

# DSIA JOURNAL

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# ELECTRICAL

INFRASTRUCTURE

PAGE 24

PAGE 4

ACTIVE ELECTRONICALLY  
STEERED ARRAY (AESA)  
ANTENNA TESTING

PAGE 9

MEASURING COMBUSTION  
PRODUCTS IN SMALL ARMS  
BLOWBACK GASES

PAGE 16

MODULAR HUMAN  
SURROGATE FOR  
NON-LETHAL WEAPONS  
(NLW) TESTING

PAGE 34

AMERICAN  
"ASTROLOGISTICS"



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# DSIAC JOURNAL

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## CONTENTS

**4** Active Electronically Steered Array (AESA) Antenna Testing ▶  
**MS** Military Sensing

**9** Measuring Combustion Products in Small Arms Blowback Gases ▶  
**WS** Weapon Systems

**16** Modular Human Surrogate for Non-Lethal Weapons (NLW) Testing ▶  
**NW** Non-lethal Weapons  
*\*Technology Spotlight*

**24** Sustainable Mobile Electrical Infrastructure ▶  
**DE** Directed Energy

**34** American “Astrologistics” ▶  
**EN** Energetics

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## MESSAGE FROM THE EDITOR



By **Brian Benesch**

**A**s an extension to our regular operations, the DSIAC Basic Center of Operation (BCO) has conducted 58 externally-funded efforts to date on behalf of the defense system (DS) community. These externally-funded efforts are known as core analysis tasks (CATs). CATs are established in support of DS government customers who want to leverage DSIAC expertise for specific scientific or technical research and analysis efforts that exceed the DSIAC BCO's free services (such as technical inquiries). DSIAC has had the privilege of augmenting our BCO mission support to the DS community, averaging 10+ CATs per year since its establishment in the beginning of 2014.

Although the work performed as part of a CAT varies in terms of the work scope specifics, it carries a few common traits. CAT work is within the technical scope of DSIAC's mission (i.e., related to any of the nine focus areas chartered to DSIAC) and is analytical or research related.

CATs are established in support of defense system government customers who want to leverage DSIAC expertise for specific scientific or technical research and analysis efforts that exceed the DSIAC BCO's free services.

Additionally, each CAT produces new scientific and technical information that is uploaded to the Defense Technical Information Center (DTIC) for knowledge reuse within the U.S. Department of Defense (DoD) community. Finally, CAT projects are always less than 1-year efforts, with funding that cannot exceed \$1 million.

We have performed a variety of work efforts for various different government customers. For example, DSIAC developed a survivability training program for The Office of the Director, Test & Evaluation; designed and tested a technology prototype for the U.S. Army Research Laboratory (ARL); implemented an analytical war-gaming capability for the U.S. Air Force Research Laboratory; characterized tire damage to combat vehicles for the Program Management Office Advanced Amphibious Assault; conducted reliability analysis of weapon systems for the Army Materiel Systems

Analysis Activity; and established a multifunction radio frequency radar database for the Defense Advanced Research Projects Agency and ARL. These are just a sampling of the vast array of work we have done under CAT efforts.

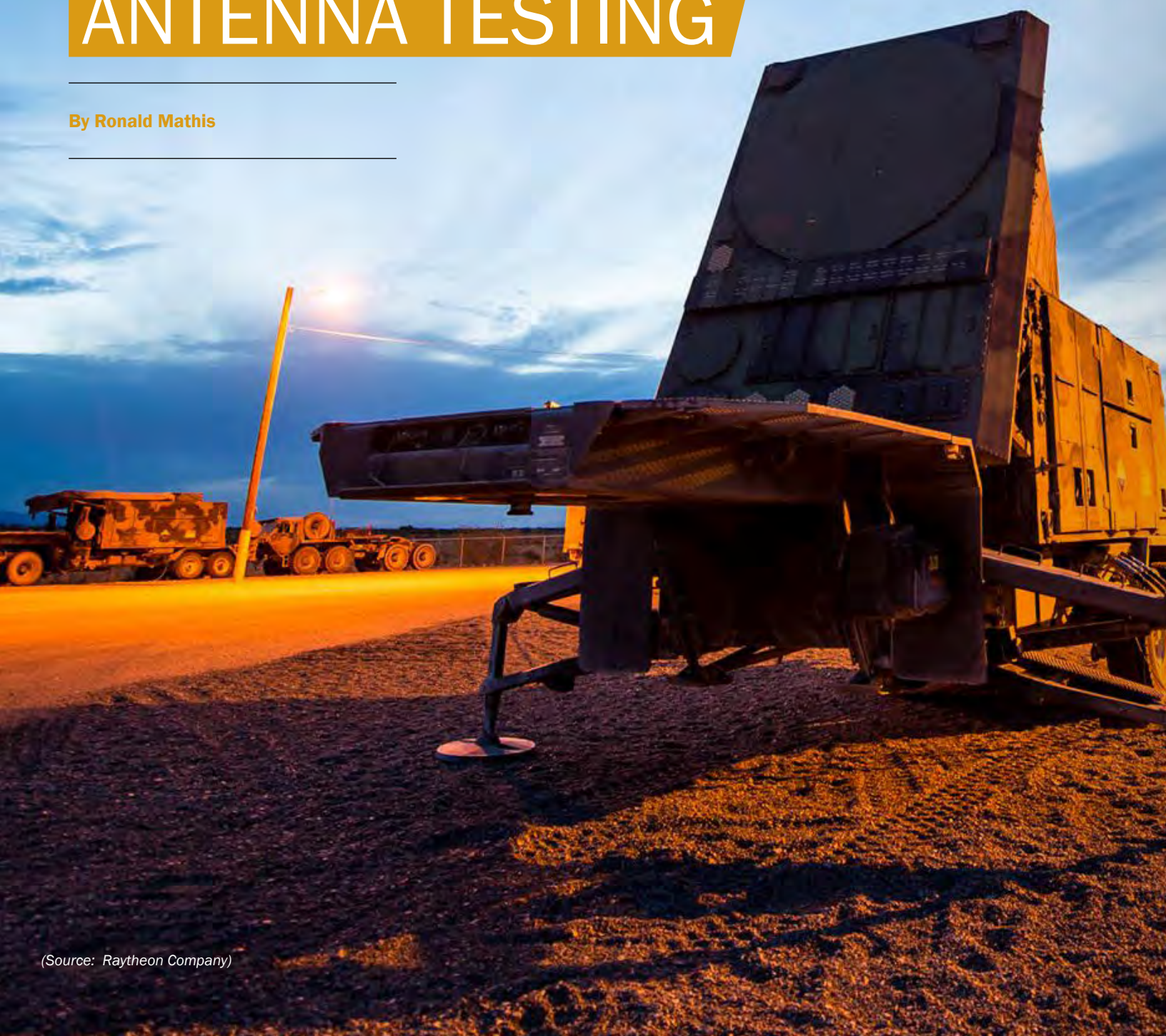
The CAT program provides the DoD community with a contracting vehicle to obtain specialized support for specific projects from DSIAC. You can easily and directly obtain DSIAC support for your project by using a CAT; the process to initiate one is designed to be fast, flexible, and low cost. CATs are normally awarded within 6 to 8 weeks from the time that the work requirements are defined and approved. For more information on the CAT program, visit DTIC's newly-updated website (<https://dodiac.dtic.mil>) and/or contact us at DSIAC directly ([contact@dsiac.org](mailto:contact@dsiac.org) /443-360-4600). We look forward to continuing to support the DoD, not only through our regularly scheduled BCO activities, but through our additional CAT work as well. ■

A handwritten signature in black ink that reads "Brian Benesch".

# ACTIVE ELECTRONICALLY STEERED ARRAY (AESA)

## ANTENNA TESTING

By Ronald Mathis



## INTRODUCTION

**A**ctive electronically steered array antennas are replacing conventional single-beam antennas in many of the new and emerging weapons systems. AESA antennas are not new, but their use is expanding because new technologies are enabling higher power, more compact implementations. This article describes the expanded test requirements for AESA antennas over single-beam antennas and describes a new test system approach. The new approach enables multiple simultaneous measurements, reduces test time, and enables closed-loop testing.

## ANTENNA TESTING

Antennas may be tested individually or as part of a subsystem or system, such as a radar, jammer, or an aircraft. Tests are frequently conducted in anechoic chambers because they are more compact than outdoor ranges and the chamber eliminates interference with other radio frequency (RF)/microwave systems near the test facility. Tests are typically conducted to verify performance and may include measuring a variety of parameters such as power, signal fidelity, beam shape, beam polarization, beam pointing accuracy, and beam scan or switching rates.

Mechanically-steered, single-antenna, single beam systems do not normally require complex test setups. A few, or even a single test antenna (referred to as a probe horn), are mounted on a support or on the wall of the chamber. Scanning is performed by moving the antenna under test (AUT), which is mounted on a positioner. Rotation in azimuth and elevation can be performed either by the positioner or the beam-steering system of the AUT or some combination of the two. A typical test setup for a single antenna is illustrated in Figure 1.

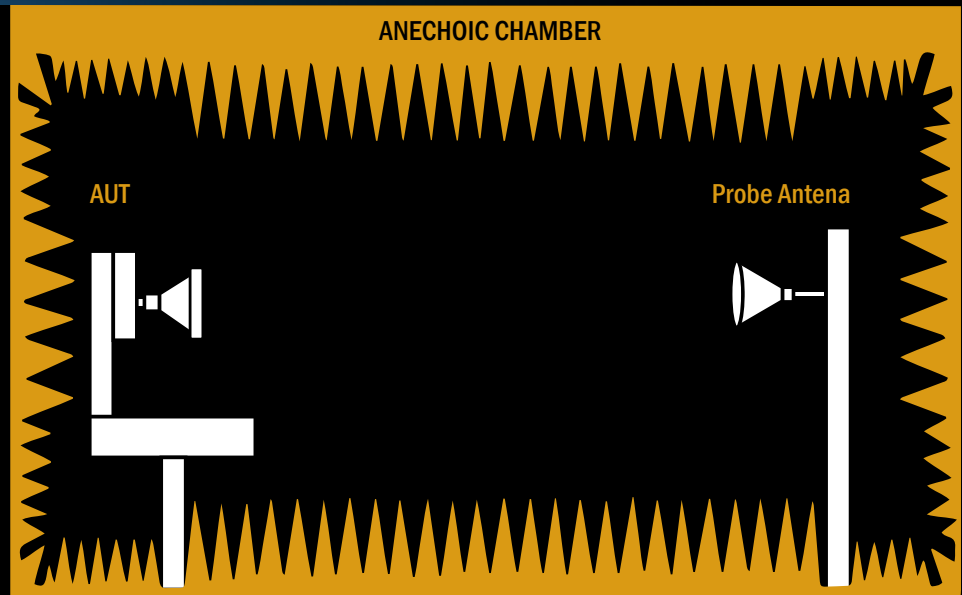


Figure 1: Typical Single-Antenna Test Chamber (Source: U.S. Naval Air Systems Command [NAVAIR]).

## CHALLENGES OF AESA ANTENNA TESTING

AESA antennas are fundamentally different from single-, mechanically-steered antennas. They consist of a two-dimensional (2-D) array of antenna elements and are controlled electronically by adjusting the phase differences between elements. The array structure can remain fixed, while the antenna beam can be steered electronically over a large range of angles. Multiple beams are produced by dividing the 2-D array of elements into subsets of elements or subarrays. Each subarray can be controlled independently of the other subarrays. Therefore, each of the subarrays can simultaneously point beams in different directions and radiate or receive different signals at different frequencies. Figure 2 illustrates a phased array operating in a single dimension, where the relative phase between each element of an array of individual antennas is adjusted to form and steer a beam in a particular direction.

Some of the key capabilities/test issues of AESA antennas can be summarized as follows:

1. The antennas can produce multiple independent, simultaneous beams.
2. The beams may be static or dynamic (stationary or sweeping in azimuth or elevation).
3. Beams can also switch rapidly to different directions and between different polarization states.
4. The increased number of degrees of freedom of a multibeam AESA system exponentially increases the number of test points. This increase, in turn, substantially increases test time, even with test automation.
5. Closed-loop testing, in which the AUT is integrated with other systems in a hardware-in-the-loop simulation, produces dynamic, nondeterministic beam movement. This means that the specific direction that any beam will point during a test cannot be known prior to a test but must be determined in near real time.

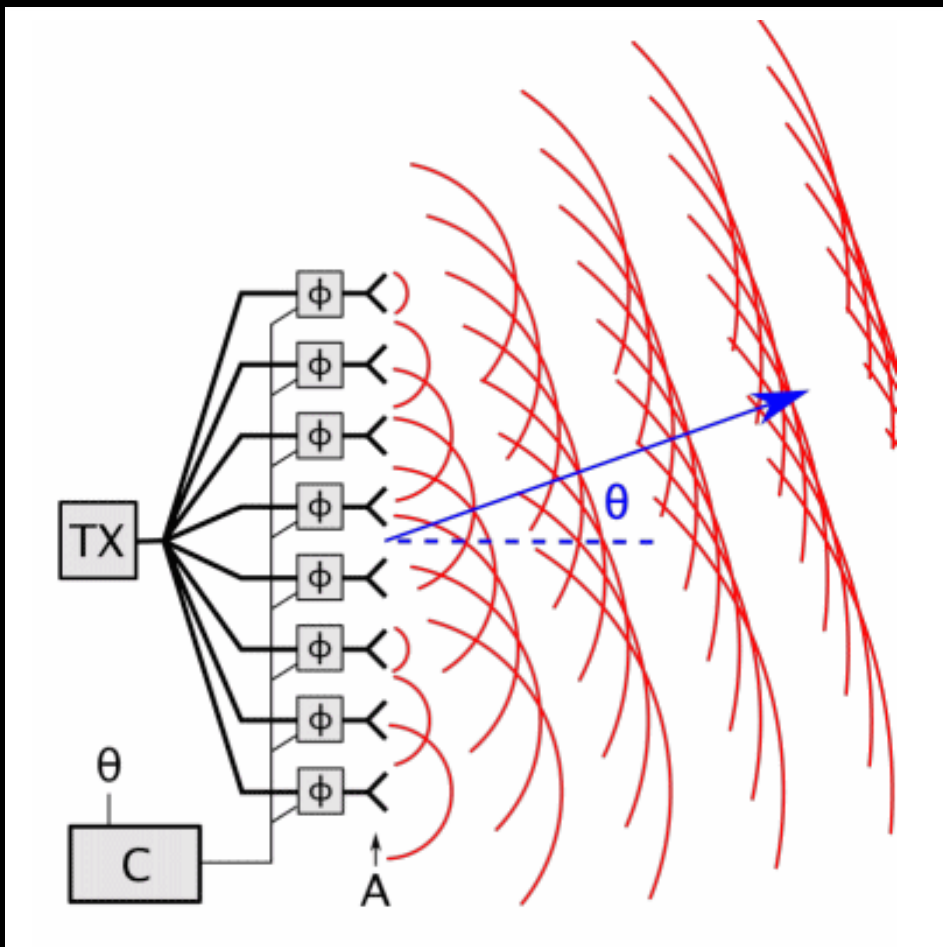


Figure 2: Illustration of a Phased Array Antenna (Source: NAVAIR).

AESA antennas also have some challenges (e.g., transmitting broadband signals at different angles). Since beam steering is based on phase and phase is frequency dependent, beam pointing is strictly narrowband. This means that the shape of broadband beams will vary as direction is changed—a phenomenon known as beam squint. It is also possible that broadband signals may be distorted at large angles. While it may be possible to partially compensate for this effect, this distortion does add to the test's complexity. One question is how much modulation degradation is produced by a beam pointed far off boresight compared with the same modulation when the beam is pointed along boresight (i.e., normal to the plane

of the antenna array). Another issue is isolation between subarrays. Will the modulation on one subarray affect the modulation on an adjacent subarray? If so, by how much? These and other issues add to the test's complexity of AESA antennas.

AESA antennas have been a versatile and useful means of expanding the effectiveness of weapons systems. However, thorough testing of AESA antenna systems is more complex than systems with mechanically-steered, single-beam antennas. A complete characterization of system performance requires additional testing unique to AESA systems.

AESA antennas have been a versatile and useful means of expanding the effectiveness of weapons systems.

### NEW AESA ANTENNA TEST APPROACH

Figure 3 illustrates the new test system approach. The beam or beams from the AESA antenna are detected using a 2-D array of probe horns mounted on the chamber wall. Individual probe horns are connected to an RF switch (not shown) by pairs of coaxial cables routed behind the absorber material on the chamber wall. Each beam can be received and tracked simultaneously with the other beams by switching the appropriate probe horns to the appropriate receivers.

The probe horn array is arranged in a square pattern. Other patterns can be envisioned, but any possible performance gain for a different pattern (e.g., a diamond pattern) is not sufficient to warrant additional complexity and cost. There is also a tradeoff between angular resolution and the number of probe horns; this tradeoff is affected by the frequency range for which the chamber was designed. For example, at lower frequencies, the beams are wider and fewer horns are required to intercept beams at any direction. At much higher frequencies, the beams are narrower, and more probe horns are required. An upper frequency range can be reached for which the beams are so narrow that they must be pointed near a probe horn to be received. The optimum arrangement of probe horns is

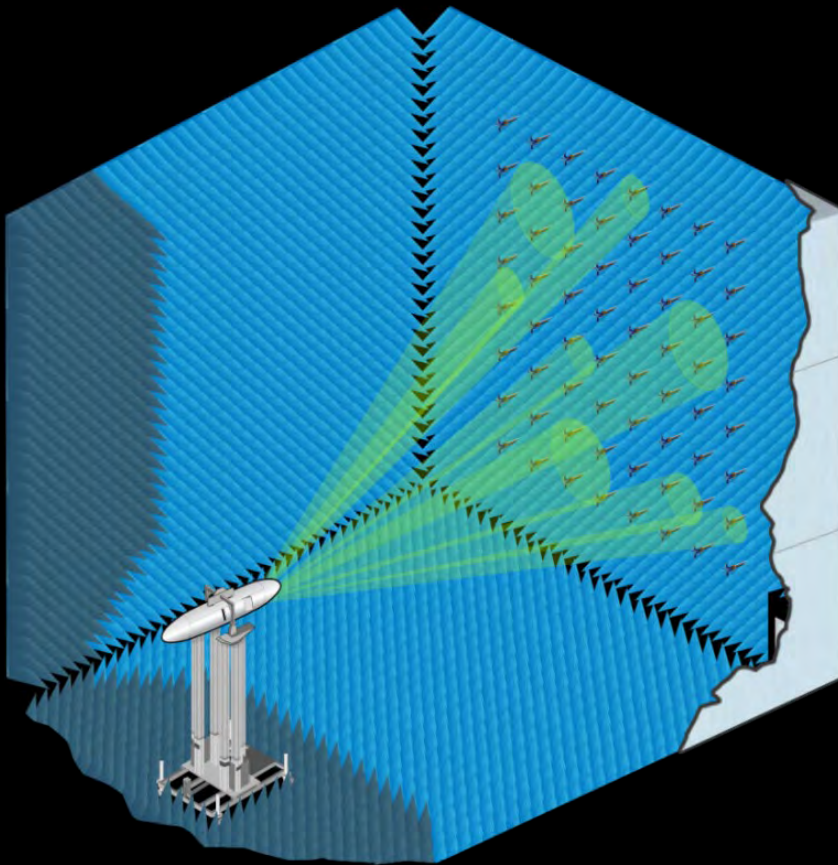


Figure 3: Notional Diagram of a Pod With an AESA Antenna Radiating in an Anechoic Chamber (Source: NAVAIR).

determined by tradeoffs unique to each chamber.

This approach requires a fast, computer-controlled microwave switch. Each probe horn has two outputs to accommodate vertical and horizontal polarization; hence, each horn requires a pair of coaxial cables. The switch must be large enough to accommodate a pair of cables from each probe horn. The number of outputs depends on the number of simultaneous measurements required. More outputs drive up the switch's cost.

## MEASUREMENTS

### Static Measurements

Static measurements, such as power, polarization, and signal fidelity, are

the same for any antenna and do not normally require a large array of probe horns. In fact, static tests of a multibeam system could be performed with a single-probe horn by rotating the AUT so that each beam is sequentially pointed at the single-probe horn. Of course, this single-beam approach is much slower than a parallel approach. It is also possible to increase the number of fixed probe horns to accommodate multiple simultaneous fixed beams. This would enable multiple simultaneous static measurements in fixed directions.

### Fixed Static Measurements

Fixed static measurements are not generally adequate for fully testing AESA antennas because of their dependence

on transmit angle. For example, a static measurement of signal fidelity at boresight must be repeated, with the beam pointed at other angles because of its dependence on angle. Again, such tests can be carried out with a single probe horn by rotating the AUT but with the substantially increased number of test points; the test time will increase accordingly. Fully testing an AESA antenna requires the ability to test each beam over its full range of directions. This measurement concept enables testing independent, multiple simultaneous beams.

### Dynamic Measurements

Testing each beam over its full range of directions also enables dynamic measurements, such as beam switching time. Since AESA antennas can be electronically steered, they are typically capable of near-instantaneous switching between different directions. Further, each beam can function independently of, and simultaneously with, the other beams. This measurement approach enables multiple simultaneous dynamic measurements.

The most challenging example of dynamic measurements is when the AUT is controlled by external systems in other laboratories enabling remote or even closed-loop operations. In the case of a closed-loop operation, the beam direction is stochastic—its exact position in time cannot be predicted prior to the test. This measurement approach enables beam tracking during closed loop testing.

### Beam Position Measurements

One of many tests for AESA antennas is to verify that the actual beam direction coincides with the expected direction. This new approach was initially motivated by a requirement to determine a beam direction without a

prior estimate of the direction, and such a measurement is possible. However, in most test scenarios, an expected beam direction is known. Even with closed loop testing, an approximate expected direction or path can most likely be estimated.

Determining beam location is based on measuring the power at the four horns closest to the expected location. Then, a surface fit routine is used to find the actual beam location. The surface fit procedure requires knowing the beam shape at each probe horn and conducting a calibration procedure prior to testing in which the beam shape at each probe horn is measured and recorded.

Tracking a beam that is moving during testing is also possible. A series of position measurements are made, with the step size determined by the time it takes to compute a position. Each new position is estimated from the previous position and the expected path and slew rate. When the next measurement is made, the estimated position is updated. This iterative measurement-prediction approach is similar to that used in navigation applications of Kalman filtering. This process can be used to extend the operation to higher frequency beams not always visible to four adjacent probe horns.

Finally, with multiple simultaneous beams, overlapping beams are possible. When two beams are each pointed near the same probe horns and partially overlap, separately identifying the beams is necessary. In most cases, each beam will typically have a unique frequency, thus enabling band pass filtering during post processing to isolate them. However, if they have similar frequencies, modulation can be used to mix each beam to a unique intermediate frequency that can be separately filtered.

Since AESA antennas can be electronically steered, they are typically capable of near-instantaneous switching between different directions.

## SUMMARY

AESA antennas are much more complex than single-beam mechanical antennas. For example, the angular dependence of their beam quality, with the potential for multiple simultaneous beams, leads to an exponentially increasing number of test points required to thoroughly characterize a system using an AESA antenna. The traditional single-probe horn approach of one measurement at a time can lead to an impossible length of time required for thorough testing.

The approach described here employs an array of probe horns covering an entire chamber wall. This enables parallel testing of multiple simultaneous beams, thereby substantially reducing test time. This approach also enables tracking a beam or beams at the wall during dynamic testing. ■

## BIOGRAPHY

**RONALD MATHIS** is a physicist for the Electronic Warfare Integrated Laboratory at Naval Air Systems Command, Point Mugu, California, where he researches and develops advanced electronics support mode technologies supporting the electronic warfare (EW) domain. He supports technology for RF sensing, signal processing, identification, detection, tracking, and geolocation of emitters of the ALQ-218 receiver used within the EA-18G Growler. Dr. Mathis has been involved with the Weapons Division for the past 5 years and is a primary contributor in digital signal processing, systems development, and hardware integration and tests. He developed 19 patents related to RF signal processing, including EW applications, using photonics and fiber optics. Dr. Mathis holds a Ph.D. in physics from the Missouri University of Science and Technology.



# MEASURING COMBUSTION

## PRODUCTS IN SMALL ARMS BLOWBACK GASES

By Adam M. Jacob, Douglas Ray,  
Arnt Johnsen, and Daniel Cler

### INTRODUCTION

**B**ecause no standardized method of measuring “blowback” in a small arms system exists, there is a desire to develop one.

When a suppressor is added to a small arms system, it typically tends to increase the system’s back pressure. Fundamentally, back pressure is caused by a reduction in flow rate at the muzzle of the barrel due to an increase in pressure caused by the suppressor. A suppressor traps high-pressure gas and blocks the flow from the barrel’s muzzle. After the flow starts to settle down in the suppressor, a more constant flow field is established. At this point, the suppressor acts more like a plenum attached to the muzzle, allowing the gas pressure to

(Photo Source: Dreamstime.com)



decrease much more slowly as it blows down. Significant pressure can still be present in the chamber when the bolt starts to open. At this point, propellant gases escape from the chamber at the same time they are exiting the muzzle. These gases are “blown back” toward the operator, thus the term “blowback.”

This article describes how electrochemical sensors are used to measure and quantify the combustion products of the blowback gases using suppressed and unsuppressed small arms systems by a “Chamber Test Method” as well as a “Breathing Zone Test Method.” In addition to gaseous combustion products, metals are also aerosolized during combustion and firing of a round and measured.

## EXPERIMENTATION

### **Background and Methodology**

Blowback gases consist of combustion products that result from the burning primer and propellant from the ammunition cartridge within the small arms system as well as metal particles aerosolized from the primer, propellant, and projectile. While the combustion products consist of a variety of gases, the three primary toxic gaseous constituents are carbon monoxide (CO), ammonia (NH<sub>3</sub>), and hydrogen cyanide (HCN).

The effects of these toxins can vary. Carbon monoxide impairs the blood’s ability to transport oxygen. Although this is typically a long-term exposure issue, it is also important for short-term exposure at high concentrations. The effects of ammonia are immediate at the onset of exposure and consist of eye, nose, and throat irritation. The ammonia constituent causes the most significant operational issues in blowback gases due to these physiological effects. Short-duration exposure to hydrogen cyanide

can cause eye irritation, breathing difficulty, headache, nausea, and vomiting [1].

Metals are aerosolized from the primer and propellant as well as the projectile as it travels down the barrel and the outer layer of the projectile ablates. This can also cause short-term onset of health issues, most commonly called “metal fume fever” [2]. Metal fume fever typically results in flu-like symptoms. Some of the primary metallic toxins of interest are copper (CU), zinc (Zn), bismuth (Bi), and lead (Pb).

A two-pronged approach at measuring blowback was used. First, blowback was assessed from a “total blowback” standpoint, measuring the total gases and aerosols that are blown back out of the weapon’s chamber and operating group area. This is called the “Chamber Test Method.” Next, blowback was measured and assessed from the system level considering the directionality of the event and measuring the blowback gases that reach the operator’s breathing zone. This is called the “Breathing Zone Test Method.”

In most cases, the full system toxicity (weapon and ammunition) has previously been measured by using TOP 2-2-614, “Test Operations Procedure: Toxic Hazards Tests for Vehicles and Other Equipment” [3]. The ratio of each gaseous constituent is already known. As such, much can be gained simply from measuring the concentration of only a single gas (called an “indicator gas”) and then estimating the concentrations of other gases based on the known ratios to that indicator gas. In the case of current propellants, CO is the most prevalent toxic gas, is the easiest to measure, and is a good choice for an indicator gas. While adding a suppressor to the system could have some small effect on the combustion

compared to the unsuppressed system, this effect would be negligible.

Strategic data collection through a systematically designed experiment provides a gateway to answer questions about what input variables are driving changes in the output of a system, product, or process and to establish traceability. The key advantage of using designed experiments is that the experimenter controls which combinations of inputs are explored. This allows control over which ranges to explore as well as establishes relationships between inputs and outputs. It is the direct opposite of observational data, where the user has no direct control and there is no active manipulation of inputs. Design of experiments and thorough test planning facilitates managing statistical risk in achieving test objectives and ensures test matrix balance and test execution robustness to support meaningful, valid, statistically defensible results.

The test matrices for each test method were designed using design of experiments (DOE) best practices, leveraging analysis from past test data to inform the prospective power and sample size analysis, and assuming 95%

Design of experiments and thorough test planning facilitates managing statistical risk in achieving test objectives and ensures test matrix balance and test execution robustness.

statistical confidence, 80% minimum threshold for statistical power, standard deviation (root mean squared error [RMSE]) determined from within-group variations in previous analysis (peak CO = 124 ppm), factors, and factor-levels of interest (firing mode, inlet side, and configuration). A set of 32-run matrices provides approximately 80% power to detect effects equal to or greater than the within-group standard deviation (RMSE) for all main effects and two-factor interactions, 98.3% power to detect effects equal to or greater than 1.5 x RMSE, and 99.97% power to detect effects equal to or greater than 2 x RMSE for all main effects and two-factor interactions (at 95% statistical confidence).

Randomization, replication, and blocking are fundamental to DOE. Randomization is used to minimize the risk of nuisance variables, such as temporally correlated error sources, thus corrupting the test results. With some risk, modifications can be made to statistically “ideal,” full randomization for practical test execution reasons (as done with this test matrix). However, it is imperative that the test be run in the order specified in the test matrices rather than reordering to simplify test execution because this will result in significant reduction to test statistical power.

### **Chamber Test Method**

The objective of the Chamber Test Method is to measure the direct effect adding a specific suppressor or muzzle device has on the amount of gases and aerosolized metals blown back toward the operator (Figure 1). The chamber method was performed by measuring the concentration of the total amount of toxic gases and the mass of filtered metallic aerosols blown backward into a chamber of known size with the suppressor or muzzle device in question

installed. A handheld gas analyzer was used for all gas measurements [4]. Metals were collected by passing air from the chamber through an Isopore membrane filter with a 0.4- $\mu\text{m}$  pore size produced by Millipore (HHTTP type). The filter used a three-piece, 37-mm cassette, with the end cap remover to allow the whole filter face to be exposed to the gas inside the chamber. The air was pulled through the filter at a flow rate of 2 liters per minute by an AirChek

XR5000 pump from SKC. The sampling time was 3 min. Thus, the total amount of air that passed through the filter was 6 liters.

The chamber design follows closely with previous work in toxicity measurements [5]. Since the chamber volume and, therefore, the measured gas concentrations can vary depending on the weapon, scenario, and configuration tested, quantity of gas is reported by



Figure 1: Chamber With Weapon Muzzle Inside (Total Propellant Gas, Top) and Muzzle Outside (Blowback Gas Only, Bottom) (Source: Norwegian Defence Research Establishment [FFI]).

mass. If the number of moles present and the molecular mass of a gas are known, the mass of that gas can be calculated using Equation 1.

$$m_{gas} = n \times M_{gas}, \quad (1)$$

where  $M_{gas}$  is the mass of the gas in grams (g),  $n$  is the number of moles, and  $M_{gas}$  is the molecular mass of the gas in grams per mole (g/mol).

The ideal gas law can be used to calculate the number of moles ( $n$ ) of each gas using Equation 2.

$$n = \frac{P \times V_{gas}}{R \times T}, \quad (2)$$

where  $P$  is the pressure in pascals (Pa),  $V_{gas}$  is the volume of gas in cubic meters ( $m^3$ ),  $R$  is the ideal gas constant in joules per mole kelvin ( $J/mol \cdot K$ ), and  $T$  is the temperature in degrees kelvin (K).

Since the volume of the chamber is variable and the measured characteristic is a concentration of each gas in parts per million (PPM), the total volume of each gas can be calculated using Equation 3.

$$V_{gas} = V_{chamber} \times C_{gas}, \quad (3)$$

where  $V_{chamber}$  is the total volume of the chamber ( $m^3$ ) and  $C_{gas}$  is the concentration of the gas (PPM).

Equation 3 can then be substituted into Equation 2 to get Equation 4.

$$n = \frac{P \times V_{chamber} \times C_{gas}}{R \times T}. \quad (4)$$

If the gas pressure is approximately atmospheric and the temperature is room temperature, conversion factors ( $k_{gas}$ ) can be calculated for each gas to calculate the mass of each gas in milligrams (mg) by using the molecular mass of each gas (see Table 1). Equation 1 can then be simplified to Equation 5 to calculate the mass of gas in milligrams.

Table 1. Conversion Factors for Mass Calculations

GAS	CONVERSION FACTOR ( $k_{gas}$ )
CO	1.16
HCN	1.12
NH <sub>3</sub>	0.71

$$m_{gas} = k_{gas} \times C_{gas} \times V_{chamber}. \quad (5)$$

To analyze metals, each filter was digested with 10 ml of aqua regia (mixture of HCl and HNO<sub>3</sub>) at 175 °C for 30 min in a Mars 6 microwave instrument from CEM. After digestion, the sample was transferred to a 100-ml bottle and diluted to 100 ml with ultrapure water. The diluted sample was analyzed by inductively coupled plasma-sector focusing mass spectrometry, inductively coupled plasma-atom emission spectroscopy, and atomic fluorescence spectroscopy at ALS Scandinavia AB in Luleå, Sweden. The following elements were analyzed: Fe, As, Ba, Cd, Cr, Cu, Hg, Mn, Ni, Pb, Zn, Sn, Sr, Bi, Sb, Ti, Co K, Mg, Na, Al, Ca, Mo, and V.

## Breathing Zone Test Method

The objective of the Breathing Zone Test Method is to assess blowback from a system level by measuring concentrations of toxic gases in the location of the weapon system operator's breathing zone during firing with a suppressor, muzzle device, or other accessory of interest. Metals were not filtered or analyzed during this test method.

Testing was performed in an indoor range. A 4- by 8-ft sheet of plywood was used as a blast wall between the muzzle and the rest of the weapon, including the gas block. The weapon was hard mounted with its muzzle placed through the center of the blast wall. This prevented muzzle gases from mixing with blowback gases during measurement and ensured that the environment was free of airflow, wind, and obstructions during data collection. A 4-inch air inlet funnel was affixed at the location of the operator's breathing zone, as measured from an approximate 50% operator shouldering the subject weapon system. Testing accounted for left- and right-handed operators, per Figure 2.



Figure 2: Weapon and Sampling Setup for the Breathing Zone Test Method, Left Inlet (Source: FFI).

## RESULTS AND DISCUSSION

### Chamber Test Method

The results from the Chamber Test Method showed consistent and repeatable results. Using Equations 1 through 5, quantities are reported in milligrams of gas. Figure 3 shows each data point (shown as points) as well as the mean for each configuration tracked by the blue tracking line. Figure 4 shows the analysis of variance (ANOVA).

The primary metallic aerosols measured were Cu, Zn, and Bi. Pb was not measured because lead-free ammunition was used for the test. However, lead would also be of interest in ammunition with lead content in the primer, propellant, or projectile. Results of metallic aerosol measurements for the muzzle inside and outside the chamber, respectively, are shown in Figures 5 and 6.

Note that there is an overall reduction of Cu, Zn, and Bi from the full weapon when a suppressor is added. This indicates that these metals are, to some extent, deposited inside the suppressor when a suppressor is installed on the weapon. Cu is significantly reduced when a suppressor is added. This reflects previous testing, which showed a suppressor gaining weight after extended firing.

When the suppressor is placed outside the chamber, Cu is still reduced with a suppressor. However, Zn remains relatively unchanged, and Bi increases. This is likely because the primary source of Cu is the projectile and these particles substantially leave the muzzle during firing. In contrast, the primary source of Bi is the propellant. When the gases are blown back, the aerosolized Bi particles are then blown back as well, increasing the total amount in the blowback gas.

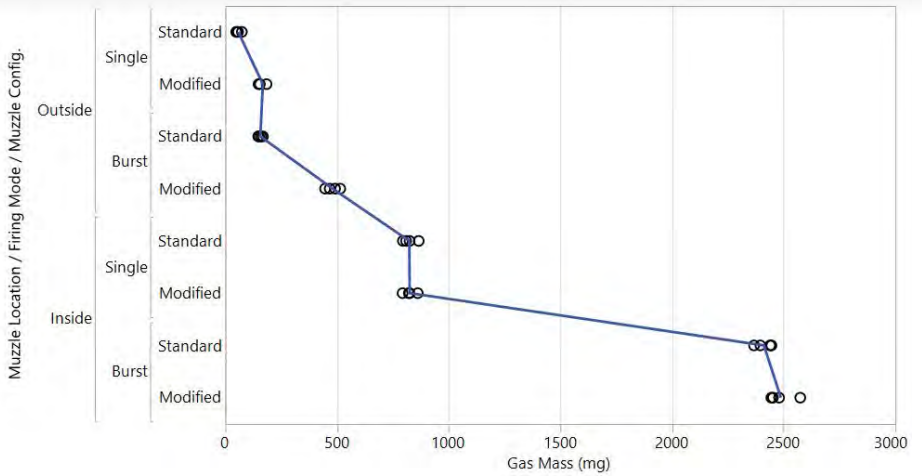


Figure 3: Mass of CO Produced – All Shots (Source: U.S. Army Armament Research, Development and Engineering Center [ARDEC]).

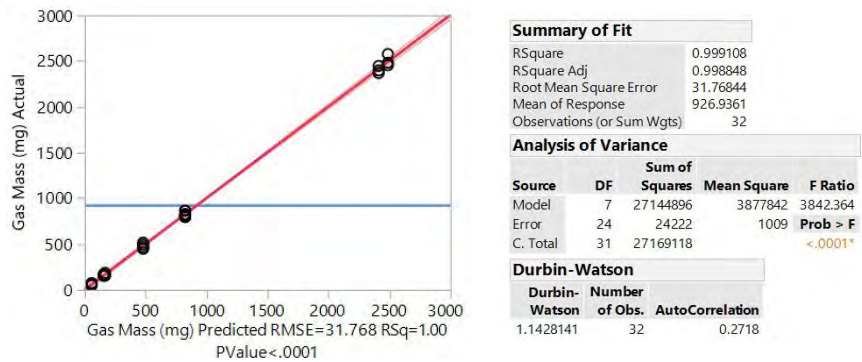


Figure 4: Actual vs. Predicted Mass of CO and Summary of Fit and ANOVA (Source: ARDEC).

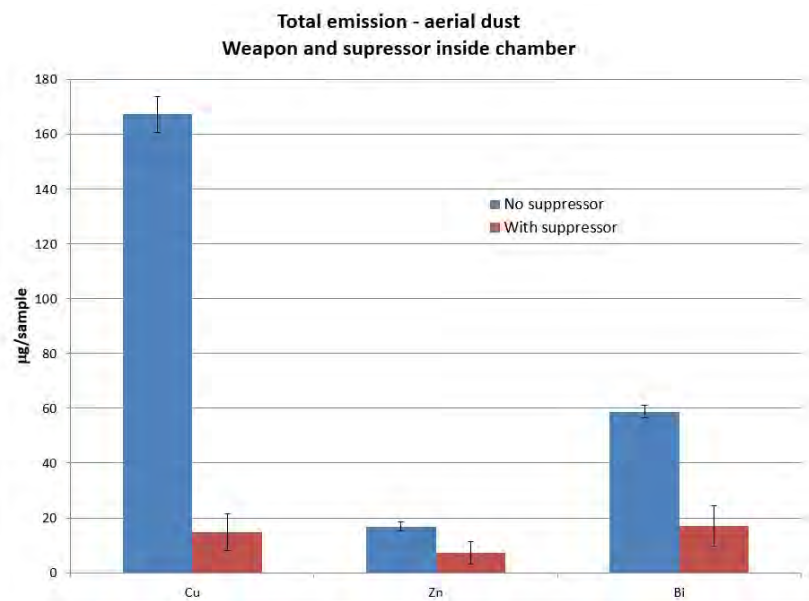


Figure 5: Mass of Aerial Dust Produced – Full Weapon Inside Chamber (Total Dust) (Source: FFI).

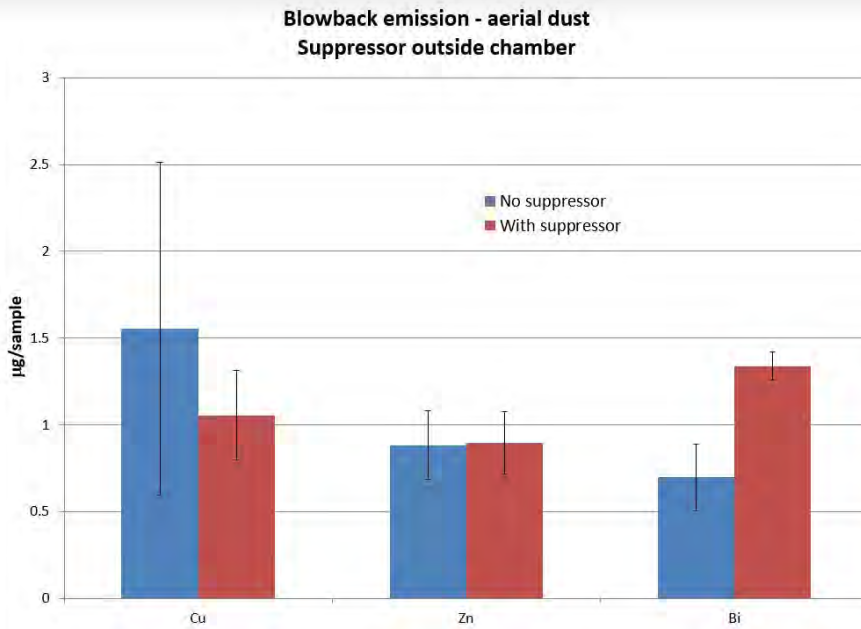


Figure 6: Mass of Aerial Dust Produced – Muzzle Outside of Chamber (Blowback Dust Only) (Source: FFI).

### Breathing Zone Test Method

The results from the Breathing Zone Test Method were not as consistent or repeatable but showed insight and basic trends into what happens with the gas after it leaves the chamber and operating group of the weapon in a given configuration. Quantities are reported in concentration of gas in PPM and are reported in 45-s time weighted averages. Peak, 15- and 30-s time weighted averages, were also calculated but not reported here. Figure 7 shows

each data point for 45-s time weighted averages (shown as points) as well as the mean for each configuration tracked by the blue tracking line. Figure 8 shows the ANOVA.

### CONCLUSIONS

Adding the suppressor to the weapon system results in measurable differences of blowback gases using the methods described. While certain toxins were measured for this test, it is important to tailor the measurements

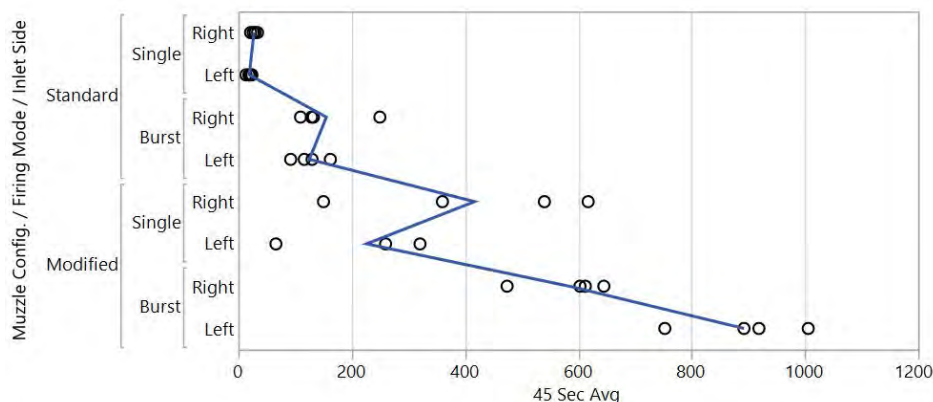


Figure 7: Concentration of CO Produced – 45-s Time Weighted Averages – All Shots (Source: ARDEC).

Adding the suppressor to the weapon system results in measurable differences of blowback gases.

to the toxins that are of interest for the assessed system.

The Breathing Zone Test Method is less repeatable but shows different results that would not be observed with the Chamber Test Method alone. Data has shown that this method can measure differences in concentration at the operator's face. This shows that the method can assess directionality, which plays a role in operational impact.

The Chamber Test Method measures the total blowback gases, regardless of directionality after they leave the chamber and operating group. Since chambers of different sizes can be used to account for potentially different sized weapons or different amounts of gases produced, Chamber Test Method results should always be reported in mass of gas to eliminate the effect of the chamber volume on the results. This allows appropriate comparison of results between different chambers, regardless of size. The Chamber Test Method, in contrast to the Breathing Zone Method, is very repeatable and consistent but does not consider the system-level effects, such as other changes to the weapon system to redirect the gas. This indicates that neither method alone is sufficient to assess the true operational impact of the blowback gas and the best assessment is the combination of both methods.

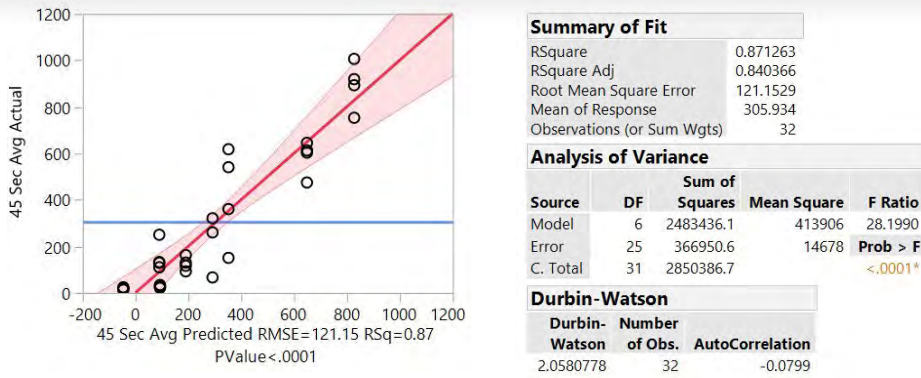


Figure 8: Actual vs. Predicted Concentration of CO Summary of Fit and ANOVA (Source: ARDEC).

The metallic dust filtering showed that, in general, metals aerosolized from the projectile are largely deposited within the suppressor. Metals aerosolized from the primer and propellant constituents tend to blow back proportionally with the rest of the blowback gases in the system.

Finally, it is important to consider that the order of testing is critical to randomize error. The order of testing was developed through DOE methods, with the intent to randomize error within the test. The important consideration is that one cannot simply test all of one configuration and setup, then switch to next, and so on. Even if that is easier or quicker, it could result in potential systematic error that must be randomized. ■

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(Source: CFDRC).



# MODULAR HUMAN SURROGATE

## for Non-Lethal Weapons (NLW) Testing

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By Keith Sedberry and Shannon Foley

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# INTRODUCTION

**N**on-lethal weapons provide operating forces the needed capabilities to clear personnel, control group movements, target selected individuals, and secure areas without destroying them. The U.S. Department of Defense (DoD) Directive 3000.03E, Policy for Non-Lethal Weapons, dated 27 September 2017, defines NLW as “...explicitly designed and primarily employed to incapacitate targeted personnel or materiel immediately, while minimizing fatalities, permanent injury to personnel, and undesired damage to property in the target area or environment” [1]. In addition, federal and local law enforcement personnel have used NLW since the early 1980s, with the primary goal to prevent or reduce the loss of life and limit the damage done to property. Some of the fielded NLW are shown in Figure 1.

To explore the effects of NLW on human targets, one must first identify the stimuli, its mechanics, and the intended effects. Table 1 shows an example list of NLW stimuli and corresponding metrics for experimental data collection. Reversibility is a key tenet of NLW, and risk of significant injury (RSI) is the metric used to quantify reversibility of human collateral effects [3].

NLW must carefully balance effectiveness with potential injury risk.



Figure 1: Currently Fielded NLW: (a) Acoustic Hailing Device, (b) Green Laser Interdiction System Gun, (c) Taser X26, (d) 12-Gauge Munitions, (e) M-84 Flash Bang Grenade, and (f) Modular Crowd Control Munition (Source: Joint Non-Lethal Weapons Program [JNLWP] [2], U.S. Marine Corps., and Program-Executive Office Soldier).

Figure 2 shows that traditional weapons have a threshold, or dose, that when crossed, measures the effectiveness of the weapon. NLW are bound on both sides by effectiveness and risk of injury [3].

RSI, a critically important system attribute for an NLW, is made up of at least two probabilities—the probability of a given dose and the probability that the dose will cause a significant injury. The probability of delivering a given dose may depend on the hardware, software, and environmental factors. NLW developers must identify the necessary dose to achieve the desired effect while remaining within the bounds of acceptable injury risk. For NLW, effectiveness and injury potential are

frequently the constraints bounding the developmental trade space. Characterizing these two aspects is critical to NLW development and testing. Additionally, operating conditions often influence the dose of the stimuli on the target. Measuring the dose of the stimuli in a realistic environment is often an important aspect of NLW development and testing.

The JNLWP in the DoD has developed software and computer models that predict the risk of significant injury to human targets of these stimuli. The Human Effects Modeling Analysis Program (HEMAP) within the JNLWP’s Human Effects Office has developed a collection of detailed models that provides predictions for a range of human effects and permits a standardized and centralized approach for NLW human effects assessments. HEMAP software includes the capability to assess injury potential from blunt trauma, thermal injury, blasts and

Table 1. NLW Stimuli and Corresponding Experimental Metrics

NLW Stimuli	Metric for Data Collection
Acoustic/auditory	Sound (dB)
Blast/overpressure	Pressure over time
Broadband/laser light	Intensity (W/cm <sup>2</sup> )
Blunt impact	Loading (force)
Electromuscular (Taser, HEMI <sup>a</sup> )	Voltage, PRR, current, charge
RF heating	Temperature (°F/°C/K)

<sup>a</sup> HEMI = human electro-muscular incapacitation.

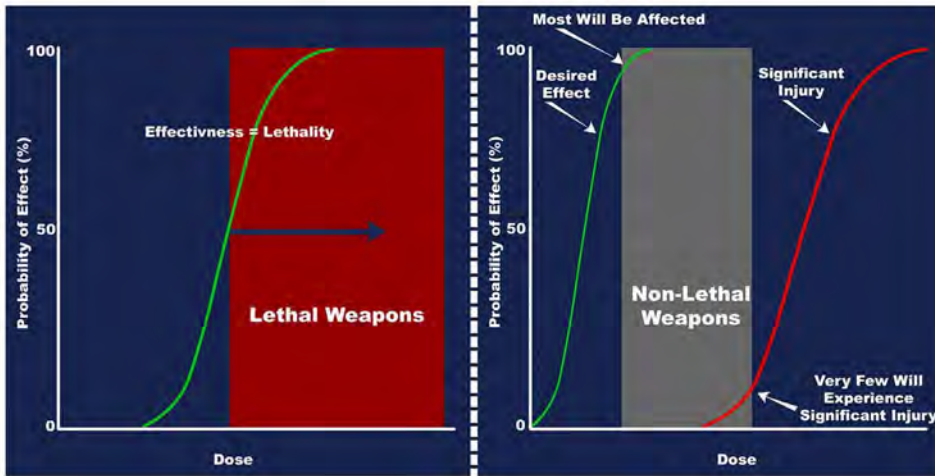


Figure 2: Traditional Weapons (Left) vs. NLW (Right) (Source: JNLWP [4]).

acoustic stimuli, and the visual effects of broadband optical stimuli. Other effects include radio frequency (RF)-directed energy, thermal laser effects, electromuscular (EM) disruption, underwater acoustic effects, mild traumatic brain injury (TBI), and behavioral response effects.

Modeling allows developers to evaluate the effectiveness against the risk of significant injury of an NLW. As part of that process, researchers need to validate, verify, and accredit the various implemented models. For this purpose, the DoD and the NLW community need a common method to gather experimental input data that can be used for comparison to those models, gain meaningful human response data from NLW exposures, and obtain a testing platform with realistic and relevant human features which can gather multiple NLW exposures concurrently. The human-like features of the testing surrogate are essential to accurately represent certain exposure levels. Additionally, mechanical surrogate models are fast running, in complex operational scenarios, and can be used to assess effects of clothing and other artifacts.

The JNLWP has developed software and computer models that predict the risk of significant injury to human targets of these stimuli.

The automotive industry has developed many human surrogate dummies for crash test purposes. Those dummies are calibrated for whole body acceleration and low-velocity, high-mass collisions. Whereas for NLW, blunt impact mechanical response needs to be assessed under conditions relevant to high-velocity, low-mass conditions. Previous NLW surrogates or manikins have focused on one or two areas of interest, such as blast and temperature or acoustics only. Numerous examples have been developed over the years. A manikin for assessing blast incapacitation and lethality was an anthropomorphic test device used to assess blast threats, especially in air-containing

organs [5]. Characterizing potential blast effects is a critical component in the human effects processes for RSI analysis. Johns Hopkins University/ Applied Physics Laboratory (JHU/APL) developed the human surrogate torso model for nonpenetrating ballistic impact [6]. In addition, a human surrogate head model for blast TBI was developed by JHU/APL [7] and demonstrated during live fire blast experiments [8]. Other head phantoms have been created for measuring RF heating inside the head due to magnetic resonance imaging EM equipment [9]. There are numerous acoustic manikins, such as KEMAR and the Bruel and Kjaer 4128 head and torso simulator.

The NLW research and acquisition communities may be best served with a collection of various types of models to meet the variety of needs. Blunt impact injury, for example, may require computation models that are easy to propagate and can quickly assess sensitivity to material property values and projectile ballistic changes, in addition to a high-fidelity test surrogate capable of measuring the various exposures and validating the computational models. This dynamic back and forth between mechanical and computational models provides researchers and developers with an opportunity to characterize and influence the design trade space. Modularity of the surrogate is important for NLW considerations due to the wide variety of stimuli evaluated. Various combinations may need to be tested simultaneously. Further, instrumentation not needed for a given test can be temporarily removed to prevent damage.

To address the needs of the NLW community, a modular human test surrogate was developed that can produce human response data to a wide variety of NLW using a combination of

commercial off-the-shelf (COTS) and custom sensor platforms (Figure 3). This modular human surrogate can be paired with a portable data collection system placed in a testing environment and monitored remotely, as needed. At present, two prototypes of the NLW testing surrogate have been delivered to the JNLWP at Marine Corps Base Quantico, VA.

The modular NLW human surrogate consists of the following parts:

- Anatomical head complete with removable eyes and ears and a rear access panel,
- Neck attachments for fixed or flexible neck interfacing,
- Two torsos using the same form factor—one for blunt impact and one for EM weapon evaluations, and
- COTS and custom sensors and data collection equipment.



Figure 3: Modular NLW Surrogate With Sensors and Data Collection Equipment (Source: CFD Research Corporation [CFDRC]).

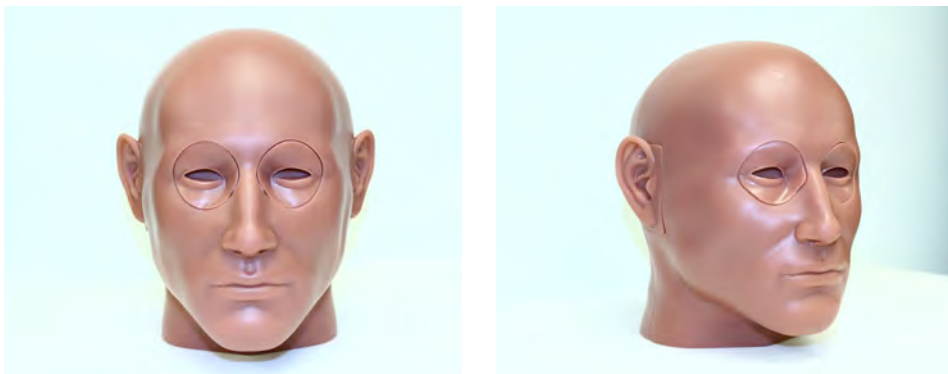


Figure 4: Modular Anatomical Head (Source: CFDRC).

## ANATOMICAL HEAD

The anatomical head was designed after the 50th percentile male geometry and heavily modified to become modular in nature. For example, the eyes and ears were made modular for easy removal or exchange. This is key to replacing a broken sensor or, more importantly, changing the eye or ear sensor hardware for a different testing need. The anatomical head is composed of an outer layer of silicone material representing the skin on a human head. The inner layer of the anatomical head, the skull piece, is made of a harder polyurethane material. Both layers are secured after being produced from molds, improving the integrity and ruggedness of the finalized head for the surrogate. An access panel was designed into the modular NLW human surrogate to allow access to instrumentation before, during, and after testing and to ease switching out sensors based on need. Figure 4 shows the anatomical head.

## REMOVABLE EYES AND EARS

The eyes and ears are made from the same silicone materials as the outer skin of the anatomical head. Design

features were created inside the skull, allowing the ears and eyes to be secured to the head. The modular ears allow two configurations—one with acoustic or pressure sensors mounted at the tympanic membrane area and one for sensors mounted at the entrance to the ear canal. In acoustic testing and characterization, it is important to include the anatomical ear canal, as it acts as a natural amplifier.

## FIXED AND FLEXIBLE NECK

The modular NLW surrogate supports a fixed or flexible neck, depending on whether head movement/acceleration needs to be measured. For example, using a laser-dazzling NLW does not require measuring head movement, so a fixed neck would be ideal for that testing. For a flashbang grenade with pressure, light, and sound components, the head movement in response to the pressure component needs a flexible (and realistic) neck. The modular surrogate supports a flexible Hybrid III neck using a 6 degrees of freedom (6DOF) or other sensor suite to measure head movement. The two neck configurations integrated with the anatomical head using the custom neck attachment are shown in Figure 5.

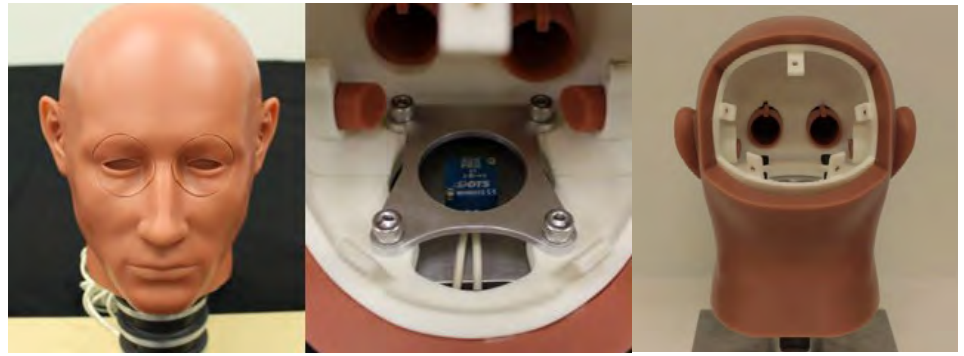


Figure 5: Flexible Neck Configuration (Left), 6DOF Sensor on Neck Mount (Center), and Fixed Neck Configuration (Right) (Source: CFDR).

## TORSO CONFIGURATIONS

The modular NLW surrogate currently utilizes two torso configurations aimed at different NLW testing and evaluation needs (shown in Figure 6). The first embodiment was developed as a modular torso capable of switching out pressure sensors and accelerometers to measure the blunt impact forces on the front of the chest. This configuration has an array of sensors suspended in a blend of materials that can be changed



Figure 6: Blunt Torso (Left), Six-Pad EM Torso (Middle), and Single-Pad EM Torso (Right) (Source: CFDR).

based on testing focus. For example, if higher blunt impact loadings are expected, the sensor suite can be easily switched but still utilize the same form factor. This is important for correlations and future NLW testing needs. The outer layer of this torso has a realistic skin-type material.

The second torso is designed for evaluating EM-type NLW. This torso has the same form factor as the first torso because it is important to maintain consistency across the geometries of the NLW surrogate. The current iteration of the EM torso uses an acrylonitrile butadiene styrene three-dimensional printed back and partial front structure. The front of the torso has a modular and removable single or multipad design

with a conductive foam outer layer. EM NLW such as a Taser use barbs that discharge a voltage which incapacitates a human target. The EM torso on the NLW surrogate has roughly the same resistance as the human body (600 ohm) and can return important metrics such as peak voltage, net charge, pulse repetition rate, pulse duration, etc. Future iterations of this torso could utilize realistic skin-type materials.

One important advantage in using a realistic and anatomical torso is the ability to outfit the torso with articles of clothing or other protective equipment, if desired. For example, a Taser weapon fired into a torso with a heavy jacket might penetrate differently than into a torso test article with no clothing. The

flexibility of this modular NLW surrogate gives NLW manufacturers and designers the ability to evaluate how their weapons will function against a realistic target.

## SENSOR SELECTION AND INTEGRATION

The goal for each sensor solution was to use as many COTS sensors as possible to avoid longer and more difficult integration for data collection.

### Pressure and Sound

COTS pressure transducers in two configurations (tube and pancake) were selected with a 50-psi range because most NLW do not approach this upper threshold. The pressure transducers can be mounted in the eye and at the ear for data collection (Figure 7). For sound, a piezoelectric microphone was

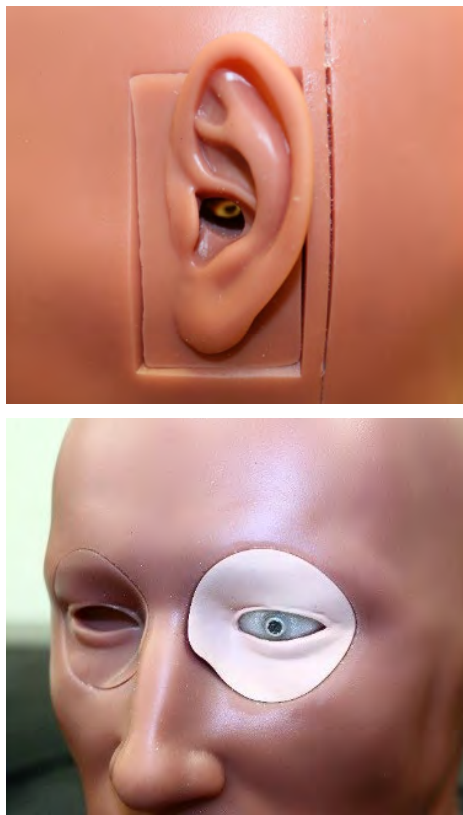


Figure 7: Pressure Sensors Mounted in the Ear at the Tympanic Membrane (Top) and Left Eye (Bottom) (Source: CFDR).

selected with an upper end threshold of 190+ dB. Microphones were placed inside ear at tympanic membrane or outside the ear flush with skin.

### Light

The light sensor was developed in conjunction with JHU/APL. COTS components containing a photodiode, shutter, and optical cable were mounted inside the removable eye, which routed to a control box (Figure 8). This system functions much like the human eye, where the shutter response can be adjusted based on the type of environment the human surrogate is



Figure 8: Eye Sensor Mounted in Surrogate (Top), Benchtop Mount (Middle), and Exposed to Green Laser Light (Bottom) (Source: CFDR).

placed in (light/dark/etc.). As the eye is exposed to broadband or laser light, the shutter closes, mimicking the human eye response. The light exposure data is captured on a separate power meter.

### Temperature

One of the removable eyes was embedded with thermocouples in an array format to capture heating (Figure 9). The thermocouples were placed roughly 3 mm deep in the eye.

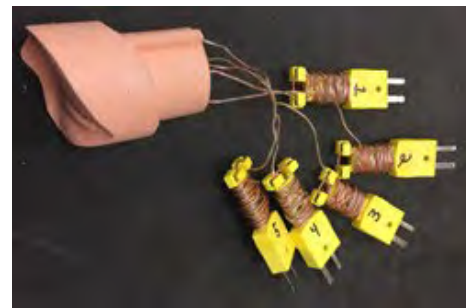


Figure 9: Thermocouples Mounted Into Left Eye (Source: CFDR).

### Blunt Impact

Two areas of importance for blunt impact are the head and the torso. The head of the modular NLW surrogate is outfitted with a 6DOF sensor placed at the top of the neck. This sensor measures linear and angular movement and loadings using a flexible neck (see Figure 5). A modular blunt impact torso was developed in conjunction with APL. The blunt torso uses an array of pressure sensors embedded in a soft tissue simulant and an accelerometer placed on the sternum of the torso. The array of sensors can be changed based on any specific location of interest on the front of the chest (Figure 6).

### EM Torso

The EM torso was designed in two configurations. Initially, the design used a six-pad approach, which evolved into

a singular-pad approach (see Figure 6). Each configuration functions the same, with the singular pad being slightly easier to replace after repeated uses. Each pad uses a conductive foam outer layer, which transmits the voltage data through the custom electronics to the rear of the torso where the electronics box and output cable connectors are located. The overall resistance of the system is like the human body (approximately 600 ohm), with step-down resistors to ensure the voltage sampled is at a safe level for the data acquisition system.

## USE CASE TESTING AND EVALUATION

To date, the modular NLW surrogate has been verified to collect and produce the desired information and metrics for each NLW modality listed in Table 1. While many NLW were not available for testing, the individual stimuli (green laser, sound, etc.) of these weapons were tested in a benchtop and controlled evaluation area.

The NLW torso in the EM configuration was evaluated using a M26 Taser weapon system. A demonstration with a t-shirt over the torso was conducted for the JNLWP at Marine Corps Base Quantico. In that evaluation, a Marine Corps captain proficient with the weapon discharged two cartridges into the torso in front of JNLWP personnel to show the torso's function. Images from that evaluation are shown in Figure 10.

To verify that the torso was collecting reliable data, the metrics from the tests were compared to published data from a Taser on the M26 weapon. The results from this comparison showed very good agreement in all metrics. The differences were likely from newer or different supply batteries in the M26.



Figure 10: EM Torso Evaluation at CFDR (Top) and Demonstration at the Joint Non-Lethal Weapons Directorate (JNLWD) (Bottom) (Source: CFDR).

The comparison data is shown in Table 2.

The ocular sensor system was evaluated using two commercially-available, laser-protective sets of eyewear against a commercially-available laser pointer. The testing setup is shown in Figure 11, along with some of the results (Table 3). The testing results showed that both sets of laser eyewear had similar performance for this exposure.

Finally, a use case test was conducted where multiple sensors captured data concurrently, as might be necessary in collecting data from an NLW such as a flashbang. These types of NLW output broadband light, loud sound, and blast overpressure. As no access to a flashbang was available, a pyrotechnic



Figure 11: Ocular Sensor Evaluation Using COTS Laser Protective Eyewear (Source: CFDR).

commonly used for entertainment and outputs similar to stimuli effects was used. The NLW surrogate head was outfitted with the eye sensor, pressure sensor in the eye and one ear, and a sound sensor in the opposite ear. All sensors were sampled at the same time during the test. The testing setup and a photo during the test are shown in Figure 12. Results are shown in Table 4. All sensors and data collection functioned within expected ranges.

Table 2: Comparison Between Data Measured From the Test Surrogate and NLW System

Measured/Calculated Metric	NLW-Surrogate Results (CFDR)	Specifications (M26 Taser)
Pulses per second (PPS)	15.6	15 PPS (alkaline batteries)
Main phase duration	10 μs	8.8 to 8.9 μs
Entire pulse duration	45 μs	32 to 60 μs
Main pulse voltage	12 kV	9.4 to 9.7 kV
Pulse Charge	71.2 μC +/- 6.3 μC	70 to 120 μC

Table 3: Comparative Test Results of Ocular Sensor System

	Without Eyewear (Peak Intensity in W/cm <sup>2</sup> )	With Honeywell Eyewear (Peak Intensity in W/cm <sup>2</sup> )	With NoIR Eyewear (Peak Intensity in W/cm <sup>2</sup> )
<b>Average</b>	0.001075	0.000184	0.000192
<b>Percent difference</b>	0	83%	82%



Figure 12: Surrogate Head Evaluation With Sound, Pressure, and Ocular Sensors Using Concurrent Data Collection (Source: CFDR).

Table 4: Results of Surrogate Flashbang Test for Pressure and Sound Exposure

Test Number	Peak Sound Level (dB)	Pressure (psi)
Test 1 (70-inch offset)	141	0.40
Test 2 (70-inch offset)	138	0.38
Test 3 (36-inch offset)	158	0.90

## CONCLUSIONS

An NLW human surrogate mechanical model and testing methodology has been shown to have the ability to capture data from a variety of NLW and NLW-like stimuli. The high-fidelity, anthropomorphic, and modular human form factor will aid the NLW community by having one common testing standard to allow correlation, comparison, validation, and data sharing. The modular NLW surrogate described here can be outfitted with COTS and custom sensors for injury areas of interest such as the ears, eyes, face, head, neck, and torso. As future needs arise, new sensors and sensor packages can be integrated into the NLW human

surrogate, making this surrogate highly adaptable to the many different possible stimuli and operational scenarios. ■

## ACKNOWLEDGMENTS

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(Photo Source: dreamstime.com)



# SUSTAINABLE MOBILE ELECTRICAL INFRASTRUCTURE

By Corey Bergsrud, Alex Zellner, and Eric Scott

## INTRODUCTION

**E**nergy is a fundamental enabler of military capability. However, world population growth, increase in developed populations requiring greater demand on energy, rebalancing to the Asia-Pacific region, next-generation

weapons platforms, and concepts of operation (CONOPS) prompt an enduring challenge for the availability and cost of operational energy for future campaigns. Operational energy is defined as “energy required for training, moving, and sustaining military forces and weapons platforms for military operations” [1]. An overarching challenge to supporting our Warfighters comes from the dependency and

resupply of food, water, ammunition, and liquid fuel. With a possible increase in operational tempo on the rise in support of rebalancing against great-power competitors and their fortified anti-access/area denial (A2/AD) and information regions, the indefinite necessities and associated support logistics will become immeasurably taxing, with increased risk of uncertainty.



However, technological and market trends in robotics, artificial intelligence (AI), and directed energy (DE)/electromagnetic (EM) weapons (as a weapon against adversaries and/or a wireless power recharger for our platforms) incorporated with novel CONOPS offer opportunities to offset these challenges. This also provides leap-ahead preeminence for America's innovative academic, industrial, and military bases with their scientific and technological marvels, paired up with our unparalleled military Warfighters. Through increased robotic presence and tasking, we can decrease human Warfighter presence from risky missions and tasking, thus essentially reducing the food and water challenges albeit with greater electrical power demands. Through DE and EM weapons, we can reduce the ammunition challenge albeit with greater electrical power demands. And through wireless power beaming, we can reduce dependency on liquid fuel as a source of energy; in turn, we can reduce the logistics tail through developing a sustainable mobile electrical infrastructure tailored to support greater electrical demands.

However, many throughout the world are investing in this future in some aspect as the character of war is changing [2]. Whoever achieves a harmonious integration of these technologies (i.e., robotics, AI, DE/EM weapons and recharging, etc.) inserted into novel strategic and tactical CONOPS first will vastly benefit from the resultant whole as the "whole is greater than the sum of its parts." Recognizing that electrical power is a key enabler to fully realizing this, future research and development investigation efforts are taking place at the U.S. Naval Surface Warfare Center (NSWC) – Crane Division in Crane, IN. These efforts include a diverse team of engineers and scientists to address the question on how to create a sustainable

## An overarching challenge to supporting our Warfighters comes from the dependency and resupply of food, water, ammunition, and liquid fuel.

mobile electrical infrastructure. This article looks to wireless power (WP) as an enabler for achieving a sustainable mobile electrical infrastructure.

### FUTURE ENERGY-INTENSIVE CAPABILITIES

In pursuit of military dominance, there is an ever-increasing demand for more energy, albeit with ever-increasing capabilities. Some areas of growth to aid the Warfighter include robotics with increasing functionalities, directed energy, and EM weapons, which are ever-increasing and energy-intensive.

Robotics with increasing functionalities continue to accelerate their utility to support the Warfighter. Part of the Naval science and technology (S&T) strategy [3] autonomy and unmanned systems vision is to achieve an integrated hybrid force of manned and unmanned systems. Moreover, The U.S. Army is pursuing a robotic and autonomous systems strategy [4] aimed at integrating new technologies into future organizations focused on human-machine collaboration. Some expected outcomes of human-machine teaming will be as a force multiplier, reducing risk to the Warfighters, lightening their physical and cognitive workloads, and offering greater lethality. To achieve greater robotic tasking with the Warfighters, it is vital that the U.S.

Department of Defense (DoD) recognize and address Warfighter concerns [5] such as establishing trust [2, 4–6] and maintaining energy support systems.

DE and EM weapons continue to accelerate their need to support the Warfighter. For DE, this includes high-energy laser and high-powered microwave technologies. For EM weapons, this includes electronic warfare (EW) in the radio frequency (RF) and electro-optical/infrared (EO/IR) systems and rail-gun technologies. All these are energy-intensive but offer immense benefits in overmatching adversaries.

### DEPARTMENT OBJECTIVES

Part of the Naval S&T strategy [3] power and energy vision recommends increasing naval forces, freedom of action through energy security, efficient power systems, and combat capability through high-energy and pulsed power systems. This strategy vision also recommends providing the desired power where and when needed at the manned and unmanned platform, system, and personal levels. Some of the objectives set by the DoD to achieve this vision include increasing utility of renewables, improving operational energy assurance, and reducing resupply burden and logistics vulnerability [3, 7]. To support these future developments, we look to WP as an enabler for achieving a sustainable mobile electrical infrastructure.

### WIRELESS POWER

Two primary forms of WP are near-field resonant inductive coupling and far-field power beaming. The former includes a set of coils (transmitting and receiving) separated by a short distance, where electrical power is transferred wirelessly via magnetic field energy. Applications of resonant inductive coupling can be seen

in wireless cell phone or toothbrush chargers, for example. Resonant inductive coupling technology is being explored to recharge robotics. The latter typically includes either laser or RF wavelengths where electrical power is transferred wirelessly from a transmitter to a receiver unit at much greater distances via light or electric field energy, respectively. Far-field WP transfer technologies are explored as a capability to power robotics at a greater distance away from a transmitting station, such as wirelessly powering an unmanned aerial vehicle while still in flight. In fact, Mr. William Brown of Raytheon Corp., considered a pioneer of WP technologies and applications, developed and demonstrated a WP beam used to power and position a helicopter back in the late 1960s under a contract from the U.S. Air Force [8]. The holy grail of far-field WP beaming is the concept of a large,

The holy grail of far-field WP beaming is the concept of a large, solar-powered satellite used to harvest immense amounts of solar energy in space.

solar-powered satellite used to harvest immense amounts of solar energy in space, convert the solar energy into an RF power beam transmitted to Earth where it is received, and convert to usable direct current (DC) power by a rectifying antenna (rectenna) array. Several more applied examples of WP beaming exist and can be found in

Strassner and Chang [9].

Researchers and scientists at NSWC Crane are conceptualizing and pursuing realization of various CONOPS themes enabled by WP technologies with integrated robotics and Warfighter teaming toward developing a sustainable mobile electrical infrastructure.

## WP ASSESSMENT TOOL

A WP tool was developed to provide rapid assessment of various WP scenarios (e.g., satellite-to-ground or aerial, space-to-space, ground-to-ground or aerial, and aerial-to-ground or aerial). Figure 1 shows the WP assessment tool that Crane developed [10]. The tool currently contains tabs for WP analysis and two other tabs (i.e., coplanar strip-line analysis and diode analysis), with future work allowing more assessment capability. Built using numerous existing

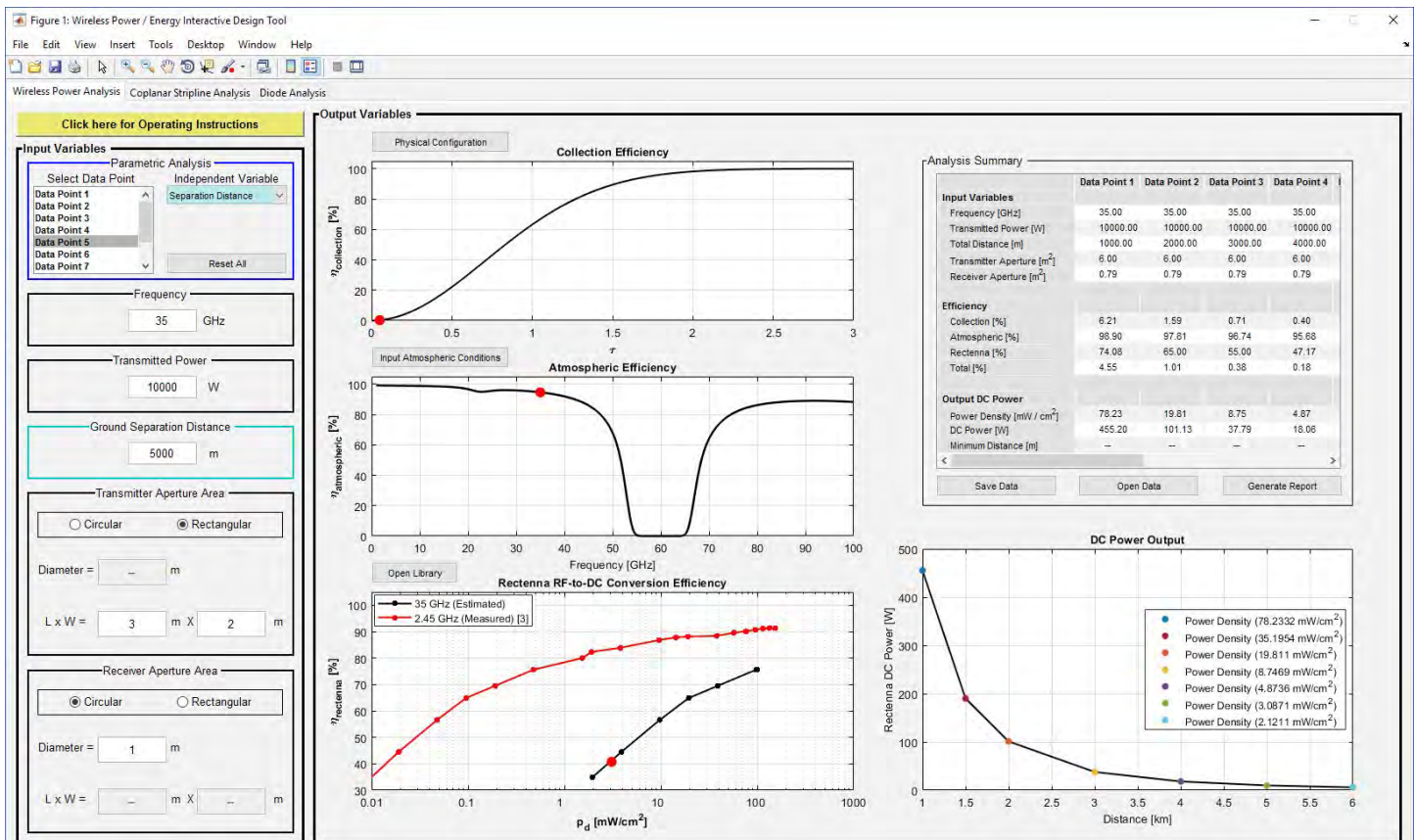


Figure 1: The Wireless Power Analysis Tab Display of the WP GUI Tool Containing Input and Output Variables Sections (Source: Bergsrud and Zellner [10]).

formulas, closed form equations, measured data, and creativity in the functionalities and displays, this tool is designed to elegantly stitch complex correlations between design variables and the bounding laws of physics to provide a good estimation of expected DC power output.

All tabs have a “Click Here for Operating Instructions” button. These instructions include supporting equations and formulas with references, detailed descriptions of components on the graphical user interface (GUI), and step-by-step example walk-throughs for each of the three tabs.

In Figure 1, two main sections of the GUI are Input and Output Variables. Included in the Input Variables section is the Parametric Analysis section and edit boxes for all dependent and independent input variables. Included in the Output Variables section are the efficiency graphs, analysis summary table, and DC power output graph.

The parametric analysis box allows the user to enter parametric study information (i.e., dependent and independent variables) collectively saved as a data point for each instance. The user would first select an independent variable (i.e., frequency, transmit power, separation distance, and receive aperture or transmitter aperture areas) of interest to study. The selected independent variable is highlighted in a turquoise color for convenience to the user. The user would then enter dependent variable values. The dependent variable values will remain fixed for each data point, while the independent variable will change based on user inputs toward their study of interest. Quick iterative changes can be made to all variables, allowing users to rapidly assess correlated effects on intermediate and output values while

automatically updating their data points for those changes.

After the user has entered enough data for the appropriate variables, the efficiency graphs in the center column of Figure 1 will start to populate. The collection efficiency graph displays the percentage of the propagating wave collected on the interface of the receiving aperture (as a function of transmit and receive aperture sizes, frequency, and distance). The atmospheric efficiency graph displays the percentage of the propagating wave not attenuated in the atmosphere (as a function of frequency). The rectenna RF-to-DC conversion efficiency graph displays the percentage of the collected wave on the receiver converted to DC power (as a function of power density).

All input variables, efficiencies (including total efficiency), and relevant output variables (i.e., power density, DC power output, and minimum allowable distance) for all data points are displayed in the analysis summary table of the Output Variables section.

The total DC power output is the product

of the three efficiency values and the transmitted power value. This output value is plotted against the user-selected independent variable for all data points in the DC power output graph shown in Figure 2. This graph helps the user compare and analyze data points so he or she can study how variations in the chosen variable affect the resulting estimated availability of DC power. For example, this graph can be used to study zones (green, yellow, and red) of available power.

While using the tool, a user may encounter a warning pop-up (see Figure 3) that can be fixed by changing the input variables. Electrical components can be destroyed or burnt out if they receive more power than designed to handle

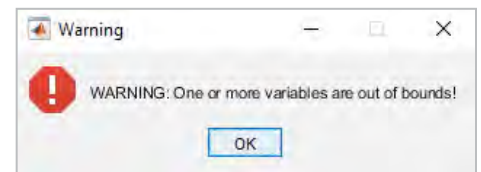


Figure 3: A Warning Dialog Box That Appears If the Power Density Exceeds a Certain Threshold (Source: Bergsrud and Zellner [10]).

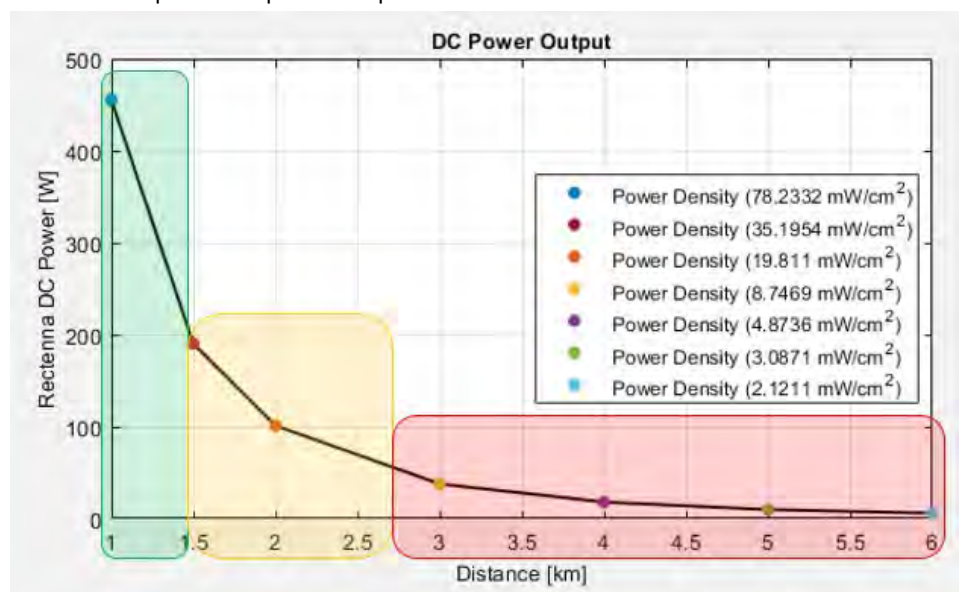


Figure 2: End-Result Displaying Estimated DC Power Plotted to Help the User Compare and Analyze Data Points (Source: Bergsrud and Zellner [10]).

The atmospheric attenuation sub-GUI allows the user to set atmospheric conditions for a more accurate atmospheric efficiency calculation.

or fail to turn on if too little power is received. The GUI is designed to help catch these bounds and notify the user.

To increase the accuracy of DC power output estimation, three pop-out sub-GUIs are available to the user that allow more specific information to be entered as they pertain to receiver and transmitter orientations, atmospheric attenuation of the power beam, and measured RF-to-DC conversion information. These sub-GUIs can be accessed by pressing one of the three buttons above the respective three efficiency graphs.

The physical configuration sub-GUI (Figure 4) allows the user to set altitudes and transmit and receive antenna orientations in a two-dimensional configuration. Based on those inputs, it allows the user to generate a visual display of his or her configuration settings. Cosine loss factors are incorporated in this assessment.

The atmospheric attenuation sub-GUI (Figure 5) allows the user to set atmospheric conditions for a more accurate atmospheric efficiency calculation by using specific attenuation equations from the International Telecommunications Union and a built-in climatology database from the National Oceanic and Atmospheric Administration's Earth System Research

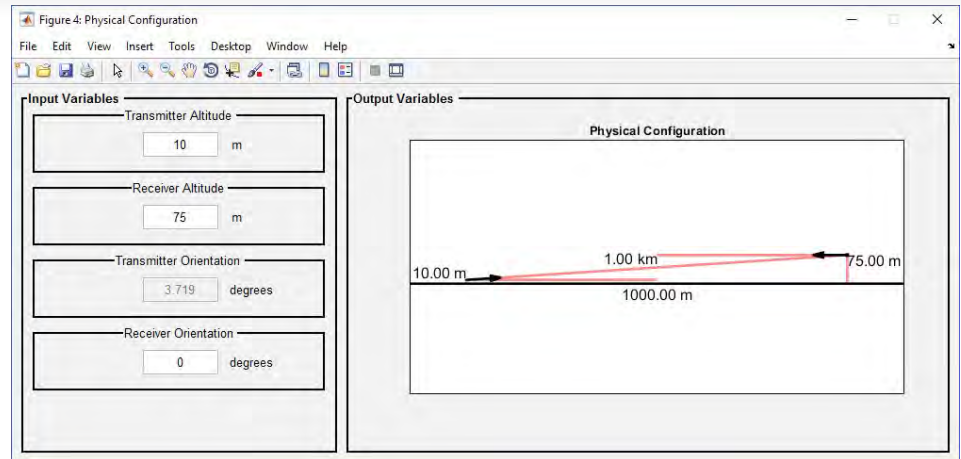


Figure 4: Physical Configuration Sub-GUI (Source: Bergsrud and Zellner [10]).

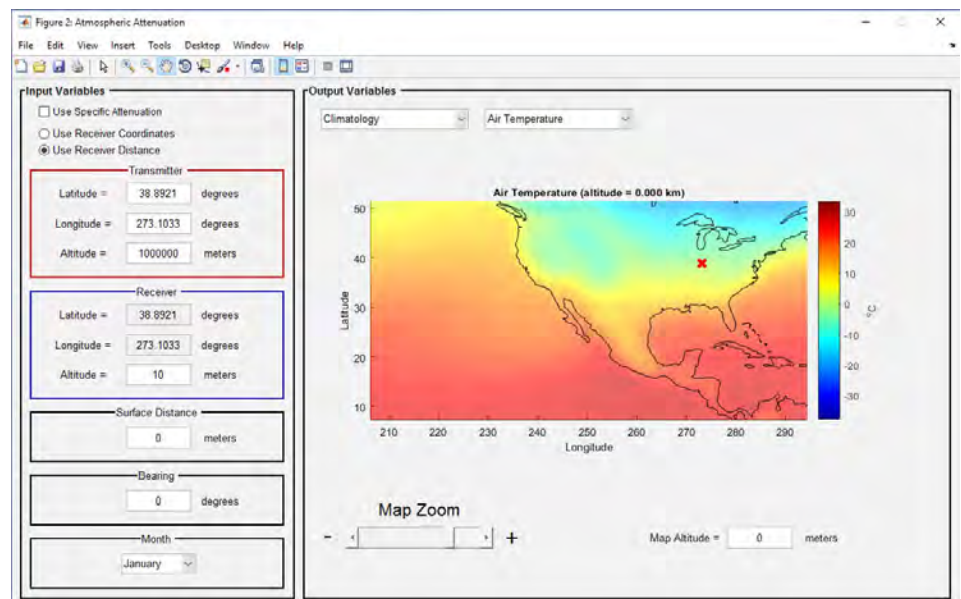


Figure 5: Atmospheric Attenuation Pop-out Sub-GUI (Source: Bergsrud and Zellner [10]).

Laboratory [11, 12].

The open library sub-GUI allows the user to input and save their own rectenna RF-to-DC conversion efficiency data (Figure 6) as a function of power density and view data from other reputable sources [13–15].

The variables in each of the sub-GUIs are autopopulated to default values so that new users may focus on the main input variables if desired, without opening these sub-GUIs.

## WP From Satellite-to-Ground Assessment

One assessment of interest is using a satellite(s) beaming power to ground operating bases. The physical configuration pop-out sub-GUI (Figure 4) allows the user to set the altitude of the satellite as well as orientations of the power transmitter (on a satellite) and a power receiver, i.e., rectifying antenna (rectenna) array on the Earth.

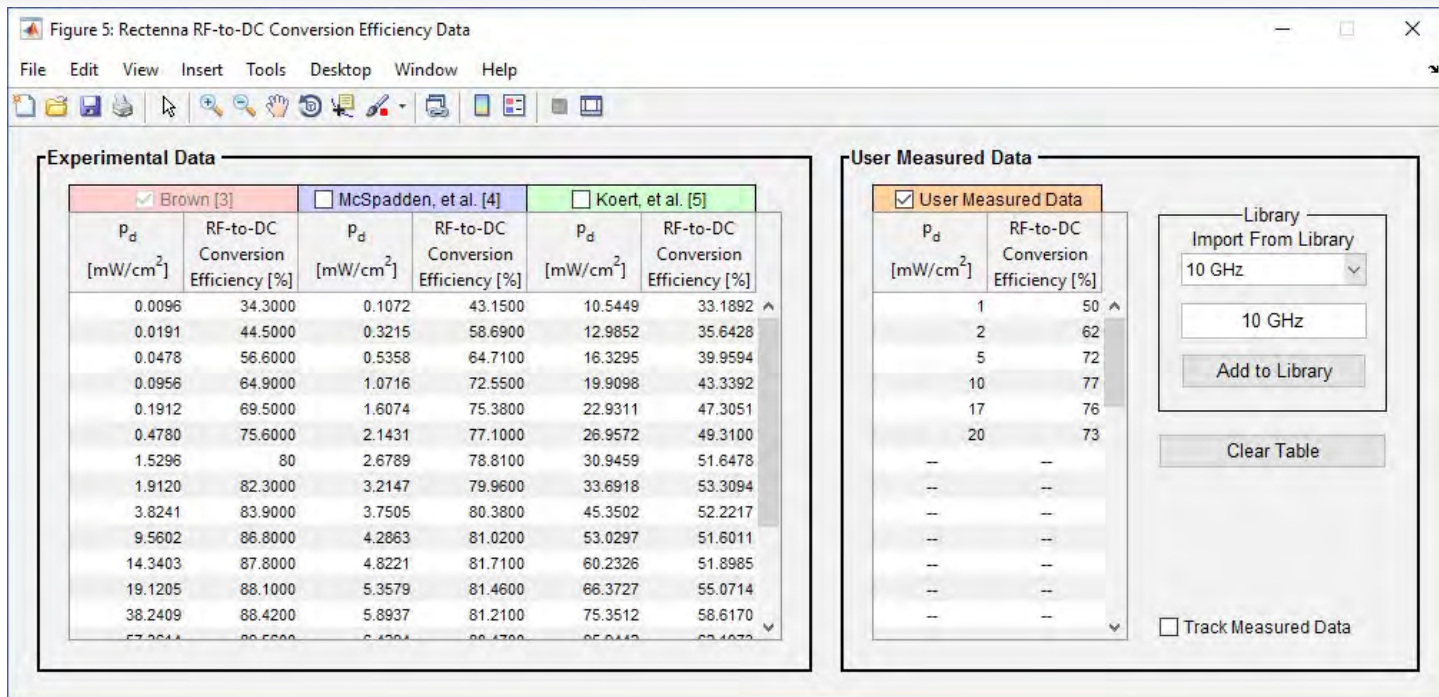


Figure 6: Rectenna RF-to-DC Conversion Efficiency Data Pop-out Sub-GUI (Source: Bergsrud and Zellner [10]).

### Footprint Study

A first study of the satellite-to-ground scenario is setting the receiver aperture area to be the independent variable, with all dependent variables set constant. Three example diameter sizes were selected for candidate operating bases: 25-m remote operating base, 100-m forward operating base, and a 250-m main operating base. The result of this study is shown in Figure 7.

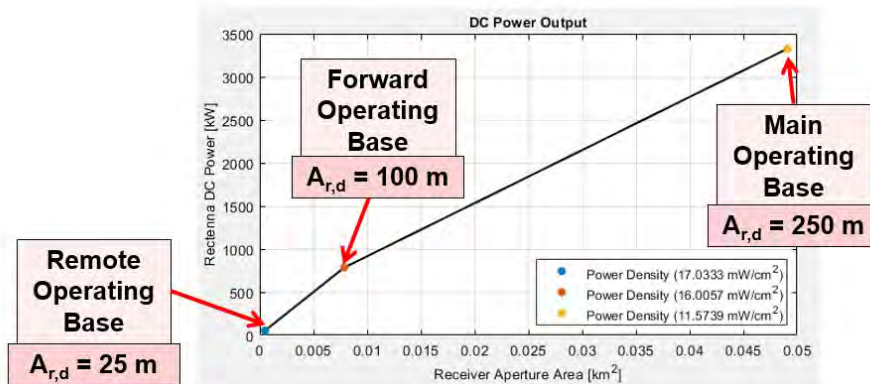


Figure 7: A Study Example to Estimate the Amount of DC Power Received for Theoretically Different-Sized Operating Bases From a Satellite at 500 km (Source: Bergsrud and Zellner [10]).

### Orbit Study

In addition to studying the amount of power received by these three types of operating bases, another valuable study comes from the cosine loss effects of a solar-powered satellite passing over the operating bases (Figure 8). The estimated total amount of DC power received at an operating base is maximized when the satellite is directly over the receivers and diminishes as the satellite continues its orbit. This is achieved by maintaining altitude of the satellite and increasing/decreasing the

ground separation distance. The overall distance, as well as the angle of the incident wave, changes between data points, thus affecting the overall DC power.

## SUSTAINABLE MOBILE ELECTRICAL INFRASTRUCTURE

MG Mick Ryan of the Australian Army stated “... technology alone is unlikely to provide a sustained competitive

advantage. But when new technology is combined with new operating concepts and new organizational models, innovation is more likely to provide sustained advantage” [2]. In pursuit of developing a sustainable mobile electrical infrastructure, Crane developers engaged with Warfighters and explored various robotic concepts applied in theater that may bring positive value gain. Moreover, a diverse team of Crane developers explored WP

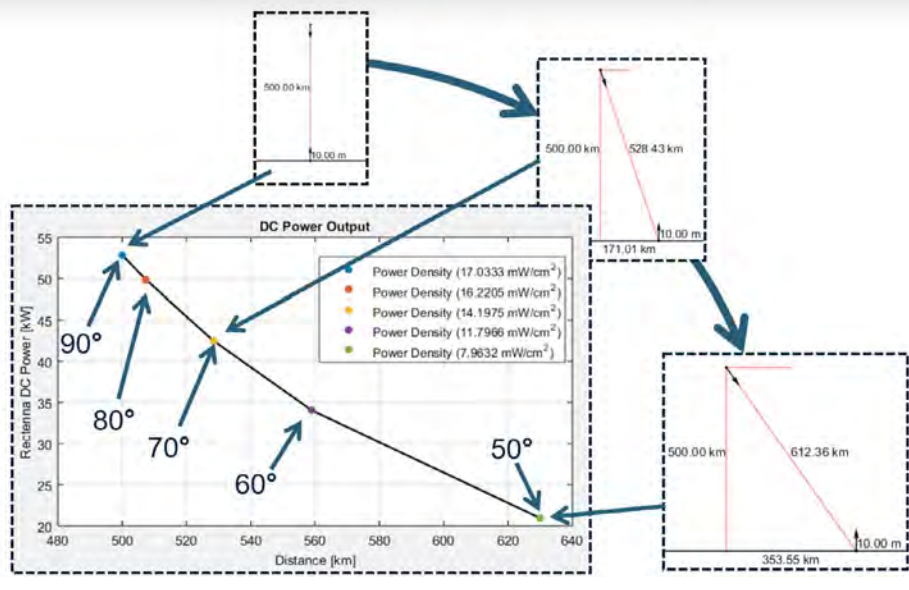


Figure 8: Effects of a Solar-Powered Satellite Passing Over Operating Bases (Source: Bergsrud and Zellner [10]).

utility, robotic, and Warfighter integration concepts as possible future tactic and strategic realities toward developing a sustainable mobile electrical infrastructure to support that vision.

### Better Understanding the Warfighter's World

Crane scientist and engineers working on the sustainable mobile electrical infrastructure concepts have been interacting with Warfighters to better understand how they see the world (i.e., day-in-the-life or customer discovery process and then identify possible robotic tasking). Two key interactions occurred relative to this work—(1) brainstorming session with Explosive Ordinance Disposal (EOD) detachment group at NSWC Crane Division and (2) Expeditionary Maneuver Support Directorate war-gaming exercise for camouflage, concealment, and deception. In both cases, the developers and Warfighters worked together to come up with operational use cases of robotics catered to certain scenarios. Further literature reviews revealed that using robotics for EOD is one area of

overlap between the Army and the Navy [16]. Thus, to help build trust between robotic tasking and the Warfighters, NSWC Crane developers targeted their concept development efforts towards EOD themes.

### Proposed Concept

A vehicle that Warfighters are familiar with is the all-terrain vehicle (ATV). Thus, NSWC Crane developers are working toward a robotic ATV with integrated mission robots and wireless power-recharging capability, as seen in Figures 9–11. The robotic ATV or mother bot (Mbot) can work semi-autonomously without a Warfighter passenger or be driven by a Warfighter. Mbot will be equipped with two near-field WP charging pads in the rear for recharging two multirotor copter aerial daughter bots (A-Dbots). A-Dbots will play the role of scouts to help increase situational awareness around Mbot. In addition, Mbot will be equipped with an electrical power system (EPS) kit, including a hybrid solar/RF array, storage bank, and power management system designed to support both Mbot and A-Dbots. Moreover, an ATV trailer equipped with an EPS kit with a WP charging pad could support a rover daughter bot (R-Dbot).



Figure 9: ATV (Mbot) Deploys to Search Area for Threats; A-Dbot #1 Scouts Ahead of Mbot to Increase Situational Awareness (Source: Victoria Baker, NSWC Crane Division).



Figure 10: A-Dbot #1 Detects Threat and Reports to Mbot (Source: Victoria Baker, NSW Crane Division).

Both EPS packages will enable longer mission durations by integrating energy capability.

Finally, Figure 12 illustrates a possible future force protection and wireless energy delivery from satellite CONOPS. The satellite beams power to the mobile electrical infrastructure for recharging, thus reducing the traditional fuel logistics reenergize approach. In addition, Figure 12 shows an integrated Warfighter and/or multiagent robotic systems (Mbot and Dbots) teaming force protection architecture to a base station tactical command center with energy monitoring.

## CONCLUSION

As the United States evolves to rebalance against rising great power competitors as a global leader, it must leverage and unleash its greatest asset—our innovative minds and support structure—for a new robotic age to overmatch and provide leap-ahead dominance in rapidly growing key technology areas. In helping to

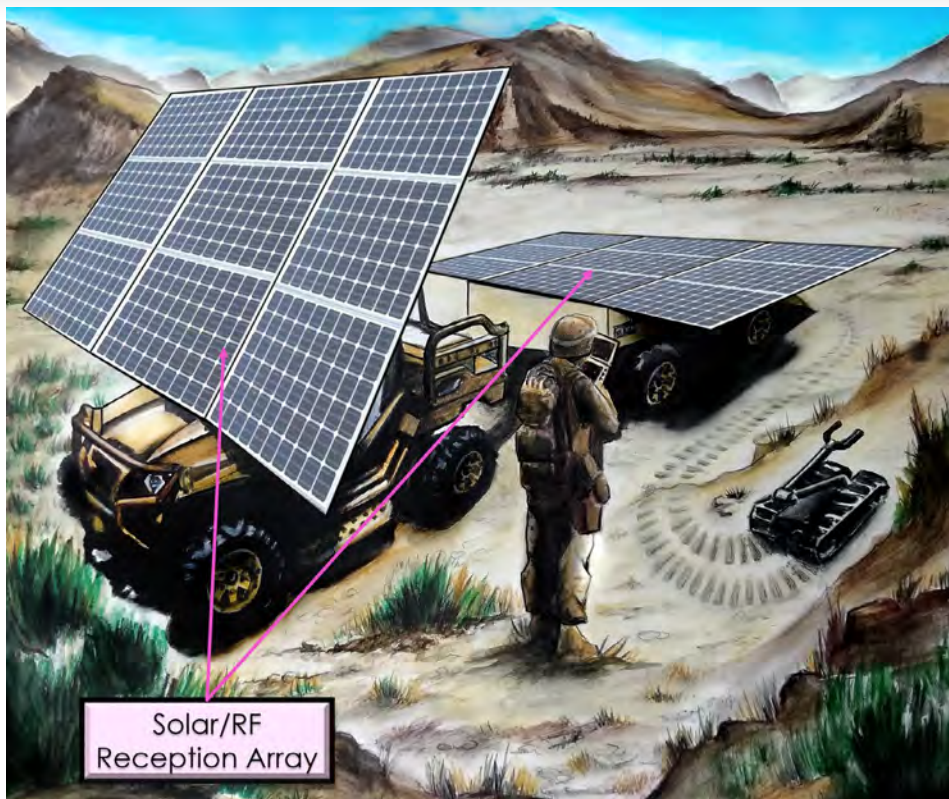


Figure 11: Operator Commands Mbot to Deploy R-Dbot to Neutralize the Threat (Source: Victoria Baker, NSW Crane Division).

## Near-field WP utility offers a way to autonomously recharge robots without Warfighting presence.

pivot against this challenge, developers at NSW Crane developed a WP assessment tool and conceptualized a sustainable mobile electrical infrastructure composed of WP utility, robotics, and Warfighter integration. Crane developers have engaged with Warfighters in a customer discovery process approach to better understand the Warfighters' world and then apply new concepts into that world, with the Warfighters as a reality check and value

proposition. Integrating robotic tasking with Warfighters designed toward an EOD theme was a good first approach.

Increasing robotic tasking reduces Warfighter cognitive and physical loads, keeps them further out of harm's way, and increases lethality of the force. This, in turn, may help reduce the food and water resupply challenges. To support a higher electrical demand through autonomous robotic tasking increase, developers are looking at a WP utility to sustain a forward robotic presence. Near-field WP utility offers a way to autonomously recharge robots without Warfighting presence. Moreover, far-field WP utility offers a way to electrically recharge mobile Earth-operating base stations from space, thus reducing traditional energy resupply lines' vulnerabilities. Integrating WP and robotics with Warfighters may offer a

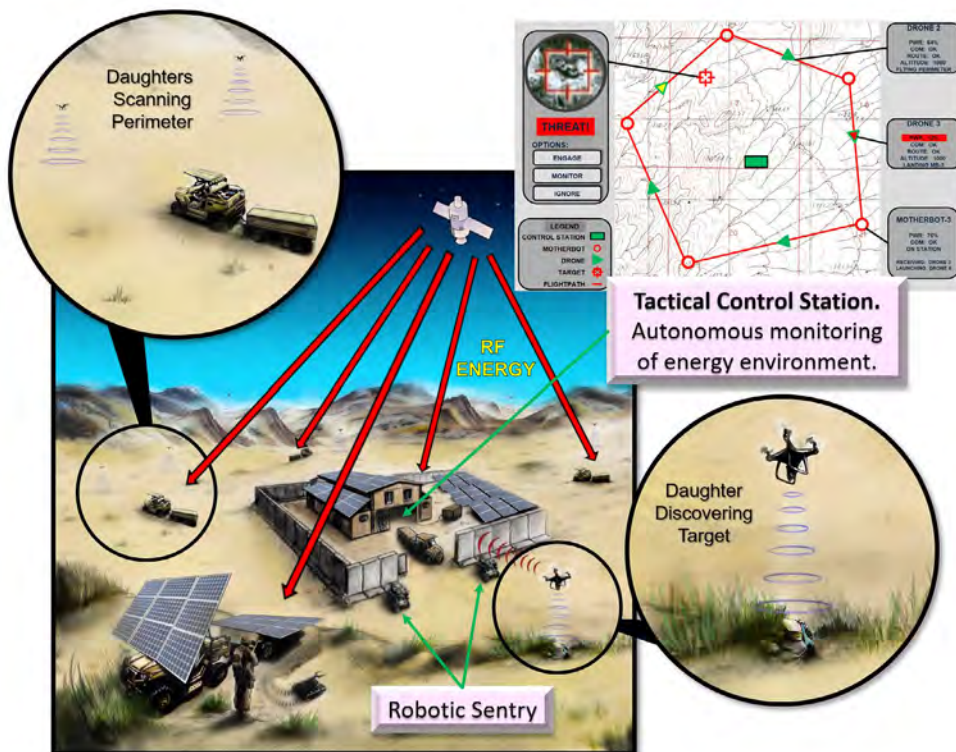


Figure 12: Possible Future CONOPS With Wireless Power, Robotics, and Warfighter Integration of a Mobile Electric Infrastructure (Source: Victoria Baker, NSWC Crane Division).

longer, sustained advantage against adversaries as well as claim and grow key market space through DoD-generated American innovations. ■

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## BIOGRAPHIES

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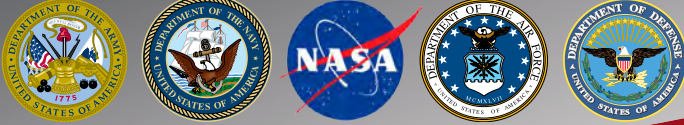
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# Joint Army Navy NASA Air Force

## Interagency Propulsion Committee



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# AMERICAN “ASTROLOGISTICS”

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By James Michael Snead

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## INTRODUCTION

**W**hen addressing the National Space Council on June 18, 2018, President Trump made clear his spacefaring vision for America when he said: “My administration is reclaiming America’s heritage as the world’s greatest spacefaring nation.” He went on to state his desire to establish a new sixth branch of the armed forces—the U.S. Space Force. At the August 13, 2018 signing of the 2019 National Defense Authorization Act, the President stated, “In order to maintain America’s military supremacy, we must always be

on the cutting edge. ... Just like the air, the land, the sea, space has become a warfighting domain. We must have American dominance in space.” Achieving this dominance will require developing not only new military space systems but spacefaring logistics to deploy and sustain forward-deployed personnel and systems during times of peace and conflict.

Terrestrial logistics capabilities supporting forward deployed American forces have civil (e.g., ports), commercial (e.g., passenger and cargo transport), and military components. Military materiel acquirers and logistics planners will need to provide comparable spacefaring logistics capabilities

to support U.S. military personnel and capabilities forward deployed to space. It is difficult to conceive of a U.S. Space Force (and a U.S. Space Guard) having effective operational capabilities in space absent such spacefaring logistics capabilities. Hence, establishing an American spacefaring logistics infrastructure is essential for executing the President’s charge to “have American dominance in space” and return America to being “the world’s greatest spacefaring nation.” What will come as a surprise is that America’s aerospace industry now has the industrial mastery to develop and start deploying the needed civil-commercial-military spacefaring logistics infrastructure.

# SPACEFARING LOGISTICS CAPABILITIES

Drawing upon the definition of military logistics, spacefaring logistics can be defined as follows:

*Spacefaring logistics is the science of planning and carrying out the movement of humans and materiel to, from, and within space combined with the ability to maintain human and robotic operations in space. In its most comprehensive sense, spacefaring logistics addresses the aspects of spacefaring operations both on the Earth and in space that deal with:*

1. Design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of spacefaring materiel;
2. Movement, evacuation, and hospitalization of people in space;
3. Acquisition or construction, maintenance, operation, and

*disposition of facilities on the Earth and in space to support human and robotics space operations; and*

4. Acquisition or furnishing of services to support human and robotics space operations.

Note: This definition was originally developed by the Space Logistics Technical Committee of the American Institute of Aeronautics and Astronautics.

Going back to the founding of the United States, building national logistics infrastructure was undertaken to promote commerce and military defense. Transforming America into a true spacefaring nation will require national investments in a spacefaring logistics (hereafter referred to as “astrologistics”) infrastructure supporting civil, commercial, military, and, eventually, private users.

Establishing this new infrastructure will require updated and new capabilities. These capabilities will include

transportation to, from, and within space and on the Moon and Mars; human habitation facilities in space and on the Moon and Mars; and associated communication and command and control capabilities.

The habitation and transportation functional architecture of such an astrologistics infrastructure [1], as shown in Figure 1, could be deployed in three phases:

1. **Phase A:** Accessing low Earth orbit (LEO) regularly and safely and creating the initial shared LEO astrologistics infrastructure.
2. **Phase B:** Expanding the LEO common astrologistics infrastructure and extending this to medium and geostationary Earth orbits (GEOs), the Earth-Moon LaGrange orbits, lunar orbit, and the lunar surface.
3. **Phase C:** Extending the common astrologistics infrastructure to support human and robotic exploration of Mars, near-Earth asteroids, and throughout Earth-Mars space.

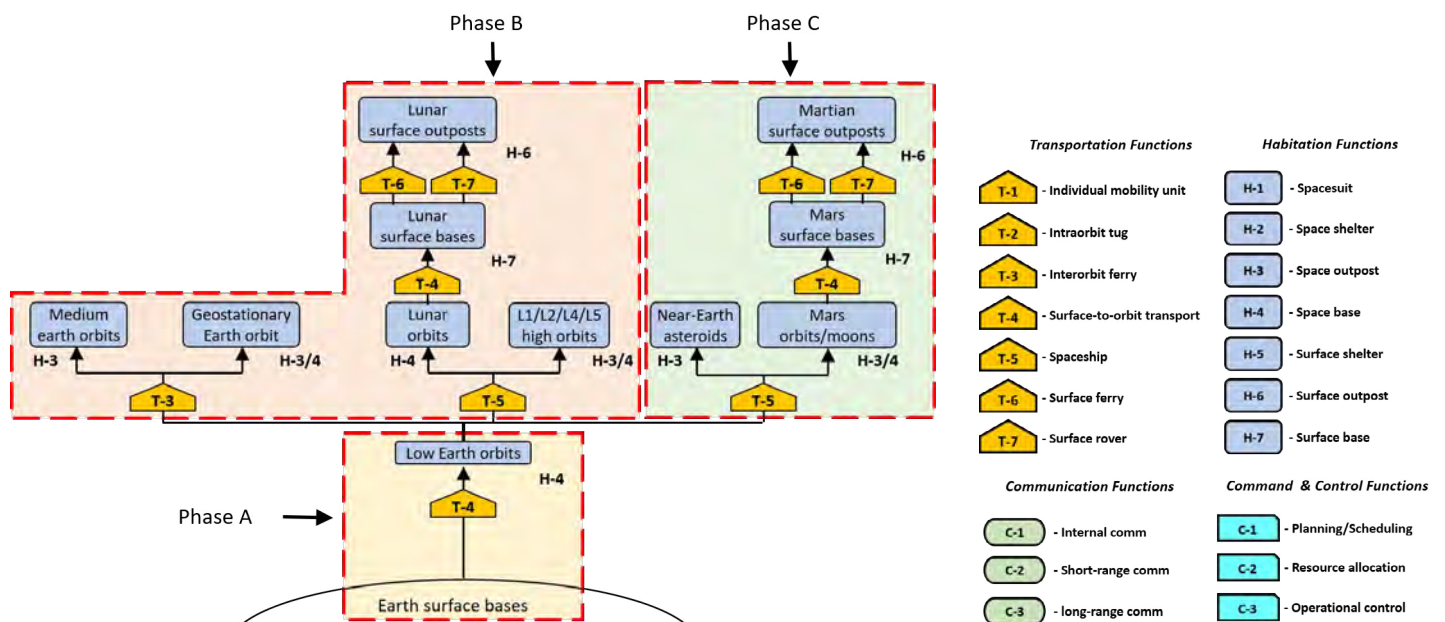


Figure 1: Astrologistics Infrastructure Habitation and Transportation Functional Architecture (Source: J.M. Snead, U.S. Air Force).

Phase A of the infrastructure buildout will regularize government and commercial human transport to LEO and establish the initial permanent logistics operations in LEO. These shared facilities, similar to how many large U.S. airports are shared, will enable the initial forward deployment of U.S. Space Force/Space Guard personnel and materiel while also enabling expanded commercial and scientific operations. The Phase B expansion will support U.S. Space Force operational capabilities to protect and defend vital U.S. commercial and military space capabilities and expand the protection of the United States and its allies from attacks through or from space. Phase B will also support the permanent return of Americans to the Moon and enable a U.S. Space Guard to exert U.S. legal authority and render assistance to U.S. government, commercial, and private operations throughout Earth-Moon space. Phase C will support the American human exploration of Mars and potential future U.S. commercial operations to mine asteroids for natural resources needed by an expanding American space enterprise.

## BUILDING SUBSTANTIAL LEO HABITATS

Nearly 70 years ago, Robert A. Heinlein, an early author of “hard” science fiction stories, stated, “Get to low-earth orbit and you’re halfway to anywhere in the solar system” [2]. Heinlein was referring to rocket ships using chemical propulsion—a limitation that is still present when developing non-nuclear space launch systems. For this reason, Phase A requires establishing logistics facilities in LEO to receive and house personnel and materiel transported from Earth and enable commercial and military space operations. Obviously, the new facilities will need to be substantial to support a permanent American

NASA is planning to use the new Saturn V-class rocket to restart human space exploration missions and launch large space probes to distant parts of the solar system.

spacefaring presence, including, for example, a U.S. Space Guard, space-mining operations, and a growing space tourism industry.

The United States built two facilities in LEO—the Skylab Space Station and the

International Space Station (ISS). The method used to deploy these two space stations substantially influenced their design.

During the 1960s Apollo program, NASA’s contractors began designing a space station to deploy using the immense Saturn V rocket. Called Skylab, the final design was a space station fabricated from a modified Saturn V third-stage hydrogen propellant tank (see Figure 2). This enabled the entire space station to launch into orbit using a single launch. Within a matter of hours after the arrival of the crew, launched separately, the station was operational. When launched in 1973, Skylab provided 350 m<sup>3</sup> of habitable volume for a crew of three—equal to the volume of a 1,500 ft<sup>2</sup> home or 117 m<sup>3</sup> per person. It demonstrated the value of assembling

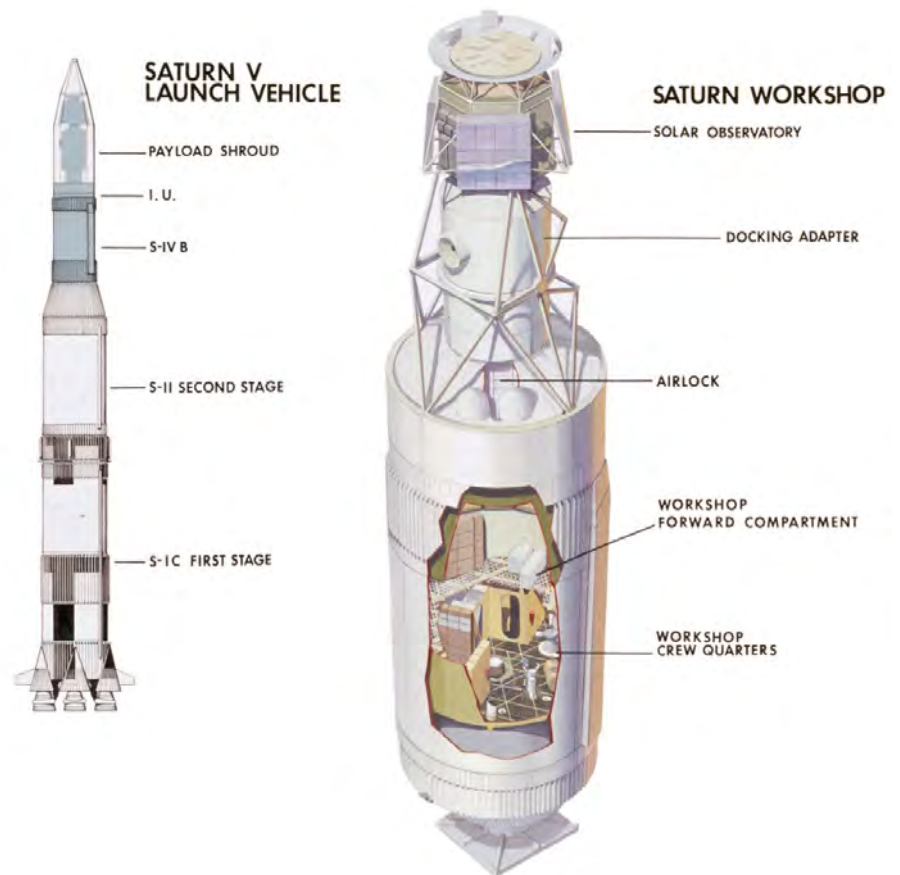


Figure 2: Saturn V Launch Vehicle Used to Launch the Skylab Space Station and Skylab Cutaway Illustration (Source: National Aeronautics and Space Administration [NASA]).

space stations using large modules having ample internal volume to move around.

In contrast, the ISS was assembled from smaller modules. Its assembly required 27 Space Shuttle missions along with multiple Russian and American unmanned launches. The ISS currently has about 1,000 m<sup>3</sup> of pressurized volume for a maximum crew of six—about 167 m<sup>3</sup> per person.

Today, NASA is completing development of a new Saturn V-class rocket—the Space Launch System (SLS) (see Figure 3). First conceived in the 1990s as a derivative of the Space Shuttle, NASA is planning to use it to restart human space exploration missions beyond LEO and launch large space probes to distant parts of the solar system. As the 1973 launch of the Skylab demonstrated, an unmanned version of the SLS can be used to place large habitation modules into LEO.

At the Michoud Assembly Facility outside New Orleans, where the 8.3-m diameter SLS core is now being built, habitation modules up to 10-m (33-ft) diameter x 30 m (100 ft) long could be built as SLS payloads. Figure 4 illustrates a LEO space base using two module designs—one 8.3-m diameter operations module and two 10-m diameter hangar modules [3]. This space base would be an H-4 habitat shown in Phase A of Figure 1.

In the 1960s, when NASA was first conceptualizing the design of Skylab, one idea considered was to reuse the propellant tanks of the rocket on orbit for pressurized habitation. During the early years of the Space Shuttle program, reusing the external tank in this manner was also evaluated. The LEO space base would require three SLS missions providing three sets of SLS core propellant tanks. Two of these sets—those launching the two hangar

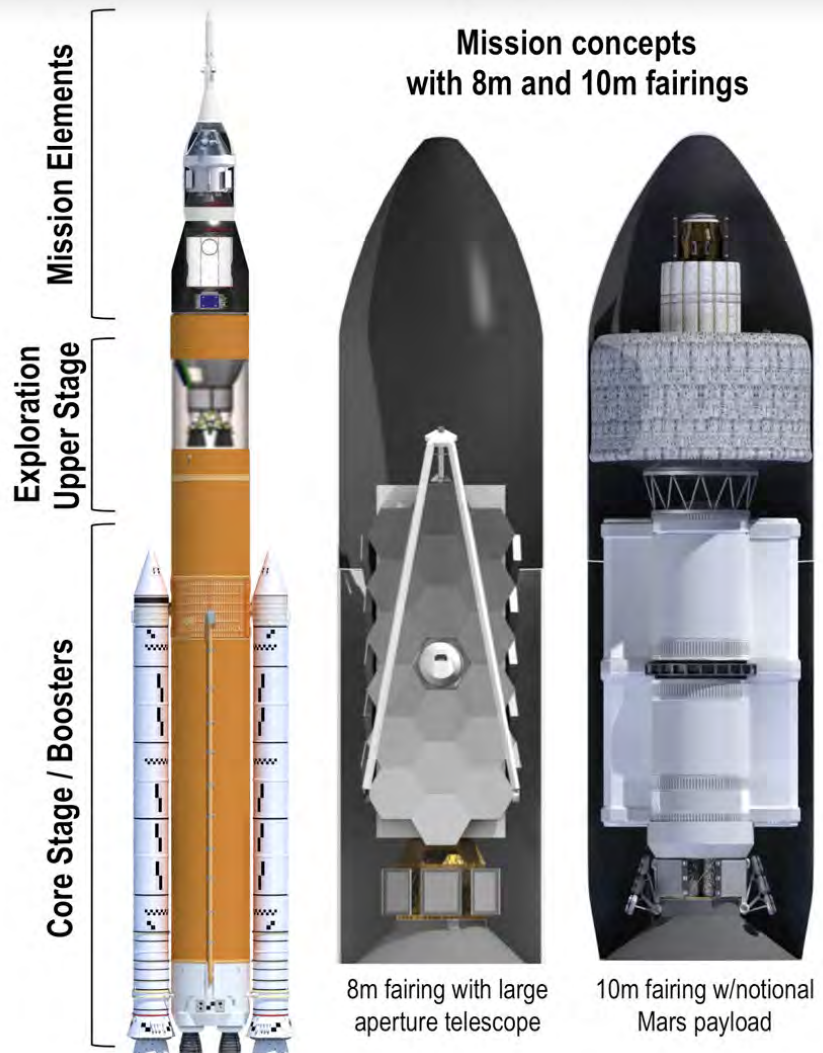


Figure 3: SLS Block 1B Configuration With the Orion Spacecraft and Possible Unmanned Payload Configurations (Source: NASA).

modules—would be incorporated into the base to store air when the hangars are depressurized. These repurposed tanks would be positioned between the two hangars. A truss would provide the structural foundation for assembling the base. The truss would also serve as a space dock for assembling and supporting other habitats and space vehicles. Lights along the truss would provide illumination when the underside of the base is in shadow.

The third SLS core would remain attached to its payload—the operations module. The operations module would be fabricated using a modified SLS core

hydrogen tank. With the retained SLS core converted into simple, pressurized habitation for crew quarters, recreation, and training, the total pressurized volume would be approximately 5,000 m<sup>3</sup>—suitable for a crew size of about 25 at 200 m<sup>3</sup> per person.

The space base incorporates two space hangars to provide assembly, servicing, repair, and training capabilities needed for routine spacefaring operations (see Figure 5). Except for the airlock and the interior compartments, each space hangar would launch as a single SLS payload. The outer space doors and the outer protective wrap protect against

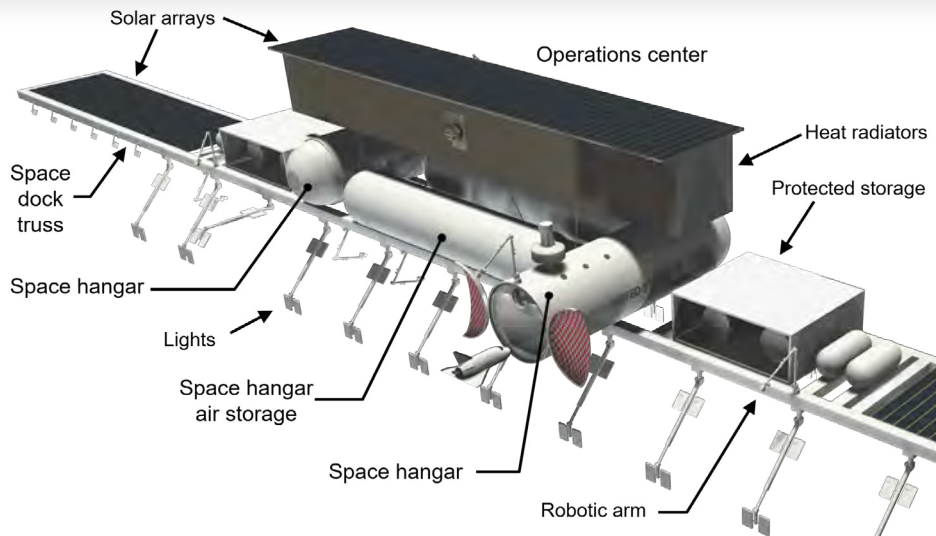


Figure 4: LEO Space Base With Two Space Hangars and a Large Space Dock (Sources: J.M. Snead, U.S. Air Force; Isiah Davenport and Dennis Stewart, Veridian).

An ISS-style airlock enables personnel access to space.

hangar to enable astrological operations at other locations, such as servicing lunar landers while in lunar orbit.

By using a hub and spoke design, where the hangars are incorporated into the hub and modified operations modules are used as spokes, substantial habitats can be assembled. Figure 7 shows a basic habitat, with four spokes assembled at the space dock [4]. This configuration would require seven SLS missions—four for the spokes and three for the hub. An expanded configuration with 12 spokes is also shown. (Note: A video showing these concepts is available at <https://www.youtube.com/watch?v=9Xu0-UrFlnQ>.)

This hub-spoke design enables the habitat to rotate about the hub to produce artificial gravity in the spokes. As shown in the cutaway illustration in Figure 7, the spoke would be divided into 14 useable floors. Each floor would be about 8 m in diameter, with about 42 m<sup>2</sup> of useable floor area. Each spoke would have 588 m<sup>2</sup> of floor area. The basic four-spoke configuration, housing about 100 people, would have 2,352 m<sup>2</sup> (25,317 ft<sup>2</sup>) of floor area, with substantial, additional useful volume in the hub. The 12-spoke configuration, with 7,056 m<sup>2</sup> (75,951 ft<sup>2</sup>) of floor area, could accommodate about 300 people.

Human logistics systems function best in a gravity environment. This enables conventional food preparation, bathroom operations, medical procedures, and

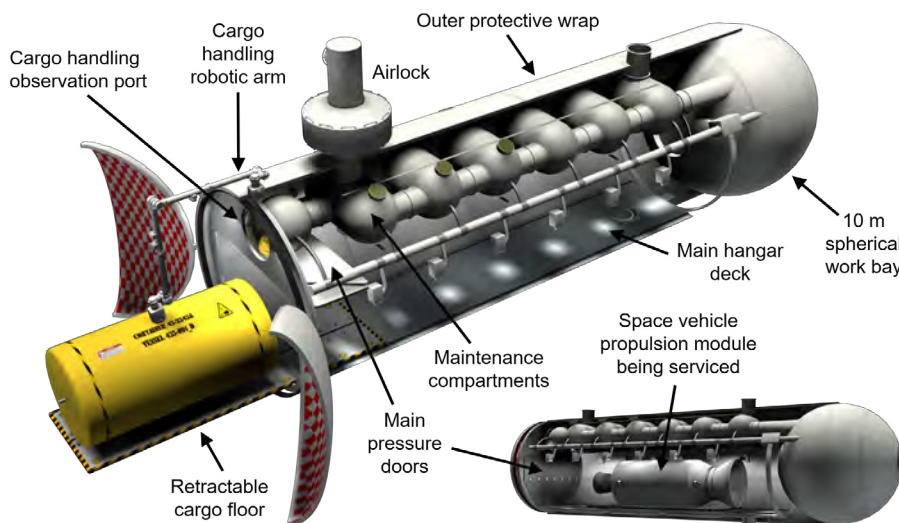


Figure 5: Space Hangar Cutaway (Sources: J.M. Snead, U.S. Air Force; Isiah Davenport and Dennis Stewart, Veridian).

micrometeoroid and small debris impact and help regulate the temperature in the hangar. An ISS-style airlock enables personnel access to space. Cargo modules and space vehicles brought into the hangar are first secured on the retractable cargo floor. The main hangar deck and the spherical work bay can be separately depressurized. The maintenance compartments provide bench-level diagnostics and repair. Access tunnels connect the

compartments to the operations center attached above the two hangars. A lower access tunnel provides access to space vehicles assembled and serviced at the space dock (see Figure 6).

With design forethought, the basic operations module and hangars can be used to assemble other space facilities and spaceships. For example, the spaceship shown in Figure 6 incorporates a version of the space

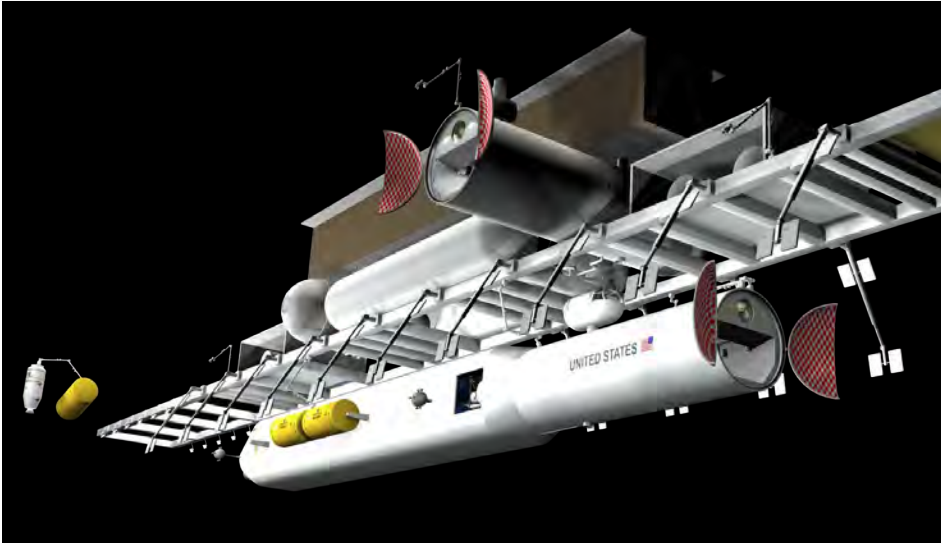


Figure 6: LEO Space Base With a Docked Spaceship (Sources: J.M. Snead, U.S. Air Force; Isiah Davenport and Dennis Stewart, Veridian).

NASA’s “Commercial Crew” program will reinstate American human space access using 1960s-style space capsules.

these can provide an initial human transport capability while building the LEO space base. However, as the base becomes operational and expansion of human operations in LEO and beyond is undertaken, “aircraft-like access to space” must be provided using new capabilities.

The United States has pursued aircraft-like access to space starting with the first aerospaceplane studies in the late 1950s. Stanley Kubrick’s 1968 movie “2001: A Space Odyssey” portrayed a two-stage-to-orbit (TSTO) spaceplane for transporting passengers to LEO (see Figure 8). When NASA first developed

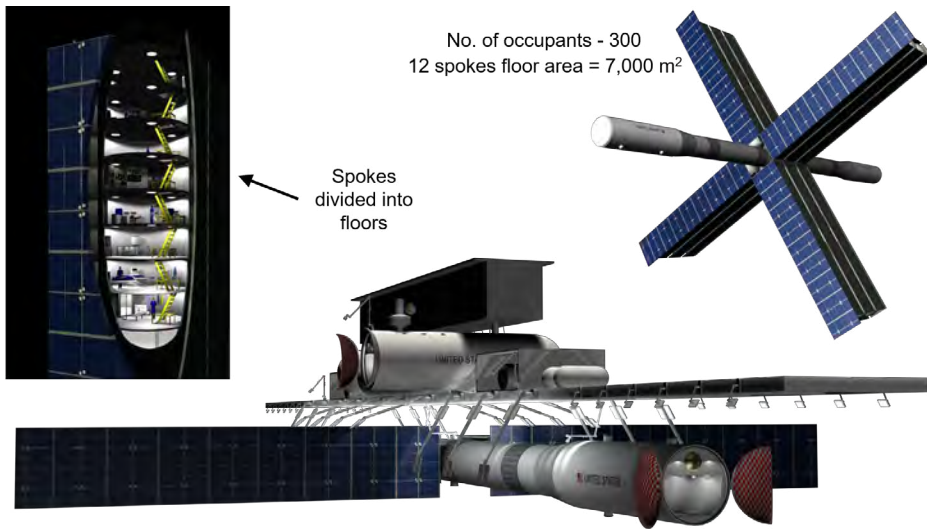


Figure 7: Four-Spoke Rotating Space Habitat Assembled at the Space Dock (Sources: J.M. Snead, U.S. Air Force; Isiah Davenport and Dennis Stewart, Veridian).

housekeeping services and eases cleaning up spills and messes. Rotating the habitat at two revolutions per minute will create a variable gravity environment from near zero-g, where the spoke attaches to the hub, to Mars gravity at the outer floor. Most human operations will occur in the outer floors, where the gravity ranges from that of the Moon to that of Mars. This provides an environment for experimentation

of biological and mechanical systems operations at lunar and Martian gravity levels.

### AIRCRAFT-LIKE, EARTH-TO-ORBIT TRANSPORTATION

NASA’s “Commercial Crew” program will reinstate American human space access using 1960s-style space capsules. In addition to transporting NASA astronauts to the International Space Station,



Figure 8: A 1968 Newspaper Advertisement for Stanley Kubrick’s movie “2001: A Space Odyssey.” The Two-Stage-to-Orbit Orion III Spaceplane Is Being Prepared for Launch (Source: MGM Studios).

the Space Shuttle in 1970, it was first envisioned as a TSTO system. Due to technology, policy, and budget considerations, a partially-reusable design was adopted. In the late 1970s, Boeing developed a quasi single-stage-to-orbit (SSTO) design, called the Reusable Aerodynamic Space Vehicle (RASV), that used a sled to assist takeoff. Boeing proposed to build a prototype of it for the federal government at a cost of \$1.4 billion (see Figure 9).



Figure 9: Boeing's Late 1970s Design of the Reusable Aerodynamic Space Vehicle (RASV) (Source: Boeing).

Responding to the development of new technologies from NASA's Space Shuttle program (e.g., reusable rocket engines, thermal protection, and propellant tanks) and Boeing's expression of confidence in building a spaceplane, the U.S. Air Force renewed its studies of manned space access systems. At the Air Force Aeronautical Systems Division (ASD) at Wright-Patterson Air Force Base, Ohio, the Transatmospheric Vehicle (TAV) Project Office was established in 1983. Major airframe companies were placed under contract to prepare TAV concepts. Several quasi-SSTO and TSTO concepts were proposed, including the RASV. After evaluation, the TAV Project Office selected a Boeing TSTO design to use as the baseline for further technology readiness and mission assessments (see Figure 10).

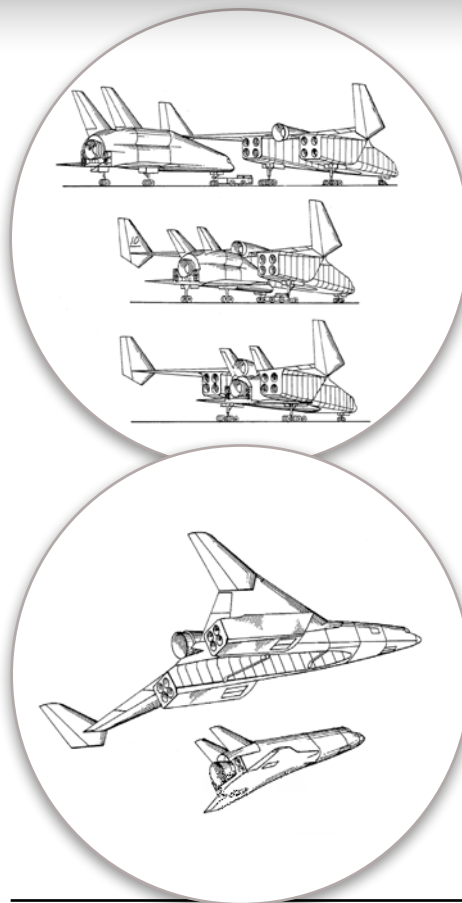


Figure 10: Boeing's 1983 Two-Stage-to-Orbit TAV Concept: (Top) Mating of the Second-Stage Orbiter to the First-Stage Carrier Aircraft and (Bottom) Separation of the Orbiter From the Carrier Aircraft—the Point Where the Orbiter Begins Its Ascent to Orbit (Source: Boeing U.S. Patent 4,802,639).

This TSTO TAV concept would take off and land on a runway. As shown in Figure 10, mating the second-stage orbiter to the first-stage carrier aircraft only requires a standard aircraft tug. Once mated and fueled, the TAV takes off under jet power, climbing to its cruise altitude of 30,000 ft. At the appropriate location, modified Space Shuttle main engines (now referred to as the RS-25) on the first and second stages are turned on. The TAV performs a zoom climb to 103,000 ft, where the orbiter separates from the carrier aircraft. While the carrier aircraft returns and lands at the base, the orbiter continues to LEO. When its mission is completed, the orbiter reenters and lands unpowered, just like the Space

Shuttle orbiter. Shown in Figure 11, the TAV orbiter is similar in overall size to the Space Shuttle orbiter. An unmanned cargo version and a crewed passenger version of the orbiter would most likely be developed, providing the T-4 transportation function shown in Phase A of Figure 1.

In early 1985, the TAV Project Office completed its formal mission analyses and technology readiness assessment. The assessment was done per the criteria defined by an Air Force General Officer steering group formed to oversee the TAV studies, as this was expected to become a major acquisition program like the B-2, C-17, and F-22 underway at ASD. Based on the assessment's favorable results, ASD formally recommended starting full-scale development of a TSTO TAV system.

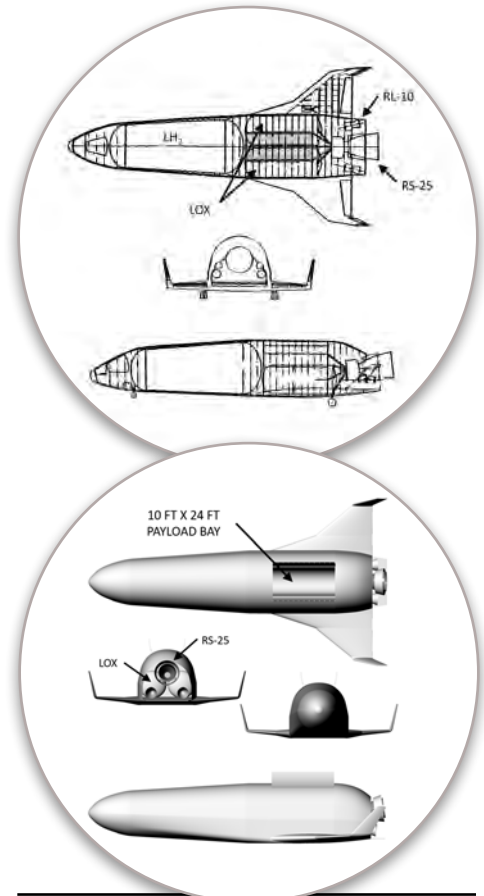


Figure 11: The Boeing TSTO TAV Orbiter (Sources: [Top] Boeing and [Bottom] J.M. Sneed).



This would have led to an operational, manned spaceflight capability in the late 1990s. While this recommendation was not pursued by the Air Force, for over 30 years, America's aerospace industry has had the industrial mastery necessary to undertake developing fully-reusable TSTO TAVs capable of aircraft-like access to space.

What is particularly important to understand is that the Air Force only operates aircraft that have been airworthiness certified—unlike the Space Shuttle or the current NASA Commercial Crew system. If a TSTO TAV had been developed, it would have met these airworthiness requirements. Airworthiness focuses on safety rather than how the vehicle is configured. In the early 1950s, Boeing developed the jet-powered KC-135 tanker for the Air Force, enabling Boeing to develop the Boeing 707 commercial airliner. Along with the Douglas DC-8, these two jet airliners jumpstarted the commercial jet age. Had the Air Force pursued a TSTO TAV in the late 1980s and early 1990s, a commercial variant could have possibly been operating in the early 2000s. Like the military TAV, the commercial TAVs would have been airworthiness certified as required for commercial passenger transport.

America's aerospace industry has had the industrial mastery necessary to undertake developing fully-reusable TSTO TAVs capable of aircraft-like access to space.

## CONCLUSION

Developing TSTO TAVs, perhaps using Boeing's concept, will enable the United States to quickly develop aircraft-like access to space to support expanded civil, commercial, and military operations in space. When combined with using the SLS to build large LEO bases, habitats, and other needed capabilities, such as fuel depots, America can quickly take impressive steps to reclaim "America's heritage as the world's greatest spacefaring nation." ■

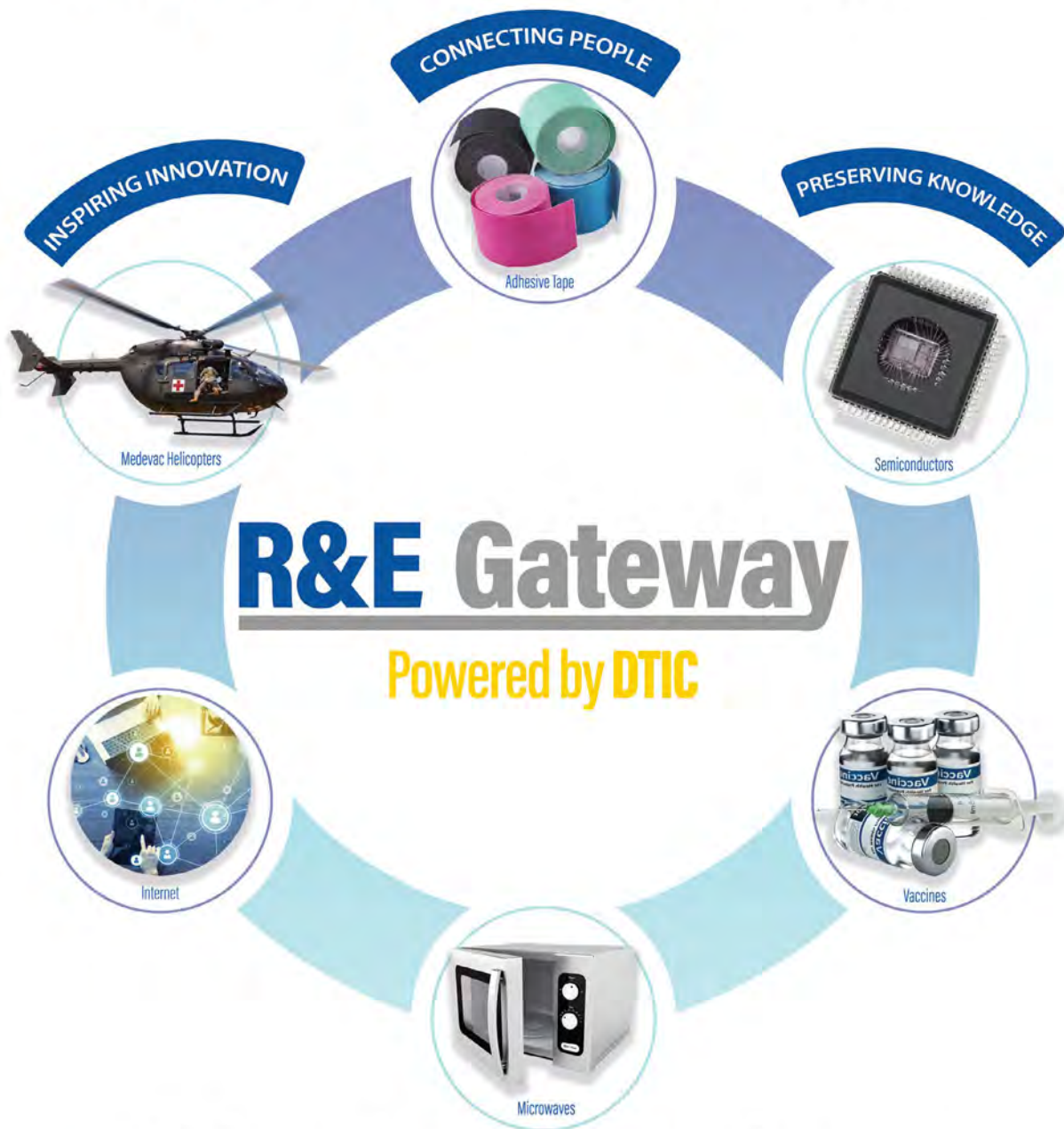
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## BIOGRAPHY

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