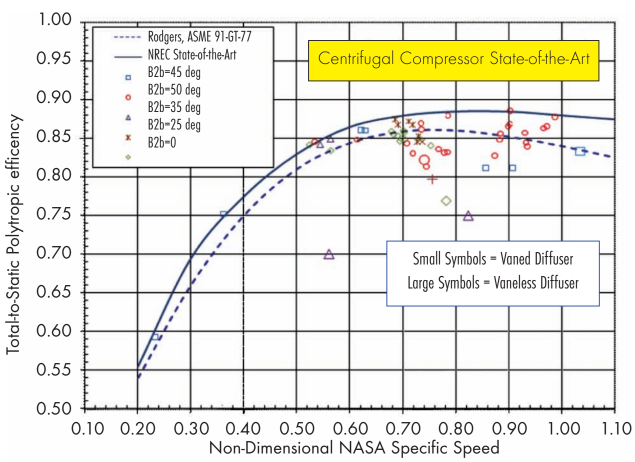

Figure 9. **State-of-the-art centrifugal compressor efficiencies.**

Achieving the desired levels of thermal efficiency demands turbomachinery performance at state-of-the-art levels and beyond. The key turbomachinery technologies required to develop the targeted levels of performance can be categorized as follows:

- Innovative aerodynamic design concepts for achieving higher diffusion and reduced entropy production
- Advanced design methods for optimization and verification of innovative aerodynamic design concepts
- Stall line management schemes for wider operability
- Clearance control and rub management for achieving the tightest running clearance
- Cost-effective fabrication techniques

There are various levels of advanced aerodynamic design concepts that can be used to increase passage diffusion and reduce entropy generation. One such design, illustrated in Figure 10, incorporates a sculpted impeller, single-row, low-solidity airfoil diffusers (LSA), and tandem deswirl vanes.

The turbomachinery aerodynamic design process integrates engineering methods such as empirically-grounded meanline and throughflow analyses with more advanced, physics-based computational mechanics (fluid and structures) methods. These calibrated engineering methods allow effective designs to be rapidly synthesized, leading to highly refined configurations able to achieve the required level of performance and range necessary for the proposed microturbine.

Structural Analysis and Materials Requirements

Operation at high tip speeds is generally not as much an aerodynamic issue as a structural issue. Unlike static applications, the ultimate operating tip speed of the compressor or turbine is largely limited by the stresses produced by centrifugal forces on the disc and blades. The stresses tend to be at maximum near the center or hub of the impeller and at the root of the blades. Shown in Figure 11 is a typical von Mises stress distribution for a high-speed impeller. To enable operation within acceptable material stress limits, selection of high strength-to-weight materials along with skillful, structural tailoring of the rotating blades and disks, is critical.

The centrifugal forces near the bore are proportional to the square of the speed (rpm) of the rotor, the square of the radius of the impeller, and the density of the material. In the structural analysis, two additional coefficients, Life Factor and Form Factor, quantify the maximum theoretical impeller tip speed that can be sustained without failure. The Life Factor is a function of the desired design life of the system, and the Form Factor is based on the type of impeller, the shape of the blades, and the hub design.

The ultimate strength of the material is highly affected by operating temperature. A plot of the theoretical maximum tip speed as a function of temperature, which is strongly dependent on how the strength and density change with temperature, is very useful in the initial process of selecting a suitable material. Figure 12 presents the results of such a calculation for a variety of materials and operating temperatures. It is immediately clear why titanium and aluminum alloys are common materials of choice for turbomachinery applications when high operating temperatures are not a concern. However, for high thermal efficiency, it is desired to operate the turbine at as high a temperature as practical, within the stress limitations of the material. This requires the use of high temperature Haynes 188 and Hastelloy X superalloys. Additionally, the use of high strength ceramics for turbine rotors is an excellent option for high temperature operation. The relatively small size of the turbine lends itself to conventional machining operations. The main drawbacks with ceramics are their tendency towards brittle fracture failures from internal flaws and microcracks. However, great advances are being made in the use of ceramic turbine blades, and such work should be equally applicable for use in radial turbines.

Combustor Design Requirements

The combustor design is impacted by size scaling issues. The decreasing size of the combustor with power leads to design configurations which have a relatively high surface-to-volume ratio. This means that the surface area of the combustor liner which surrounds the flame, and which must be cooled, is relatively high for a given volumetric heat release. In addition, practical limitations on cooling slot dimensions compromise the film-cooling effectiveness and consistency of performance that can be achieved with conventional approaches. This increases the amount of combustion air which must be devoted to cooling, leaving less for other important functions such as dilution and mixing to improve the uniformity of the exit temperature profile. There are various advanced concepts which show promise of making more effective use of the available cooling. These include transpiration cooling and impingement "backside" convective cooling of the liner. An alternative to increasing the efficiency of cooling techniques is to use protective thermal barrier coatings or ceramic liner materials which allow operation at higher temperatures.

The requirement to operate with logistic fuels poses a number of issues at this low fuel rate. At the low supply pressure of the liquid fuel, atomization by conventional means is very difficult. This is due to the fact that the fuel injection orifices become very small, making them prone to plugging. A rotating atomizer (fuel slinger) is an alternative approach which is well-suited for small combustors and is widely used in cruise missile engines. Another method that potentially works well at low fuel flow rates is to vaporize the fuel before introducing it into the combustor. This is usually accomplished by means of a vaporizing tube which protrudes into the flame zone of the combustor and through which the fuel is injected into the combustor as a jet of vapor. Both of these approaches offer a potential solution to the low-flow fuel preparation problem.

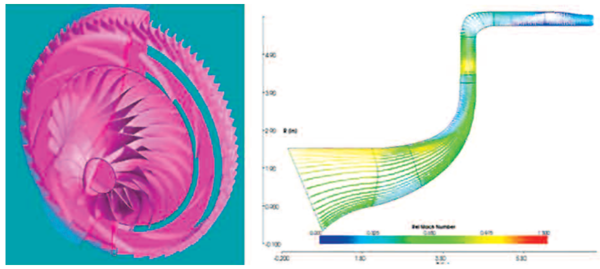

Figure 10. **Advanced small centrifugal compressor design.**

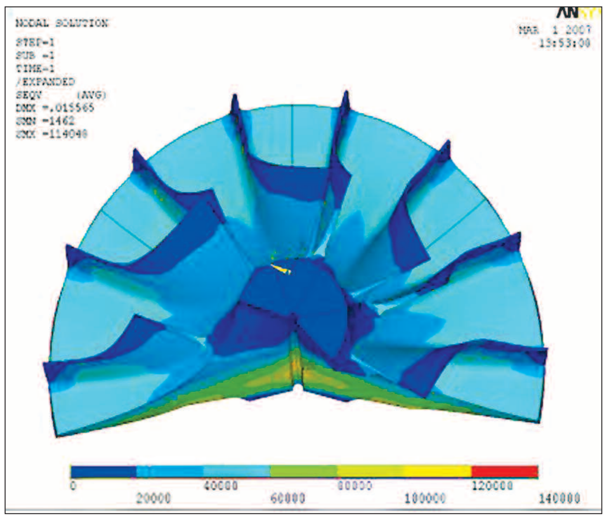

Figure 11. **Typical von Mises stress distribution of a high-speed impeller.**

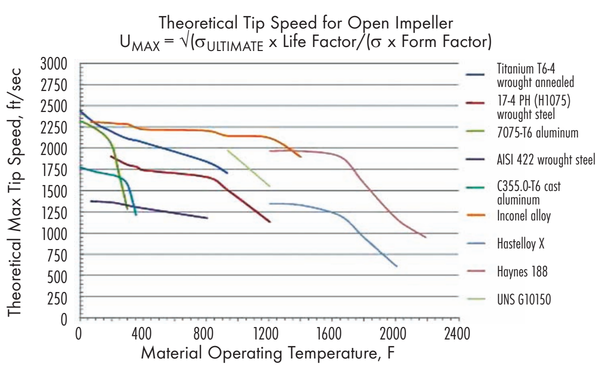

Figure 12. **Maximum impeller tip speeds for various materials and operating temperatures.**

Recuperator Design Requirements

As is the case in most thermal systems, the size, weight, and cost of the heat-transfer equipment represent a substantial portion of the total. This is particularly true for the gas turbine recuperator. The design conditions for the recuperator are dependent on the requirements of the gas turbine application. In general, however, the recuperator is required to provide a thermal effectiveness of 90% or greater and a total pressure loss of 5% or less. These conditions must be satisfied in a configuration which is as small as possible, requiring the use of extremely compact and robust heat-transfer geometries.

Early attempts at developing small gas-turbine engines in the 1960s focused on automotive applications. In these engines, recuperation was provided by a rotary regenerator consisting of a ceramic disk containing small-diameter honeycomb passages. Front and back rubbing face seals separate the two streams as the disk rotates through each, carrying heat from the hot to the cold stream. The ability to utilize ceramic material in this type of configuration satisfies many of the design requirements, including compactness, low weight, reasonable material cost, and tolerance to high temperatures. The main disadvantage which has prevented successful implementation is the inherent high wear rate of the rubbing seals which leads to high maintenance and limited life.

The more conventional approach to gas turbine recuperation is to use a stationary recuperator design, which is typically some variation of a plate-fin geometry. Thermodynamically, the only practical way to provide the required high levels of effectiveness is to use a flow configuration which is predominantly counterflow with relatively small crossflow sections at each end to provide separate inlet and outlet headers for the two streams. High-effectiveness recuperators are characterized by flow passages with very small

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hydraulic diameters on both sides to minimize size and weight.

Recuperators can be classified into two main categories: primary surface designs and extended surface (finned) designs. Primary surface configurations are constructed of corrugated sheets of metal stacked together and edge-welded to form alternating pairs of cells through which the hot and cold streams flow [1, 2]. Heat transfer occurs directly through the sheets which form the primary surface between the fluid streams. A unique version of a primary-surface configuration is the spiral recuperator [3]. This configuration is formed in a continuous manufacturing operation by coiling a pair of corrugated sheets to create two spiral-shaped flow paths. The primary-surface approach has the basic advantage of avoiding the thermal inefficiencies associated with secondary heat transfer through fins. However, it has less flexibility in tailoring the geometry of each side to match the requirements corresponding to the different flow conditions and properties of the two fluid streams. Also, practical dimensional constraints on fabrication of the corrugations limit the minimum value of hydraulic diameter that can be achieved.

The conventional extended-surface recuperator is a plate-fin heat exchanger constructed by stacking plates and fins and furnace-brazing the assembly to produce a monolithic structure. The ability to use different fin dimensions and spacing on each side provides excellent design flexibility in optimizing the configuration to accommodate the different flow characteristics of each stream. Experience has shown, however, that the stiff monolithic construction responds poorly to the extreme transient and steady-state thermal strains encountered in high-temperature gas turbine recuperator applications. A promising approach to addressing the durability issue features a plate-fin structure that is sufficiently compliant to accommodate severe thermal strains without failing [4, 5]. The basic concept involves stacking individual brazed fin unit cells, which incorporate stamped circular flanges at each end. The flanges are welded together to form a bellows-like structure that can flex and elastically absorb the extreme thermal strains encountered during engine operation. This unit-cell construction results in a design that is significantly more durable than conventional configurations.

Another approach, which offers excellent durability, is the Printed Circuit Heat Exchanger (PCHE) [6]. The PCHE configuration is manufactured by chemically etching semicircular flow channels onto metal plates of stainless steel or other high temperature material. A different etching pattern is used for each of the two streams. The plates are then stacked alternately, and the assembly is diffusion-bonded to produce an extremely robust structure. One disadvantage is that the semicircular shape of the flow channels leaves a metal web between adjacent passages, and this represents a significant amount of material and corresponding weight. Current developments are underway to modify the passage geometry and diffusion bonding process so as to reduce weight [7].

For all recuperator designs, the properties of the material of construction have a critical influence on the long-term reliability and durability of the configuration. In this regard, the most important properties are resistance to creep and to oxidation at the operating temperatures, and pressures encountered in gas turbine engine applications. In most existing designs, the 300 and 400 series of stainless steels provide acceptable performance. Increasing demands to achieve ever higher cycle efficiency levels are pushing the maximum system temperatures to the 1800°F level. In response, significant efforts are underway to investigate advanced materials for recuperator applications [8-10]. Materials under consideration include both nickel- and iron-based alloys such as alloys 840, 800H, 864, 625, 617, Haynes 214, and Plansee alloy PM2000. The ultimate challenge will be to identify and select materials that provide sufficient life at reasonable cost.

Bearing and Seal Requirements

The design of a successful bearing system for a high-speed turbomachine is integrally linked to the rotordynamics. The bearing system must supply adequate load capacity, plus appropriate stiffness and damping, to ensure that the rotor system has minimal motion from residual unbalance and is not prone to instabilities. Instead of oil- or grease-lubricated bearings, it is proposed that hydrodynamic bearings using air to generate a hydrodynamic film that supports the shaft be used as the lubricant. The most common type of gas-lubricated journal bearing is the foil bearing. The rotating shaft is supported by a compliant foil journal lining. Once the shaft is spinning fast enough, the working fluid pushes the foil away from the shaft so that contact no longer occurs between the shaft and the foil. The shaft and foil are separated by the hydrodynamic high pressure generated by the rotation pulling gas into the bearing via viscosity effects. A high speed of the shaft with respect to the foil is required to initiate this air gap, and once this has been achieved, no wear occurs. Unlike aero or hydrostatic bearings, foil bearings require no external system for pressurized working fluid, so the hydrodynamic bearing is self-starting. The disadvantage associated with foil gas bearings is their relatively low load capacity, in addition to wear during start-up conditions where the foil and shaft are in contact. Excellent work is being undertaken by a number of researchers to develop predictive tools for foil bearings that are validated against test measurements [11].

Just as bearings are coupled to the rotordynamic performance of turbomachines, the seals are coupled to the aerodynamic performance of the same turbomachinery. To only a slightly lesser degree, the rotordynamics and seals are also coupled. The most common seals used in high-performance turbomachines are mechanical seals and labyrinth seals. Mechanical seals are commercially available, but are limited by a speed and load parameter. If a mechanical seal can be applied, then zero or near zero leakage can be maintained. Alternatively, a gas seal with a small leakage rate can be applied, and the most common gas seal can be applied, such as a labyrinth seal.

A labyrinth seal is composed of many straight grooves that press tightly inside another axle or inside a hole, so that the fluid has to pass through a long and tortuous path to escape. Sometimes labyrinth teeth exist on the outer and inner portions. These interlock, producing the long characteristic path to slow leakage. For labyrinth seals on a rotating shaft, a very small clearance must exist between the tips of the labyrinth threads and the running surface. Labyrinth seals on rotating shafts provide non-contact sealing action by controlling the passage of fluid through a variety of chambers by centrifugal motion, as well as by the formation of controlled fluid vortices. At higher speeds, centrifugal motion forces the liquid towards the outside, and therefore, away from any passages. Similarly, if the labyrinth chambers are correctly designed, any liquid that has escaped the main chamber becomes entrapped in a labyrinth chamber, where it is forced into a vortex-like motion. This acts to prevent its escape, and also acts to repel any other fluid. Because of the leakage rates, these seals detract from the aerodynamic performance. The disadvantage associated with labyrinth seals is

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the destabilizing aerodynamic cross-coupling, resulting in instabilities in the rotordynamics. A number of stabilizing aspects can be employed to improve the rotordynamics. These include: honeycomb seals, hole pattern seals, compliant finger seals, and foil seals.

CONCLUSION

Technology advancements in computational fluid dynamic modeling tools available for designing small-scale compressors and turbines, combined with advanced high-strength superalloys and ceramics, offer an important opportunity to develop a high-performance microturbine-generator. While small-scale microturbine-generators have been built, thermal efficiencies suffer significantly from poor compressor and turbine performance. The need to increase turbomachinery adiabatic efficiencies to levels approaching 80% is a critical design goal that can be met through sound design practices buttressed by advanced computational mechanics tools. Further, high-strength superalloys and ceramics are making possible the fabrication of components that can operate at the high temperatures necessary to achieve excellent thermal efficiencies.

Compact, high-speed generators are also becoming commercially available for microturbine systems. A key issue is cost-effective systems integration based on synergistic deployment of advanced technologies over a wide range of disciplines, including aerodynamics, rotordynamics, combustion, heat transfer, and mechanical design. Given a concentrated effort, a compact, high-performance microturbine-generator should be very achievable for military portable power requirements.

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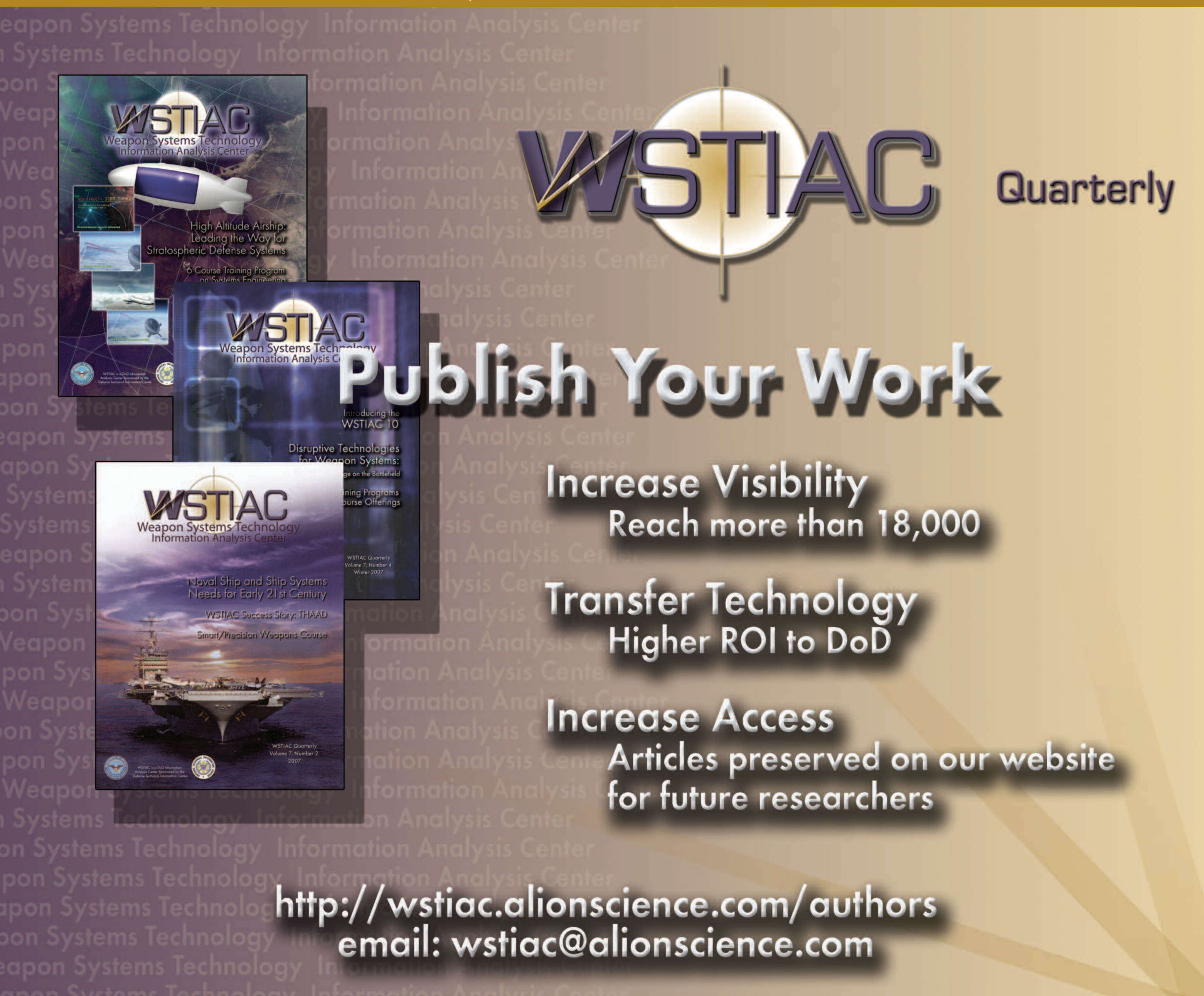

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