



AFRL-RH-FS-TR-2020-0010

**General Dynamics Information Technology
Directed Energy Bioeffects Research II
Task Order 7 Final Report**

Contract No. FA8650-13-D-6368

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General Dynamics Information Technology

February 2020

Final Report for October 2015 – February 2020

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**Air Force Research Laboratory
711th Human Performance Wing
Airman Systems Directorate
Bioeffects Division
Radio Frequency Bioeffects Branch**

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The experiments reported were conducted according to the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

"General Dynamics Information Technology Directed Energy Bioeffects Research II Task Order 7 Final Report Contract No. FA8650-13-D-6368 (Final Report for October 2015 - February 2020)"

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REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
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1. REPORT DATE (DD-MM-YYYY) 13-02-2020		2. REPORT TYPE Final		3. DATES COVERED (From – To) 1 Oct 2015 – 13 Feb 2020
4. TITLE AND SUBTITLE General Dynamics Information Technology Directed Energy Bioeffects Research II Task Order 7 Final Report Contract No. FA8650-13-D-6368 (Final Report for October 2015 – February 2020)			5a. CONTRACT NUMBER FA8650-13-D-6368-0007	
			5b. GRANT NUMBER N/A	
			5c. PROGRAM ELEMENT NUMBER 62202F	
			5d. PROJECT NUMBER N/A	
6. AUTHOR(S) (b) (6)			5e. TASK NUMBER N/A	
			5f. WORK UNIT NUMBER HOEB	
			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) General Dynamics Information Technology (b) (6)			10. SPONSOR/MONITOR'S ACRONYM(S) 711 HPW/RHDR	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Materiel Command, Air Force Research Laboratory 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (b) (6)			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RH-FS-TR-2020-0010	
			12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution B: Distribution authorized to U.S. Government agencies only (proprietary information, February 2020). Other requests for this document shall be referred to 711 HPW/RHDR, (b) (6)	
13. SUPPLEMENTARY NOTES				
14. ABSTRACT Understanding the biological effects of directed energy is a primary goal of the Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (711 HPW/RHDR) at Joint Base San Antonio (JBSA) Fort Sam Houston, Texas. General Dynamics Information Technology (GDIT) scientists, with specialized expertise in biological and biophysical research, completed biological effects research in support of the development and deployment of future directed energy (DE) weapons and other emerging technologies beneficial to the Air Force and the warfighter. The research provided data to aid in the development of tactics, training, and procedures for the safe and optimal use of DE weapons. This research provided data that evaluates and supports the DE system effectiveness, its policy acceptability, and optimal use. Research efforts were directly aimed at identifying any biological impact from radio frequency (RF) exposures ranging from direct current (DC) – terahertz (THz) frequencies, and to nanosecond duration pulses. Interestingly, each different type of RF exposure caused sets of unique biological responses. The investigation and classification of each response allowed GDIT scientists to develop models to predict those responses. This body of research focused upon Active Denial Technology (ADT) and high power microwave bioeffects. This report describes in detail the different research efforts and associated deliverables generated for each project assigned to GDIT under the Directed Energy Bioeffects Research II program for Task Order 7 (Directed Energy System Effects Optimization).				
15. SUBJECT TERMS Active Denial Technology, Biotechnology, nonlethal weapons, Directed Energy, electro-muscular incapacitation, millimeter wave, biomarkers, bioeffects, nanosecond electrical pulse, high peak power				
16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 28
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	19a. NAME OF RESPONSIBLE PERSON (b) (6)	
			19b. TELEPHONE NUMBER (include area code) N/A	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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LIST OF ACRONYMS

711 HPW/RHDR	Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate (formerly Human Effectiveness Directorate), Bioeffects Division, Radio Frequency Bioeffects Branch
ADS	Active Denial System
ADT	Active Denial Technology
AFI	Air Force Instruction
AFRL	Air Force Research Laboratory
AFRL/RDHA	Air Force Research Laboratory, Directed Energy Directorate
ARDEC	Army Armament Research, Development and Engineering Center
BAL	Blood Alcohol Level
BTEC	Buffington, Thomas, Edwards, and Clark Model
CEM ₄₃	Cumulative Equivalent Minutes at 43 °C
CHIRP	Cranial High Pressure from RF Pulses
CLT	Carbon-Loaded Teflon®
DC	Direct Current
DE	Directed Energy
DEBRII	Directed Energy Bioeffects Research II
DEPS	Directed Energy Professional Society
DE2DC	Directed Energy to DC Exhibition
DoD	Department of Defense
DTM	Dynamic Thermal Model
FDTD	Finite-difference time-domain
GDIT	General Dynamics Information Technology
GHz	Gigahertz
HDF5	Hierarchical Data Format 5
HEAP	Human Effects Advisory Panel
IACUC	Institutional Animal Care and Use Committee
IDA	Institute for Defense Analyses
IR	Infrared
JBSA	Joint Base San Antonio
JNLWD	Joint Non-Lethal Weapons Directorate
MMW	Millimeter wave
MRI	Magnetic Resonance Imaging
M&S	Modeling and Simulation
NHP	Non-Human Primate
nsEP	Nanosecond Electrical Pulse
PLY	Polygon File Format
PPE	Personal Protection Equipment
RDT&E	Research, Development, Test, & Evaluation
RF	Radio Frequency
RFR	Radio Frequency Radiation
SAR	Specific Absorption Rate

SG	Silent Guardian™
SSADT	Solid-State Active Denial Technology
THz	Terahertz
TSRL	Tri-Service Research Laboratory
1D	One-Dimension(al)
3D	Three-Dimension(al)

EXECUTIVE SUMMARY

Understanding the biological effects of directed energy is a primary goal of the Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (711 HPW/RHDR) at Joint Base San Antonio (JBSA) Fort Sam Houston, Texas. General Dynamics Information Technology (GDIT) scientists, with specialized expertise in biological and biophysical research, completed biological effects research in support of the development and deployment of future directed energy (DE) weapons and other emerging technologies beneficial to the Air Force and the warfighter. The research provided data to aid in the development of tactics, training, and procedures for the safe and optimal use of DE weapons. This research provided data that evaluates and supports the DE system effectiveness, its policy acceptability, and optimal use. Research efforts were directly aimed at identifying any biological impact from radio frequency (RF) exposures ranging from direct current (DC) – terahertz (THz) frequencies, and to nanosecond duration pulses. Interestingly, each different type of RF exposure caused sets of unique biological responses. The investigation and classification of each response allowed GDIT scientists to develop models to predict those responses. This body of research focused upon Active Denial Technology (ADT) and high power microwave bioeffects. This report describes in detail the different research efforts and associated deliverables generated for each project assigned to GDIT under the Directed Energy Bioeffects Research II program for Task Order 7 (Directed Energy System Effects Optimization).

1.0 INTRODUCTION

The objective of this contract was to conduct exploratory and developmental research and provide support relating to health and safety standards for human exposure to directed energies and human vulnerabilities to such exposures. It included the impact of exposures to human performance. These studies assessed the physiological, behavioral, and long-term effects of radio frequency radiation (RFR) technologies.

All research projects have been approved for the use of human subjects by the Air Force Research Laboratory's Institutional Review Board in accordance with Air Force Instruction (AFI) 40-402¹ and Air Force Research Laboratory (AFRL) Instruction 40-402.

All experiments involving animal procedures were procured, maintained, and used according to an Institutional Animal Care and Use Committee (IACUC)-approved Animal Use Protocol and established animal welfare standards, compliant with: DoD Instruction 3216.01,² U.S. Department of Agriculture Animal Welfare Regulations;³ The Guide for the Care and Use of Laboratory Animals, 8th Edition, National Research Council;⁴ and AFMAN 40-401(1).⁵ The Air Force Research Laboratory at Joint Base San Antonio (JBSA) Fort Sam Houston, Texas has been accredited by AAALAC, International since 1967.

Note: Citations with an asterisk (*) denote a document submitted by a government author. GDIT will not provide a copy since document is already filed in the government case file. Citations with (**) denote documents edited by (b) (6).

¹ Department of the Air Force. (2005). *Protection of Human Subjects in Biomedical and Behavioral Research* (AFI 40-402). Retrieved January 21, 2014, from <http://www.fas.org/irp/doddir/usaf/afi40-402.pdf>

² Department of Defense (DoD). (2010). *Use of Animals in DoD Programs* (DoD Instruction Number 3216.01). Retrieved February 21, 2017, from <http://www.dtic.mil/whs/directives/corres/pdf/321601p.pdf>

³ U.S. Department of Agriculture. (2013). *USDA Animal Welfare Regulations*, 9 C.F.R. Subchapter A. Retrieved February 21, 2017, from <https://www.nal.usda.gov/awic/animal-welfare-act>

⁴ National Research Council (NRC). (2011). *Guide for the Care and Use of Laboratory Animals* (8th ed.). Washington, DC: National Academies Press.

⁵ U.S. Air Force. (2005). *The Care and Use of Laboratory Animals in DOD Programs*, AFMAN 40-401(1). Retrieved February 21, 2017, from http://www.apd.army.mil/pdf/r40_33.pdf

2.0 TASK ORDER 7: DIRECTED ENERGY SYSTEM EFFECTS OPTIMIZATION

Developmental research is a core capability of Team General Dynamics Information Technology (GDIT). Under Directed Energy Bioeffects Research II (DEBR II), we have developed test plans for field and laboratory testing of directed energy (DE) systems and bioeffects. We applied our proven methodology to perform experiments supported by detailed dosimetry, on-site designs of unique research equipment, isolated tissue preparations, and safety considerations. Our team developed operating instructions to perform laboratory experiments and field experiments without any degradation in quality or scientific rigor.

GDIT scientists provided scientific and technical support for future DE weapons development and deployment through laboratory and field testing of the bioeffects of DE weapons, and radar and communication systems. The scientific and technical support was provided by a multi-disciplinary team that assisted in technology demonstrations, training, and evaluations. This support also developed theoretical and computational models to assist in the analysis and prediction of radio frequency (RF) bioeffects. The research performed encompasses the following areas:

2.1 Program Support

Several historical Active Denial System (ADS) studies were declassified and edited for submission into the unclassified Directed Energy Professional Society (DEPS) *Journal of Directed Energy*. Two involved thermal injury (burn) studies: one on pigs and one on humans. One involved the lack of effects of millimeter wave (MMW) energy on reproduction. Another reported on the effectiveness of ADS 2 on drivers of moving vehicles. A behavioral study explored the impact of ambient environmental conditions on MMW energy perception in 10 subjects. Another study examined the effect of alcohol on MMW repel thresholds. Eight of the following manuscripts were prepared for submission to the peer-reviewed journal, *Journal of Directed Energy*; the ninth was an unpublished manuscript submitted to Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (711 HPW/RHDR).

The first document is the introduction for the special article. In 1989, explorations of radiofrequency exposure bioeffects at Brooks Air Force Base laboratory produced a realization that energy at frequencies around 10 gigahertz (GHz), which are superficially absorbed in the body, could produce warming sensations without obvious damage. Investigations into the energy required to produce subjective and behavioral effects, as well as the safety of such exposures commenced. It became apparent that a repel effect, rapid movement out of the beam of energy, could be produced at non-damaging levels and that the effect could be useful in some military-relevant situations. That initial bio-behavioral observation kicked-off engineering efforts at Kirtland Air Force Base which resulted in the development of several approximately 95-GHz devices, the most powerful of which became known as the ADS.

Interest in the novel capabilities of the ADS led the 711 HPW/RHDR, the Naval Health Research Center Detachment, and their predecessors to conduct extensive research to determine the operational utility and effectiveness of the ADS; to establish safe operating parameters and practices; and to examine potential health effects⁶. At this time, over 25 ADS-related studies have occurred. The authors in this special issue report on a mixture of work, which largely occurred in the first 15 years of research.

(b) (6) (2019, January). *DEPS Millimeter Wave Issue Introduction* (AFRL-RH-FS-OT-2019-119341, P.A. Case No. TSRL-PA-2019-0123, 25 Jan 19). Unpublished manuscript. Document submitted to *DEPS Journal of Directed Energy* as the Introduction for a special issue, which includes seven ADS articles. Submitted to 711 HPW/RHDR.

The second manuscript is a summary of ADS research and the development of the research plan. The ADS uses a beam of MMW energy at approximately 95 GHz to induce intolerable heating in the superficial layers of the skin that motivates the targeted subject to escape the beam (repel). At 95 GHz, the penetration depth has been calculated to be approximately 0.3 mm, and thus most of the MMW energy absorption in animals and humans will occur in the skin and cornea. This is significant for the ADS because many of the free nerve endings, which are thought to signal pain and thermal sensation, are located in approximately the first 0.2 mm of the cornea and 0.6 mm of the skin. This fact was key to the development of the ADS bioeffects research plan.

The research path used to investigate the safety, efficacy, and utility of the ADS was a deliberate, synchronized line of investigation answering fundamental applied bioeffects questions. The five research areas investigated were (a) eye safety and vision, (b) the risk of thermal injury to the skin, (c) altered pain responses, (d) cancer, fertility, and the risk of birth defects, and (e) whole body exposures under field conditions. The bioeffects research supports the conclusion that, when used as intended, ADS exposure presents a minimal risk of injury and is effective at producing repel responses. An independent blue-ribbon panel, organized by Pennsylvania State University, reviewed the research plan and subsequent results three times over the course of the program to validate its technical quality and relevance.

(b) (6) (2019, May). *Summary of Results from the Active Denial Biological Effects Research Program* (AFRL-RH-FS-JA-2019-119890, P.A. Case No. TSRL-PA-2019-0163, 28 May 19). Unpublished manuscript. Journal article submitted to *DEPS Journal of Directed Energy* for special issue. Submitted to 711 HPW/RHDR.

The third manuscript describes an experiment used to determine the effects of the ADS on persons in vehicles and to assess the potential usefulness of ADS in a vehicle-stopping scenario. Experiment 1 measured the time to reaction following ADS exposure onset in a static scenario.

⁶ Much of the research and development for the ADS was funded by the Joint Non-Lethal Weapons Program.

Experiment 2 measured the distance at which the vehicle was stopped or steered away from a goal area following ADS exposure onset in a moving vehicle scenario. Additionally, the driver's reaction to the ADS stimulus was measured qualitatively. Overall, ADS was found to be effective in scenarios where an adequate dose could be delivered (i.e., head on, lower vehicle speeds, and lower attenuating windshields).

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(2015, December). *Behavioral Effects of Exposure to Active Denial System on Operators of Motor Vehicles* (AFRL-RH-FS-JA-2015-114956, P.A. Case No. TSRL-PA-2015-0169, 21 Dec 15). Unpublished manuscript. Journal article submitted to *DEPS Journal of Directed Energy* for special issue. Submitted to 711 HPW/RHDR.

The fourth manuscript involved an investigation into the effects of 94-GHz exposure on the reproductive organs of the male Sprague-Dawley rat (N=120). The scrotal region of each rat (N=36 per group) was sham exposed or warmed by exposure to 94-GHz or infrared (IR) energy. Additionally, twelve other rats had their scrotal regions warmed by warm water immersion to serve as positive control. Each rat in the 94-GHz group was individually restrained in a cylindrical Plexiglas® holder and exposed for 10 s at 1 W/cm². Similar surface heating rates were produced by exposure to IR for 10 s at 1.5 W/cm². Blind analyses of sperm motility and morphology (sampled from vas deferens) and sperm production rates (sampled from testes and epididymides) were conducted 6.5, 26, and 52 days post exposure. There were no significant differences amongst the sham, 94-GHz, or IR exposed animals with respect to sperm production and motility. Morphometric measurements of sperm did not show significant differences amongst the sham, 94-GHz, and IR exposure groups. Thus, exposure of the scrotal region of Sprague-Dawley rats to 94 GHz (10 J/cm²) did not significantly affect sperm production, morphology or motility.

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(2016, April). *Lack of Effects of 94-GHz Energy Exposure on Sperm Production, Morphology, and Motility in Sprague-Dawley Rats* (AFRL-RH-FS-JA-2016-115358, P.A. Case No. TSRL-PA-2016-0231, 1 Apr 16). Unpublished manuscript. Journal article submitted to *DEPS Journal of Directed Energy* (for special issue). Submitted to 711 HPW/RHDR.

The fifth manuscript describes a study that extrapolated the dose-response relationship for millimeter wavelength radiation induced thermal injury from previously obtained rodent data to a larger animal model. Based on exposure conditions that cause damage in rats, exposure conditions were chosen that would most likely cause more than superficial burn damage in pig skin (power densities of 2-4 W/cm² and durations of 3-20 s). However, due to structural differences (relative thickness of tissues and density of hair follicles) between rat and pig skin, direct interspecies correlations of burn data are not likely to have statistical significance. Twelve Yucatan minipigs were used in this study to establish the probability of developing first- and second-degree burns versus exposure duration at three power density settings (2, 3 and 4 W/cm²) and versus the rise in the mean skin temperature over the exposed area. Additionally, the study examined the effects of repeated exposures to an area, and the time required between exposures to return to pre-exposure

temperatures. The results of the study indicated that the damage to the skin from the MMW exposures was a purely thermal effect.

(b) (6). (2016, January). *Thermal Injury in Large Animals Due to 94-GHz Radio Frequency Radiation Exposures* (AFRL-RH-FS-JA-2015-114975, P.A. Case No. TSRL-PA-15-0173, 11 Jan 16). Unpublished manuscript. Journal article submitted to DEPS *Journal of Directed Energy*. Submitted to 711 HPW/RHDR.

The sixth manuscript examined situations where potential targets had consumed alcohol to determine whether alcohol intoxication impacted the subject response. In the present study, each of 9 experimental subjects consumed alcohol and received facial exposures to 94-GHz RFR at three blood alcohol levels (BALs), 0.00, 0.08, and 0.12%. Subject faces were exposed five times to each of four energy densities, 0.0, 0.6, 1.0, and 1.4 J/cm². The presence or absence of eye blinks and face averts during exposures was recorded. Skin temperature and aversion response latencies were determined using infrared video records of subject exposures. Although subject BAL during MMW exposures was associated with some statistically significant differences in facial aversion scores, these differences were small in magnitude and their existence probably do not imply that alcohol intoxication substantially alters the degree of effectiveness or the safety margin associated with systems employing MMWs.

(b) (6) (2015, December). *Eye Blink and Face Avert Responses to 94-GHz Radio Frequency Radiation Experienced Following Alcohol Consumption* (AFRL-RH-FS-JA-2015-114900, P.A. Case No. TSRL-PA-2015-0161, 15 Dec 15). Unpublished manuscript. Journal article submitted to DEPS *Journal of Directed Energy* (for special issue). Submitted to 711 HPW/RHDR.

The seventh manuscript summarized the results from a study on the impact of ambient environmental conditions on perception of MMW energy by human subjects. The research explored energy perception in 10 subjects. The environmental manipulations (ambient air temperature and relative humidity) impacted perspiration during the MMW energy exposures: local sweating rate differed significantly across the four temperature/humidity combinations. Yet, the four conditions resulted in only a 1% variance in subject estimation of pain threshold. The overall mean estimate of 1241.7 mW/cm² conformed to previous laboratory studies conducted at a fixed environmental setting.

(b) (6) (2015). *Threshold for Pain in Response to 94-GHz Millimeter Wave Energy Experienced Under Varying Ambient Temperatures and Humidities* (TSRL-PA-13-0111, 27 Aug 13). Unpublished manuscript. Journal article submitted to DEPS *Journal of Directed Energy*. Submitted to 711 HPW/RHDR.

The eighth manuscript described the use of carbon-loaded Teflon® (CLT) as a dosimeter for 94 GHz MMW radiation. The fundamental principle underlying the applicability of CLT as a MMW dosimeter has been that the rate of the temperature rise of the CLT sheet was proportional to the incident MMW power density. By calibrating the temperature to power density response of the CLT to a National Institute of Standards and Technology traceable power meter coupled to WR-10 open-ended waveguide, field measurements of 94 ± 2 GHz using CLT could be made to within 2.2% of standard sensor over the range of 0.5 to 12 W/cm². Additionally, using a sufficiently large CLT sheet enabled one to obtain information about the beam shape and to observe any interference effects in the region of interest. Alignment of the sheet relative to the beam path was significantly less critical than measurements using open-ended waveguide. These characteristics would be highly desirable for biological experiments involving MMW exposures and made CLT a useful dosimeter for our laboratory.

(b) (6) (2015, September). *Millimeter Wave Dosimetry Using Carbon-Loaded Teflon* (AFRL-RH-FS-JA-2015-0022, P.A. Case No. TSRL-PA-2015-0131, 16 Sep 15). Unpublished manuscript. Journal article submitted to *DEPS Journal of Directed Energy*. Submitted to 711 HPW/RHDR.

The ninth document involved a study that compared the exposure data for MMW radiation-induced thermal injury in humans at 4 W/cm² and 6 W/cm² to those previously obtained involving dose-response exposure data in experimental porcine models. Where possible, this study aimed to estimate the probability for eliciting human skin burn damage to MMW exposures by comparing similar exposures from the porcine exposure database.

Due to the inherent difficulties in acquiring human subjects and exposing them to up to potential damaging levels of MMWs, the conclusions presented were based upon the results of a small study sample (N=6). Therefore, the results could serve as an initial guide to the acceptable human exposure safety margins for the employment of MMW devices, but should not be considered a definitive study.

(b) (6) (2016, February). *Thermal Injury in Human Subjects Due to 94-GHz Radio Frequency Radiation Exposures* (AFRL-RH-FS-TR-2016-0001, P.A. Case No. TSRL-PA-2016-0234, 1 Apr 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Human Effectiveness Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

Also under program support, presentations and brochures related to previous ADS research were generated to be used for site visits and/or communications with external agencies. The first was a PowerPoint presentation related to pulsed ADS exposures on humans for use during site visits.

(b) (6) (2016, October). *Pulsed Effects of Millimeter Waves (MMWs)* (AFRL-RHDR-FS-OP-2016-0001, 19 Oct 16). Oral Presentation used for site visits. Submitted to 711 HPW/RHDR.

Then there are two brochures that were distributed at the Directed Energy to DC Exhibition (DE2DC) exhibition in Washington DC.

(b) (6) (2018, December). Exhibit Graphic (AFRL-RH-FS-OT-2018-119210; P.A. Case No. TSRL-2018-0254, 11 Dec 18) used for Directed Energy to DC Exhibition (DE2DC) held in Washington, DC on 29 Apr – 2 May 19. This graphic was included in DE2DC Educational Outreach Brochure that DEPS distributed to the Pentagon and Congressional staff to entice them to visit the event. Submitted to 711 HPW/RHDR.

(b) (6) (2019, March). *Directed Energy Bioeffects Division*. Brochure for Directed Energy to DC Exhibition (DE2DC) (AFRL-RH-FS-BR-2019-119573, P.A. Case No. TSRL-PA-2019-0140, 8 Mar 19). This brochure was distributed at Directed Energy to DC Exhibition (DE2DC) held in Washington DC on 29 Apr - 2 May 19. Submitted to 711 HPW/RHDR.

Lastly, there were edits to three classified reports of previously conducted studies at 711 HPW/RHDR. The first involved declassifying a human-use, MMW study involving the Silent Guardian™ (SG) system. The new report was essentially the same as the original with only the classification markings removed. The research quantified the behavioral effects of MMW exposures from spot sizes that are approximately one-third the area of ADS. Experiment 1 determined the power density necessary to achieve pain intolerability in 90% of the human subject population. In Experiment 2, the SG system operator attempted to disrupt subjects from performing various behavioral tasks including (a) throwing balls, (b) sighting a simulated weapon either while standing erect in the open or while crouching behind a barrier, and (c) burying a simulated improvised explosive device. For all of the tasks, the subject performance was significantly degraded when engaged by the SG system. The degree of degradation was most pronounced during the simulated weapon task in which subjects were called upon to stand erect in the open.

(b) (6) (2017, May). *Thermal and Behavioral Effects of Exposure to 30-kW, 95-GHz Millimeter Wave Energy* (AFRL-RH-FS-TR-2017-0016, P.A. Case No. TSRL-PA-2017-0188, 20 Jul 17). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The next report also involved declassifying a human-use, MMW study. The report documents two studies that were conducted to quantify human behavioral responses to 95-GHz MMW exposures employing differing beam sizes and power densities. Experiment 1 examined the repel times of stationary subjects at combinations of three MMW power densities and five spot sizes. Experiment 1 results confirmed that repel times decreased with increasing beam size, although the strength of this relationship varied with power density. Experiment 2 determined to the extent to which the Experiment 1 relationships between beam size and repel time extrapolated

to moving subjects. Subjects were required to throw balls into a net while being targeted by the MMW beam. Results indicated similar performance at the 4 largest spot sizes, and better subject performance (i.e., decreased MMW effectiveness) at the smallest spot size.

(b) (6) (2017, May). *Effects of Variable Spot Size on Human Exposure to 95-GHz Millimeter Wave Energy* (AFRL-RH-FS-TR-2017-0017; P.A. Case No. TSRL-PA-2017-0191, 2 Aug 17). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The third effort involved creating a summary section of the extensive report on microwave exposures on swine. The summary and report were classified and located in the secure room.

(b) (6) (2014, February). *(U) Model for Health and Safety of Microwave Exposures in Swine*. Report located in secure room (ASAP2 Report/ASAP draft technical report_20 August 2010; a hard copy is located in folder labeled “ASAP 2”). Unpublished manuscript. Submitted to 711 HPW/RHDR.

2.2 Transmitter Support

This effort involved the ongoing support of GDIT personnel to maintain, operate, and modify the various transmitters and associated technical equipment related to the conduct of experiments at 711 HPW/RHDR. Examples of tasks completed under this effort were: a) integrating software and hardware systems to simplify and automate data collection during experimentation, b) automating the Denso robot to find the maximum in an RF field, c) repairing the 95 GHz and 500 kW transmitters, d) providing technicians to operate the transmitters in support of testing and experimentation, e) purchasing and conducting technical discussions with Polarity to acquire the 500 kW transmitter.

A twin-well calorimetry user’s guide that describes the design, calibration, testing, and operating instructions for the measurement of the whole body specific absorption rate of objects exposed to radio frequency was submitted to 711 HPW/RHDR. Twin-well calorimeters were used in one of the Thermal Validation studies.

(b) (6) (2019, December). *Twin-Well Calorimetry User Guide*. Unpublished manuscript. Submitted to 711 HPW/RHDR.

2.3 Risk of Eye Injury-high Power Short MMW Exposure (Active Denial Technology (ADT) Bioeffects Analysis)

Several human studies were planned to investigate significantly higher power densities (greater than 10 W/cm²) so that a review of previous damage studies was necessary to determine if any issues should be resolved before the exposures were conducted. A white paper was written that examined previous MMW research conducted at Brooks Air Force Base on damage to the

eyes.⁷ This study found a 7.5 J cm⁻² threshold at 35 GHz and a 5 J cm⁻² threshold at 94 GHz for corneal lesions in the rhesus monkey. These lesions were distinct, involved only the superficial layers of the cornea, and were reversible within 24 hr. The exposure times for the study varied from 1.5–5.0 s at 35 GHz and 1.0–4.0 s at 94 GHz. Powers of up to 8.0 W cm⁻² were used. It was assumed by the study that fluence was the criteria by which eye safety should be evaluated. Further evaluation of the data indicated that the experimental data was much hotter than would be expected from existing thermal models. The white paper proposed a plan to check the model and the experimental data.

(b) (6) (2015, May). *Simulation Plan: Risk of Eye Injury from High Power, Short Millimeter Wave Exposures*. Unpublished manuscript. Submitted to 711 HPW/RHDR.

Following the above research plan, a study was conducted that computationally examined the effects of MMWs on the skin and the eye. In the first task, model simulations showed that 220 GHz required less power to repel than 95 GHz primarily because the absorption coefficient was higher than the absorption coefficient for 95 GHz. This trend also applied to damage predictions, and therefore the safety margin between repel and thermal damage was approximately equal at both 95 GHz and 220 GHz. In the second task, the Buffington, Thomas, Edwards, and Clark (BTEC) model was used to compute the temperature rise and damage from MMW exposures and found a discrepancy between computed temperatures by BTEC and the (b) (6) study in 2002. To resolve this discrepancy, two experiments were recommended: 1) measure the complex dielectric constant at 35 GHz and 95 GHz, and 2) measure non-human primate (NHP) cornea heating under low powers at 35 GHz and 95 GHz.

(b) (6) (2015, December) *Modeling Thermal Effects From Millimeter Waves* (AFRL-RH-FS-TR-2016-0016, 27 Sep 16) JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

2.4 Protocol Drafts

Several human studies were proposed for future work, and protocols were drafted to outline the experiments. However, funding was not secured for the proposed Fresnel maximum and No Mas experiments. Thus, those protocols were never submitted for Institutional Review Board review. Those that were funded became separate tasks and are documented elsewhere in this final report.

(b) (6) (2002). Millimeter wave absorption in the nonhuman primate eye at 35 and 94 GHz. *Health Physics*, 83(1), 83-90.

2.5 Improved Thermal Modeling

Two efforts were funded under this task: a) a review of nociceptor responses, and b) the development of the dynamic thermal model (DTM), a parallelized computer model designed to compute the heating and cooling of the surface of a dynamic target in a dynamic directed energy environment.

The review of the nociceptor response provided the factors contributing to heat-sensitive nociceptor activation and models for the human response to thermal pain. The response of these nociceptors to noxious thermal stimulation depended on fiber density, thermal thresholds, spatial summation, and stimulus parameters such as heating rate, intensity, and duration. These factors were examined for their influence on pain sensation and, especially, withdrawal reaction. In addition to experimental studies, published quantitative models of the nociceptive pathway were reviewed, as they provided a guideline to develop a probabilistic model for predicting repel times due to thermal stimuli.

(b) (6) (2015, February). *Nociceptor Response – A Review of Literature* (AFRL-RH-FS-TR-2015-0035, P.A. Case No. TSRL-PA-2016-0241, 16 May 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711 Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The rationale for the development of DTM was outlined in an initial white paper that addressed several needs of models that predicted thermal propagation in tissue, physiological repel response, and effectiveness. The models produced results as a function of space and time. Predictions from the model were based on input to the model from the thermal source, such as:

- Spot size
- Power
- Duration of spot on tissue
- Wavelength
- Relative motion and orientation of source and target

Details into the biophysical properties of nociception and intolerable sensations were considered, as the penetration depth for the heat tolerability and the repel response may be at the level of nociceptor activation. Due to this fact, a detailed model would preferably be three-dimensional (3D), as it needed to consider area (spot size), depth, and account for time dependence (temporal summation). Lastly, the model was able to predict the area and biophysical effects of a novel heat source on the tissue.

(b) (6) (2015, July). *Thermal Model Review and Comparison*. White Paper. Submitted to 711 HPW/RHDR.

The preliminary design of DTM was presented in a white paper. The DTM would be used to predict thermal propagation in tissue, physiological response, and effectiveness of directed energy systems. The model produced results as a function of space and time. Predictions from the model were based on input to the model from the thermal source, such as:

- Spot size
- Power
- Duration of beam on target
- Wavelength
- Relative motion and orientation of source and target

(b) (6) (2015, September). *White Paper for Dynamic Thermal Model (DTM) Preliminary Design*. Submitted to 711 HPW/RHDR.

A follow-on planning document was provided that gave a proposal to develop DTM in a spiral development process. As proposed, this development would occur over 6 spirals, in which an operational code and user manual would be delivered at the end of each spiral. The plan defined which capabilities were independent and could be delivered during an earlier spiral. It also stated which capabilities needed to be developed serially because they had dependencies on the existence of other capabilities. The document provided a table to summarize the spiral development plan, and estimated man-months required to implement each of the listed capabilities, along with the total times to complete each spiral.

(b) (6) (2015, December). *White Paper for Dynamic Thermal Model (DTM) Spiral Development*. Submitted to 711 HPW/RHDR.

The next document described the operational code for Version 1.0 of DTM. It was designed for regimes where thermal conduction into the target could be simplified to one-dimension (1D) (depth) due to small radial gradients. DTM treated the heating of each facet of the surface as an independent, 1D thermodynamic problem. Because of this, communication overhead was kept very low, which allowed for rapid execution time on a parallel computer. DTM was developed in Fortran 90 code, and used Open MPI as the message-passing interface between the parallel tasks when executing. In addition, DTM could read Stanford Polygon File Format (PLY) surface files for defining targets.

(b) (6) (2017, May). *Dynamic Thermal Model (DTM) Version 1.0* (AFRL-RH-FS-TR-2017-0023, 9 Oct 17). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

A user guide was also written for the Version 1.0 spiral of DTM.

(b) (6) (2017, May). *Dynamic Thermal Model (DTM) User Guide* (AFRL-RH-FS-TR-2018-0002, 29 Jan 18). JBSA Fort

Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The source code for DTM was sent to the customer and placed on the Research, Development, Test, & Evaluation (RDT&E) Network at the Tri-Service Research Laboratory (TSRL) for the government.

(b) (6) (2017, May). Dynamic Thermal Model Software. Software (Distribution F) is located on the RDT&E Network, From TSRL_Master: /nfs_share/thermal/New_Skin_Model/DTM_Current DTM_V01.bundle was delivered to customer on 17 Jan 17, containing Dynamic Thermal Model (DTM) Software Version 1.0. DTM_V02.bundle was delivered to customer on 5 May 17, containing Dynamic Thermal Model (DTM) Software Version 1.01 and DTM-GUI Version 1.0. DTM_V02.1.bundle was delivered to customer on 18 May 17, containing Dynamic Thermal Model (DTM) Software Version 1.02 and DTM-GUI Version 1.0. Submitted to 711 HPW/RHDR.

The operational code changes for Spiral 2 (Version 1.08) of DTM included a second thermodynamics model, scripted target motion, scripted system motion, scripted system pointing, tracking, and power variation, and energy beam ground reflections.

(b) (6) (2018, January). *Dynamic Thermal Model (DTM) Spiral 2* (AFRL-RH-FS-TR-2018-0013, 2 Jul 18). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

An updated user guide for DTM Spiral 2 (Version 1.08) was provided.

(b) (6) (2018, February). *Dynamic Thermal Model (DTM) Spiral 2 User Guide* (AFRL-RH-FS-TR-2018-0020, 12 Sep 18). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The operational code changes for Spiral 3 (Version 1.09) of DTM focused on implementing shadowing of targets by other targets or objects in the simulation.

(b) (6) (2019, January). *Dynamic Thermal Model (DTM) Spiral 3* (AFRL-RH-FS-TR-2019-0028, 7 Nov 19). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

An updated user guide for DTM Spiral 3 (Version 1.09) was also provided.

(b) (6) (2019, January). *Dynamic Thermal Model (DTM) Spiral 3 User Guide* (AFRL-RH-FS-TR-2019-0027, 7 Nov 19). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

2.6 Thermal Validation

For animal and human models exposed to microwaves, numerical models had been used to calculate the specific absorption rate (SAR) of the energy absorbed into the body tissues, as well as resulting changes in tissue temperatures and blood flow. Information obtained from these models was used for predicting the biological effects of microwave exposure and setting permissible exposure limits to avoid hazards due to exposure. However, in reviewing the development of these models, we discovered that the previous efforts at validating the models had been sparse and needed improvement. Three different studies were performed for this project. In the first study, SARs were calculated from experimentally measured temperature changes in euthanized rats and were used to validate the in-house, finite-difference time-domain (FDTD) models of the rat. In the second study, SARs were again calculated from experimental measured temperature changes in rats (live and then dead) and were used to validate in-house FDTD models of the rat (with higher resolution of the digital rat phantom). This study also investigated the contribution of thermoregulation in the experimental calculations of SAR by measuring changes in skin temperature and blood perfusion and using these data to validate thermoregulatory computational modeling. In the third study, twin well calorimetry was used to measure whole-body SAR of euthanized rats. In all three studies, rats were exposed to the same RF dose ($f=2.07$ GHz continuous wave for 5 seconds at an average power density of 1.23 W/cm^2 in six different configurations). The results of these three studies are included in the following papers/reports submitted to 711 HPW/RHDR.

(b) (6) (2017, January). *Specific Absorption Rate in the Microwave-exposed Rat (*Rattus norvegicus*)* (AFRL-RH-FS-TR-2018-0003, 1 Feb 18). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

(b) (6) (2020, February). *Experiment vs. Modeling of the Specific Absorption Rate and Thermoregulatory Distribution of Heat in the Rat Exposed to High Peak Power 2.07 GHz Microwave Energy*. Unpublished manuscript. Delivered to 711 HPW/RHDR for review; not cleared as of 14 Feb 20.

(b) (6) (2020, January) *Twin-Well Calorimetry and Computational*

Modeling of the Whole-Body Specific Absorption Rate of the Radiofrequency-Exposed Rat Carcass (AFRL-RH-FS-TR-2020-XXXX). Submitted to 711 HPW/RHDR.

2.7 Solid State ADT

A new MMW transmitter, the Solid-State Active Denial Technology (SSADT) device, was developed that had an electronically steerable antenna that allowed the generation of shaped spots and illumination of multiple areas simultaneously. The new device required new dosimetry techniques to capture the energy of the rapidly steered beam and a presentation of the new techniques were presented to the ADS Human Effects Advisory Panel (HEAP).

(b) (6) (2015, June). *Solid-State Active Denial Technology (SSADT) Dosimetry Review*. Oral presentation for ADS Risk of Significant Injury HEAP held on 29 Jun – 1 Jul 15. Submitted to 711 HPW/RHDR.

Then a study was proposed that had two phases. The first compared the repel threshold for spots generated statically to similar spots generated by rapidly moving a smaller spot. The second phase conducted a classic two-point experiment on the upper body to determine if synergistic effects occurred from multiple exposures as a function of spot separation. The protocol defining the experiment was provided.

(b) (6) (2015, May). *Thermal and Behavioral Effects of Spot Shape and Separation Distance Between Spots on Human Exposures of 94-GHz Millimeter Wave Energy*. Protocol for Solid State ADT. Submitted to 711 HPW/RHDR.

The final report from that experiment concluded that repel thresholds were primarily influenced by power density and were similar for moving and static beams. Flat-top distributions repelled 0.19 s faster than Gaussian distributions, and vertically oriented exposures repelled 0.12 s faster than horizontal. Comparisons with predictions of the Capstone repel model were relatively accurate ($R^2 = 0.865$), and possible improvements were discussed. Minor blisters (diameter less than 5 mm) occurred in 5 out of 902 trials.

(b) (6) (2016, June). *Effects of the Solid State Active Denial Technology Device on Stationary Humans* (AFRL-RH-FS-TR-2016-0030, 28 Nov 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

A follow-on study was proposed using the SSADT device. The objective of that study was 1) to examine high-power, short-duration exposures, and 2) to examine constant temperature exposures using a time-varying power density. The protocol outlining the experiment was provided.

(b) (6)

(2017, May). *Thermal and Behavioral Effects of Temporal Variation of Power Density on Human Exposures of 94-GHz Millimeter Wave Energy* (F-WR-2017-0136-H). Protocol. Submitted to 711 HPW/RHDR.

The final report for the second study of human exposures to the SSADT MMW device answered questions related to the effectiveness of engaging multiple targets with low power once a sufficient temperature rise had been attained, and the effectiveness of very short, intense exposures. Unique to this study compared to other ADS protocols, the second phase conducted a method of levels exposure paradigm at power densities significantly higher than previously used in human-use protocols. The power densities were high enough in this phase that damaging levels of heat could be deposited on the skin at near reaction time thresholds (~ 250 ms), which means that the safety margin based upon the subject's ability to self-limit (remain in trial until the limit of their tolerance is reached) quoted for previous studies was not applicable.

(b) (6)

(2019, September). *Effects of the Solid State Active Denial Technology Device at High Power Densities or Constant Temperatures on Humans* (AFRL-RH-FS-TR-2019-0033, 28 Jan 20). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

In 2019, the Joint Non-Lethal Weapons Directorate (JNLWD) requested that the Institute for Defense Analyses (IDA) review the human effects modeling of ADS. As part of their review, IDA asked 711 HPW/RHDR to provide a comprehensive review of the Capstone model. Dr. Parker generated a briefing and provided it to the IDA representatives.

(b) (6)

(2019, October). *Capstone Model Review*. Oral Presentation for site visit with IDA held on October 10, 2019 at Tri-Service Research Laboratory. Submitted to 711 HPW/RHDR.

2.8 META Analysis

The goal of this analysis was to review all ADS human exposures to identify trends in the thermal profiles that would improve the current capability to estimate MMW repel effectiveness. The hypothesis explored in the first paper was that the peripheral nervous system responds to the thermal dose over the exposed area, and that the summation of the sensations by the peripheral nerves generates a signal to the brain that caused the repel behavior to occur. To evaluate the hypothesis, simple functional forms based upon the observed temperature distributions were used to estimate the repel time for a given set of MMW exposure parameters. A variable temperature model $\sum_{j=1..4} \alpha_j T_{ij} \ln A_{ij} t_{ij}$ that was dependent upon four coefficients, logarithmically on spot size, and linearly on time and temperature was found correlated directly with repel time (R =0.81). The resulting estimate would have an uncertainty that is approximately 0.5 s.

Additionally, the exponential dependence of cumulative equivalent minutes at 43 °C (CEM₄₃) thermal hazards were found to overestimate repel effects. A method to estimate the correct dependence was presented.

(b) (6) (2015, April). *Meta-Analysis of Thermal Effects from 94 GHz, Millimeter Wave (MMW) Exposures on Humans* (AFRL-RH-FS-TR-2015-0019, 20 Oct 15). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Human Effectiveness Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

Additional review of the repel model was conducted and examined incorporating temperature at the depth of the nociceptors. This study demonstrated that the surface and sub-surface skin temperatures were strongly correlated and a metric was found to evaluate the hypothesis that the repel threshold was mediated by a thermal process. The metric involving the surface temperatures did not introduce the uncertainties of measuring the power density, which was necessary to estimate the sub-surface temperatures, and thus had a better overall correlation ($R^2=0.95$). Although the nociceptors for sensing heat are located below the surface and presumably the temperature at their depth would be driving the repel response, for the analysis presented in this study, the uncertainty in estimating the sub-surface temperature masked the gains in using those temperatures to estimate repel thresholds.

(b) (6) (2015, November). *Extension of Meta-Analysis of Thermal Effects from 94 GHz, Millimeter Wave (MMW) Exposures on Humans Incorporating Skin Depth* (AFRL-RH-FS-TR-2016-0011, 8 Aug 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

The next study was the first attempt to use the subjective scores in a quantifiable manner to improve our modeling capability. Since an ADS research goal was to determine the expected repel time of an exposure, the ability to estimate the painfulness of an ADS exposure could be beneficial to the overall modeling effort. Presumably, more painful exposures would be more effective at repelling individuals.

None of the analyses of the subjective scoring found strong improvement in the modeling of repel time. The subjective scoring data correlations were generally weak (mean $R^2 < 0.25$). For almost every power level, the raw and normalized subjective scores span the range of possible response scores. Filtering based on subjective scores did not consistently improve any of the metrics used to evaluate the exposures. Any future work on subjective response of ADS exposures should develop more reliable self-assessment methodologies than currently applied 10-point scales.

Additionally, a new temperature model was developed to estimate repel times. Although the variable temperature model $\sum_j \alpha_j T_{ij} \ln A_{ij} t_{ij}$ was the best correlate for all the historical studies

involved in a recent meta-analysis, the new metric $\alpha \langle \mathbb{H}_{base} \rangle (1 + \beta \ln(S_{base})) + \gamma$ has generated a function that correlates just as well with fewer conditional parameters and with a simpler fundamental basis. The variable temperature and new models should be used to estimate the human subject effectiveness of moving and pulsed ADS emission spot exposures.

(b) (6) (2016, July). *Extension of Meta-Analysis of Thermal Effects from 94 GHz, Millimeter Wave (MMW) Exposure on Humans with Focus on Subjective Data and Additional Metric* (AFRL-RH-FS-TR-2016-0024, 11 Oct 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

A presentation of the meta-analysis methodology and results was given to the JNLWD.

(b) (6) (2015, June). *Review Hypothesis and Methodology for Meta-Analysis of Spot Size Effects and Time to Repel*. Oral presentation for JNLWD review. Submitted to 711 HPW/RHDR.

2.9 220 Modeling

This report described an investigation that had two objectives, both of which used computational modeling to examine the effects of MMW energy exposure on the skin. The first objective was to examine the relationship between spot size and skin temperature for different spot sizes that had an identical peak power. These data provided computational verification of both experimental and theoretical results that showed skin heating from 95 GHz radiation is essentially 1D for sufficiently large spots and resultant numbers were in good agreement. The second objective was to examine the computed burn estimates for spots with constant size and dose, but with various peak power densities at 95 GHz. This result was determined within agreement with earlier experimental observations. When taken in combination with the earlier analysis of 95 GHz exposures, this result implies that the 12 J limit should be reduced when peak average power levels are at or above 9 W-cm^{-2} .

(b) (6) (2016, March). *Modeling Spot Size and Heat Rate Effects From Millimeter Waves* (AFRL-RH-FS-TR-2016-0014, 10 Aug 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

2.10 High Average Power

There were several documents drafted to examine High Average Power bioeffects.

(b) (6) (2016, July). *(U) Controlled Microwave Exposure of the Rat (Rattus norvegicus) – Volume I. Behavior* (AFRL-

RH-FS-TR-2016-0009, 26 Jul 16). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Human Effectiveness Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR. (Document located in secure room.)

(b) (6) (2016, September). (U) *Controlled Microwave Exposure of the Rat (Rattus norvegicus) – Volume II. Pathology* (AFRL-RH-FS-TR-2016-0019, 6 Oct 16). JBSA Fort Sam Houston TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR. (Document located in secure room.)

(b) (6) (2016, August). Oral Presentation given to U.S. Army Armament Research, Development and Engineering Center (ARDEC) on 30 Aug 16. Submitted to 711 HPW/RHDR. (Document located in secure room; title is classified).

(b) (6) (2016, October). (U) *Literature Review of Specific Applications of Directed Energy Research* (AFRL-RH-FS-TR-2017-0005, 8 Feb 17). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR. (Document located in secure room.)

2.11 NsEP Large Animal

A protocol and final report were written to examine the effectiveness of nanosecond electrical pulses (nsEP) on swine.

(b) (6) (2017, January). (U) nsEP Protocol (RHDR-17-06). Submitted to 711 HPW/RHDR 30 Jan 17; document approved and added protocol number and obtained signatures 7 Feb 17; Ms. Terrell sent UC copy of signatures to AF Surgeon General for approval 7 Feb 17; AF Surgeon General reviewed and concurs with the IACUC's approval of protocol 10 Feb 17. (Document located in secure room.)

(b) (6) (2018, February). (U) *Nanosecond Electrical Pulse Exposures in Alert Swine*. Report approved as a deliverable and will be submitted through clearance process; government has determined appropriate security classification guide for report. Submitted to 711 HPW/RHDR. (Document located in secure room.)

2.12 NHP Eye

Damage thresholds to the NHP cornea from MMW induced lesions at 35 and 94 GHz were initially reported, but reviews of the data were concerned with the large variations in the observed temperatures and uncertainties in the MMW dosimetry. By incorporating improvements in models

and dosimetry, an experiment was conducted involving NHP corneal exposures that provides good agreement with a three-layer, 1D, thermodynamic model to predict the expected surface temperature rise. The new data indicates that the original safety margins for eye exposures were conservative over the power densities explored by 30–40%. The expected damage thresholds for power densities less than 8 W/cm² are approximately 9.8–10.5 and 6.5–7.0 J/cm² at 35 and 94 GHz, respectively. The report was initially delivered as an AFRL technical report, and was later submitted to the *Health Physics Journal* for publication.

(b) (6)

(2017, November). *Revisiting 94 GHz Millimeter Wave Exposure to the Non-Human Primate Eye* (AFRL-RH-FS-TR-2018-0009, 1 May 18). JBSA Fort Sam Houston, TX: Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch. Submitted to 711 HPW/RHDR.

(b) (6)

(2019, May). *Revisiting 94 GHz Millimeter Wave Exposure to the Non-Human Primate Eye* (AFRL-RH-FS-JA-2019-119887, P.A. Case No. TSRL-PA-2019-0161, 28 May 19). Unpublished manuscript. Journal article submitted to *Health Physics Journal* for publication. Submitted to 711 HPW/RHDR.

2.13 Swine Skin Analysis

Three studies involving ex vivo samples of pig skin were conducted to determine burn thresholds related to MMW exposures. Two studies involved various power densities and durations incident to the skin sample that was oriented normal to the beam. The third study used a single power density and duration and varied the angle of incidence. IR data of each exposure was collected and stored on the RDT&E server.

2.14 CHIRP

The Cranial High Pressure from RF Pulses (CHIRP) project is an empirical and modeling effort set out to study the effect of pressure waves generated by the absorption of intense RF exposure. On the empirical side of the CHIRP effort, GDIT technicians provided animal care, dosimetry, and transmitter operation support for numerous CHIRP experiments. On the modeling side of the CHIRP effort, the modeling and simulation (M&S) team developed and improved existing tools used to study RF radiation. One such tool is ThermoAcoustic Time-Domain Solver. ThermoAcoustic Time-Domain Solver is a FDTD-based model used to calculate the generated pressure waves from a pulse of RF radiation. The model provides a 3D map of the pressure as a function of time—allowing the user to observe the waves propagating through a digital phantom. The model has been shown to work for a variety of digital phantoms including various types of spheres, a rat, a mouse, a monkey, a pig, and a human. This model was delivered to 711 HPW/RHDR and archived on organizational servers.

The pressure generated by the absorption of intense RF exposure can be correlated to the SAR distribution. The M&S team took advantage of this relationship to explore the optimal RF exposure settings to maximize pressure in the internal ear while minimizing temperature on the skin. The optimal settings have been evaluated by comparing the SAR distributions of the skin and internal ear. To ensure that the internal ear structure is modeled properly, a hybrid digital phantom has been created by GDIT. GDIT has scaled and smoothed the AFRL/RHDR Visible Human phantom to a finer resolution and combined the human phantom with an inner ear structure phantom to create the necessary hybrid phantom. The hybrid phantom and methods developed to create the phantom will also be used in future studies.

2.15 ADT Data Archiving

In order to facilitate sharing of human, MMW exposure data between JNLWD, other research facilities and AFRL, we compiled several spreadsheets and IR data files related to various human studies onto a single hard drive and sent it to the JNLWD for review and distribution. Each of the IR data files had to be truncated to remove any identifying marks from the video, and visually verified to ensure no personally identifiable information was transmitted.

(b) (6) (2018, October). Data collected for Kirtland Small Spot Scaling Study, High Power Density Laboratory Study, and 95 GHz Variable Spot Study requested by JNLWD. Data consisted of 1 Word file (report), 1 Excel file, and several hierarchical data format 5 (HDF5) IR data files. (Data submitted on external hard drive and labeled as Distribution D). Also included a text file, which described HDF5 format. Submitted to 711 HPW/RHDR.

2.16 PPE

The U.S. Army Combat Capabilities Development Command-Soldier Center, Natick has been developing novel materials (personal protection equipment (PPE)) to be used to protect individuals from 95-GHz exposures. As part of a joint effort between the Air Force and Army, the materials were sent to TSRL to be tested with our 1 kW transmitter, which was many orders of magnitude larger than the transmitter from the University of Massachusetts Lowell. This allowed the Army team to test at powers that caused some of the samples to burn. All exposures were captured on IR video and the resultant files were converted to HDF5 format and shipped to Natick for analysis.

2.17 Pig Skin Damage

This is an ongoing study that involves damaging levels of MMW exposures on anesthetized swine in collaboration with U.S. Army Institute of Surgical Research. The exposures on the first 5 animals of the pilot study were completed, but results from histology and spatial frequency domain imaging measurements had not been received yet.

(b) (6)

(2019,

September). *Spatial Frequency Domain Imaging of Millimeter Wave Induced Skin Burns*. Abstract (No. 11211-41) for SPIE Photonics West BiOS held in San Francisco, CA on 1-6 Feb 2020. (Note: Abstract cleared through University of California, Irvine.) Submitted to 711 HPW/RHDR.

2.18 Swine MRI

The Swine Magnetic Resonance Imaging (MRI) program was a joint study between the 711 HPW/RHDR at JBSA Fort Sam Houston, TX and the 59MDW of the USAF School of Aerospace Medicine at JBSA Lackland, TX (59MDW IACUC protocol FWH20180164AR, “Magnetic resonance imaging (MRI) and biomarker model for directed energy exposure medical evaluation in swine (*Sus scrofa domestica*)”). The aim of the study was to use MRI techniques to investigate possible neurological injury in live, anesthetized swine caused by exposure to three different doses of high peak power, 915 MHz RF corresponding to three different CEM43 thermal dose thresholds. GDIT’s M&S team provided computational modeling to determine the CEM43 dose thresholds necessary for the study. GDIT’s scientists and engineers then performed dosimetry and conducted experiments with swine carcasses prior to the initiation of this study on a tissue-exempt protocol (RHDR IACUC protocol RHDR-19-06E) in order to validate the CEM43 modeling results by measuring RF-induced changes in brain temperature of swine carcasses. Using the experimental and modeling results, CEM43 and RF doses were chosen for the live animal study. Experiments with live swine subjects commenced on 18 Sept 19 and, since then, 20 subjects have been tested. GDIT’s scientists, engineers, and veterinarian technician assisted with the experiments involving RF exposure; the study is ongoing.

(b) (6) (2019, August). *Magnetic Resonance Imaging (MRI) and Biomarker Model for Directed Energy Exposure Medical Evaluation in Swine (Sus scrofa domestica)*. Paper presented at Military Health System Research Symposium (MHSRS) 2019, Directed Energy Health Effects (MHSRS-19-00231, Session 1 - #227) held in Kissimmee, FL on 19-22 Aug 2019. (Cleared, MSC2018-0281, P.A. Case No. 88ABW-2019-3817, 15 Aug 19)

(b) (6) (2020, February). *Clinical Evaluation of Neurological Injury Due to Directed Energy Exposure Using Magnetic Resonance Imaging and Biomarkers in Swine (Sus scrofa domestica)*. Poster for Military Health System Research Symposium (MHSRS) 2020. Submitted to 711 HPW/RHDR for PA clearance.

2.19 Moving Spot

The Moving spot protocol involved examining changes in repel thresholds resulting from dynamic beam movement. The initial phases had been completed under the previous contract. Due to problems with generating stable beam motion, the final phases of the experiment were significantly delayed. However, the final phases of this experiment were completed, and all data was delivered to 711 HPW/RHDR. Initial efforts to analyze the data were conducted.

2.20 Dosimetry

Improvements in instrumentation and robotics had matured sufficiently to enable new dosimetry techniques to be developed. The DENSO robot was programmed to automatically scan a region of interest for the peak E-field. Initial efforts were conducted to measure the gain of our standard gain horn, which would allow more accurate measurements of power density at 95 GHz.

(b) (6)

(2020, January). *Dosimetry and Modeling in Support of Bioeffects Studies* (AFRL-RH-FS-AB-2020-120681; P.A. Case No. TSRL-PA-2020-0109, 15 Jan 20). Abstract for Bioelectromagnetics (BioEM) 2020 scheduled to be held in Oxford, UK on 21-26 Jun 20. Submitted to 711 HPW/RHDR.

(b) (6)

(2019, August). *Using Modeling and Simulation as a Basis for Bioeffects Studies*. PowerPoint presentation for the United States Air Force Scientific Advisory Board (SAB) (Distribution D) held on 29 Sep – 1 Oct 2019 at Wright-Patterson Air Force Base. Submitted to 711 HPW/RHDR.

2.21 Surface Reflectivity Study

This effort was funded by the JNLWD to measure the dielectric properties of typical materials that would be present in a MMW exposure environment. Samples were sent to the Air Force Research Laboratory, Directed Energy Directorate (AFRL/RDHP) for vector network analyzer reflectivity measurements and a technical report for reference purposes was provided.

(b) (6)

(2020, February). *The Surface Reflectivity of Common Construction Materials Measured in the W-Band (75-110 GHz)* (AFRL-RH-FS-TR-2020-xxxx). JBSA Fort Sam Houston, TX: Air Force Research Laboratory. Delivered to government for review; not cleared as of 14 Feb 20.