AD

AD-E404 225

Technical Report ARWSE-TR-18051

THERMAL ISOLATION/BARRIERS FOR SMALL CALIBER WEAPON APPLICATIONS

Dr. Adam L. Foltz
Adam Jacob
Dr. Laurie Florio

August 2020

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

Weapons and Software Engineering Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

1. REPORT DATE (DD-MM-YYYY) August 2020	2. REPORT TYPE Final	3. DATES COVERED (*From - To)* October 2016 to October 2017

4. TITLE AND SUBTITLE

Thermal Isolation/Barriers for Small Caliber Weapon Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

Dr. Adam L. Foltz, Adam M. Jacob, and Dr. Laurie A. Florio

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army CCDC AC, WSEC
Weapons Systems and Technology Directorate
(FCDD-ACW-WF)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army CCDC AC, ESIC
Knowledge & Process Management Office (FCDD-ACE-K)
Picatinny Arsenal, NJ 07806-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Technical Report ARWSE-TR-18051

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The research conducted under this effort aimed at analyzing thermal barrier concepts intended to reduce visual signature of small caliber weapon systems (barrels, suppressors, etc.) resulting from high rates of firing. Analysis of heat transfer mechanisms and modeling and simulation of thermal barrier concepts were conducted. Basic principles were explored to identify limitations of application conditions and influencing system design parameters.

15. SUBJECT TERMS

M4A1 Thermal barriers Vacuum insulation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Adam L. Foltz
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR	17	19b. TELEPHONE NUMBER (Include area code) (973) 724-7096

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

CONTENTS

Page

Summary 1

Introduction 1

Modeling and Simulation 2

Study 1 - Constant Heat Flux, Solid Tube versus Air Gap 2
Study 2 - Constant Heat Flux, Emissivity Influence 3
Study 3 - Constant Heat Flux, Air Gap versus Vacuum 3
Study 4 - Conditions for Varied Outer Surface Tube Boundary Conditions 3
Study 5 - Constant Heat Flux, Forced Cooling Fluid Between Barrier/Solid 4
Study 6 - Complex Heat Load to Replicate Live-fire 5

Conclusions 6

Recommendations 6

References 9

Distribution List 11

FIGURES

1 Forward-looking infrared (FLIR) products (ref. 1) 1

2 Insulon® performance (ref. 2) 2

3 Model setup – top: solid tube; bottom: air gap within the tube thickness 2

4 Model setup study no. 5 4

5 Outer barrel surface temperature (study no. 6) 5

6 Test results M4A1 5

7 Test results M4A1 suppressed 6

ACKNOWLEDGMENTS

This work was funded by the the U.S. Army Combat Capabilities Development Command Armaments Center, Picatinny Arsenal, NJ, under the FY17 Systems Concept and Technology effort. The authors would like to acknowledge the following people for providing information and data used in the development of this work: Howard Kent, David Reid, Mike Scott, Louis Schnibbe, Tuhin Chatterjee, Dan Cler, Andy Littlefield, Mikhail Kats, Thomas Miskovich, Anthony Cautero, and Johnathan Parker.

This paper was also published as a book chapter in the Springer book, “Advance Materials for Defense: Development, Analysis and Applications,” edited by R. Fangueiro and S. Rana.

SUMMARY

The research conducted under this effort aimed at analyzing thermal barrier concepts intended to reduce visual signature of small caliber weapon systems (barrels, suppressors, etc.) resulting from high rates of firing. Analysis of heat transfer mechanisms and modeling and simulation of thermal barrier concepts were conducted. Basic principles were explored to identify limitations of application conditions and influencing system design parameters. Modeled results representing live-fire test cases were in good correlation with both standard M4A1 test data and vacuum barrier results. Barrier effectiveness was shown to decrease with higher heating rates as barrel temperatures increase and radiation exchange between barrel and barrier rises.

INTRODUCTION

Aggressive firing rates can result in extremely high temperatures in barrels and suppressors. To date, there has been minimal research in the area of technologies intended to dissipate heat or mitigate build-up during cook-off/aggressive firing scenarios.

Historically, enemies have had an inability to fight at night and have relied on weapon muzzle flash to provide an ad hoc aiming reference during ambushes and traditional fire fight situations. Advancements in thermal imaging technology continue to lower system costs, giving enemies improved detection capabilities at night that can jeopardize mission effectiveness and Soldier survivability. Smart phone applications and unmanned aerial vehicle mounted systems are becoming more prevalent (fig. 1), identifying the critical need for developing thermal barrier concepts for small caliber weapon applications.

Figure 1
Forward-looking infrared (FLIR) products (ref. 1)

The research area for this effort primarily focused on vacuum barrier concepts. That is, barriers that both reflect and diffuse heat, reduce heat transfer across the barrier by absence of atmosphere, and only allow end area conduction.

Particularly of interest was Insulon®, a technology developed by Concept Group (ref. 2). An Insulon® Shaped-Vacuum™ Thermal Barrier uses a vacuum layer to form a virtually impenetrable barrier to the conductive transfer of thermal energy. It has flexibility in size and shape to accommodate unique thermal design challenges. It blocks the conduction of heat or lack thereof, or it works in reverse to protect sensitive equipment, components, fluids, or materials that need to operate at optimal temperatures, even though they are surrounded by extremely high or low exterior temperatures, which is a range from -321 to 2,000 °F. It requires 40x more fiberglass to have similar conduction to a 0.1-mm Insulon® thermal barrier, 20x more expanded polystyrene, and a 25x larger air gap (ref. 2). Applications include batteries and fuel cells, automotive, military and defense, aerospace (component isolation), consumer goods (e-cigarettes), and medical devices (transport, catheters, spectroscopy, cryogenics). Figure 2 shows the Insulon® performance.

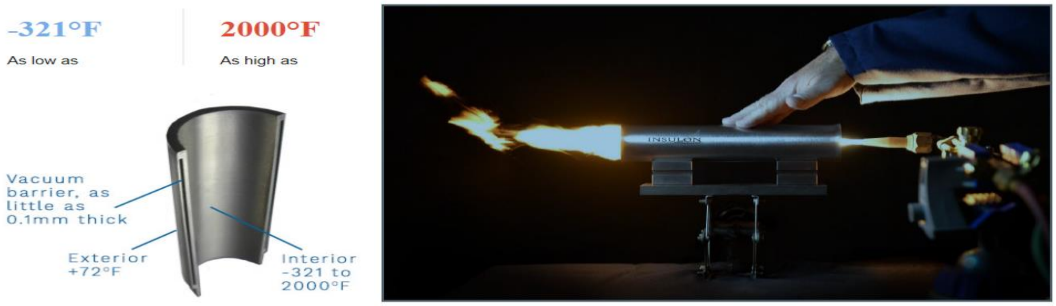

Figure 2
Insulon® performance (ref. 2)

In order to investigate the basic principles behind the thermal barrier concept, the conditions under which it may hold more promise, and the range of possible improvement in the thermal state of a system containing a barrier over a system without the barrier, a number of sets of computational simulations were conducted. All simulations were conducted using ANSYS Fluent computational fluid dynamics (CFD) software.

MODELING AND SIMULATION

In order to investigate the basic principles behind the thermal barrier concept, the conditions under which it may hold more promise, and the range of possible improvement in the thermal state of a system containing a barrier over a system without the barrier, a number of sets of computational simulations were conducted. The simulations vary in complexity starting with a simple heat flux applied to a material with just an air gap and progressing to a multi-shot firing schedule applied to gun tube with a thermal barrier shield. All simulations were conducted using ANSYS Fluent CFD software (ref. 3) and methods and results from previous modeling efforts (refs. 4 and 5). Specific studies are described in the following sections.

Study 1 - Constant Heat Flux, Solid Tube versus Air Gap

The objective of this preliminary study was to compare the thermal conditions that develop when a heat flux is applied to the inner surface of a cylindrical tube in the cases of a solid tube and a tube that contains an air gap of uniform thickness. In this way, the potential effects of a thermal barrier and the basic phenomena at work in the barrier system could be identified.

Figure 3
Model setup – top: solid tube; bottom: air gap within the tube thickness

The results of this study illustrate that while the air gap delays the increase in the temperature at the outer surface of the tube, since the radially directed heat flow is slowed by the more resistive air gap within the barrier, the temperatures at the inside surface of the barrier are generally higher than if no barrier is present. This simple model also illustrates that the main mechanism through which this thermal barrier functions is to restrict the major paths of the flow of heat to the conductive heat flow through the small solid zones at the left and right of the barrier and radiative exchange across the barrier surfaces with minimal conduction through the air gap.

Study 2 - Constant Heat Flux, Emissivity Influence

Next, the emissivity of the inner barrier gap surfaces was varied. The one large barrier from study 1 and a case with multiple smaller barriers was investigated. The results of the study 2 cases continue to indicate that the “thermal barrier” created by the air gap restricts the rate of heat flow in the radial direction, delaying the heating of the outer portions of the tube. The air gap provides greater resistance to heat flow across the thickness of the heated tube compared to a completely solid tube. Further, cases with lower emissivity and a long, uninterrupted gap space produce a better barrier to the heat flow than higher emissivity barrier surfaces and barriers with multiple conductive heat flow paths between multiple gaps. Ultimately, the results demonstrate a less effective thermal barrier with lower reflectivity/higher emissivity values.

Study 3 - Constant Heat Flux, Air Gap versus Vacuum

In the third study, the thermal conditions with a vacuum in the barrier volume filled with air in the previous studies was considered. The same geometric configuration with the solid tube and the tube with a single barrier gap was studied. The emissivity of the barrier surfaces was also varied including the potential for two different emissivities, one on the top surface of the gap and one on the bottom surface of the gap. Also included was a case with no radiation in the gap, taken as an upper limit on the potential barrier performance.

Based on the results of the investigation, a number of important temperature field characteristics can be identified. As air is replaced by a near vacuum, the barrier effectiveness increases, resulting in reduced temperatures in the solid material outside the barrier. However, the drop in exterior temperature comes at the expense of higher temperatures in the interior of the tube. The sensitivity of the thermal conditions to the emissivity with the vacuum barrier follows trends similar to those for the air-filled gap. The differences between the conditions that result with an air and vacuum-filled gap decrease as the surface emissivity increases and the radiation exchange across the gap grows. For the inner side of the barrier, higher surface temperatures are seen for the vacuum barrier case versus the air-filled gap due to the resisting heat flow. For this case, the boundary condition of no radiation represents the upper bound of the barrier performance. For the outer barrier surface, the rate of increase in temperature for the vacuum barrier eventually surpasses the solid tube case due to radiation.

Study 4 - Conditions for Varied Outer Surface Tube Boundary Conditions

The next step in the investigation varied the boundary conditions at the outer surface of the tube to examine how they influence the effectiveness of the barrier. For one set of studies, an insulated boundary condition set was employed at the outer surface of the tube so that no heat was removed from the outside surface. In the other set of studies, a mixed convection and radiation boundary condition was applied where a heat transfer coefficient and an ambient temperature were applied with a common radiative emissivity.

For the insulated outer boundary condition, no heat flow occurs, which results in temperatures that continue to rise, demonstrating negligible barrier benefits with long duration heat loading. With the mixed convective and radiative outer surface boundary condition, a steady temperature distribution was reached within the tube. The time to reach the steady state was longer for the cases with the lower emissivity where the rate of heat transfer is lower.

Overall, for a high-input heat rate and a long-duration input time period with lower levels of heat removal from the outer surface of the barrier, the results showed that the benefits of the barrier are questionable. For lower levels of heat input and short durations, the higher temperatures at the inner vacuum portions may be less problematic. Removal of the trapped energy in the interior portions of the tube may reduce the potential issues for the higher inner tube portion temperatures and might also reduce the heat transfer to the outer portions of the tube.

Study 5 - Constant Heat Flux, Forced Cooling Fluid Between Barrier/Solid

The potential issues related to the hotter inner tube temperatures, which would result from the implementation of the barrier technique, prompted an investigation into the feasibility of supplementing cooling. Forced convection cooling for a system that consists of a solid tube, a barrier shroud, and a concentric forced convection flow path between the solid tube and the barrier was investigated. The objective of this fifth study was to determine the sensitivity of the following design parameters on the thermal conditions that result when air or water flow is used to cool a heated tube with a concentric thermal vacuum barrier. The properties of the working fluid are as follows: air or water, velocity of the cooling fluid, the distance of the inner surface of the concentric thermal vacuum barrier, and the thickness of the vacuum in the thermal vacuum barrier. The thermal loading on the heated tube, the heated tube dimensions, and thickness of the solid material forming the barrier gap were held fixed. The system that is being investigated and some important parameters are depicted in figure 4.

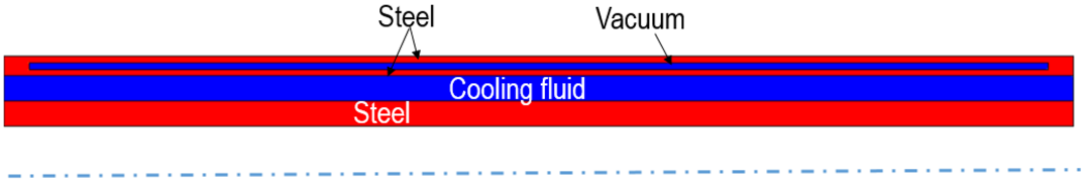

Figure 4
Model setup study no. 5

A total of 63 different configurations were simulated for the same thermal loading at the inner surface of the tube and the same tube geometry. For the air, three different air cooling velocities were studied at 20, 40, and 60 m/s. For the water, velocities that produce the equivalent mass flow rate as the air were applied at 0.0234, 0.0469, and 0.0703 m/s. For each of these velocities and fluids, three different spacing between the outer heated tube surface and the inner surface of the barrier were investigated at 3, 6, and 9 mm. Then, for each fluid, velocity, and tube-barrier spacing cases, three vacuum gap spaces in the thermal vacuum barrier of 0.508, 1.016, and 2.032 mm were applied to the system. Additionally, a case with a heated tube that had no barrier and cases for each geometric configuration with ambient zero velocity air was simulated to form a baseline for comparison.

With water as the cooling fluid, the conditions found differ significantly due to the greater heat capacity of the water and the different radiative properties (fig. 5). The temperatures at the outer surface tend to decrease with higher flow velocities, but the decrease appears to diminish with increases in the water velocity. The temperatures eventually cease increasing, indicating the heat input to the tube is being removed by the water flow. The temperatures reached at the outer surface of the tube are significantly lower compared to the air-cooled cases.

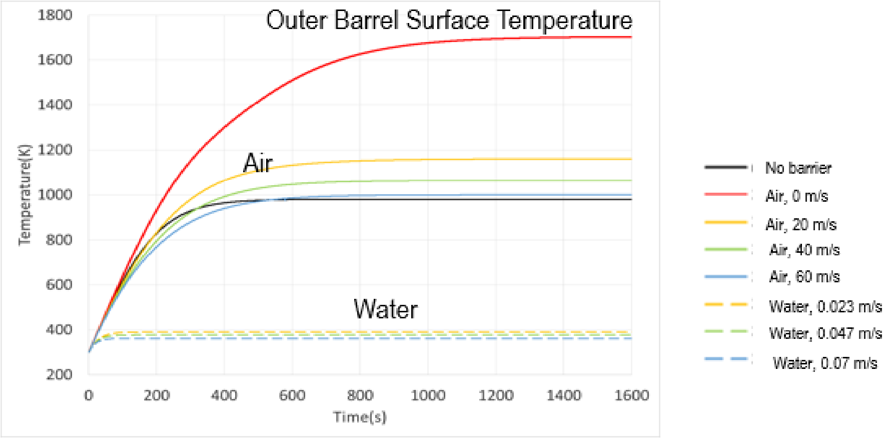

Figure 5
Outer barrel surface temperature (study no. 6)

In each case with either air or water, increasing the spacing of the cooling fluid flow path results in a slight increase in the temperature at later times. Perhaps the higher initial or net heat flow rate into the fluid results in a slight decrease in the heat outflow as the fluid is warmed and therefore results in the higher temperatures at the outer tube surface.

Study 6 - Complex Heat Load to Replicate Live-fire

In the last investigation set, a heat load more representative of live-fire conditions for a weapon system was applied. A 210-round firing sequence at 120 rounds per minute was applied to the M4 system. The barrel and barrier temperatures (average surface temperatures) are traced over time during the time period when firing is taking place as well as after firing has stopped and the gun system is cooling. The simulations were run until the exterior or outer barrier surface reaches near its maximum temperature. Live-fire testing was conducted using a baseline weapon configuration and a suppressed weapon configuration, both with and without a vacuum barrier to compare with the modeled results. Peak temperature results are shown in figures 6 and 7.

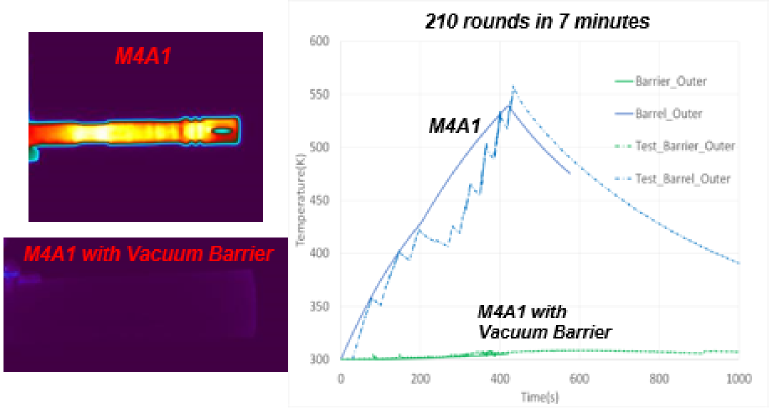

Figure 6
Test results M4A1

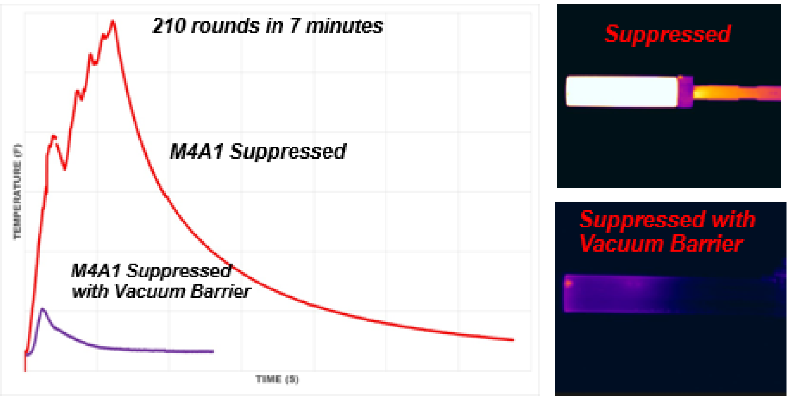

Figure 7
Test results M4A1 suppressed

CONCLUSIONS

Simulations varied in complexity starting with a simple heat flux applied to a material with just an air gap and progressed to a multi-shot firing schedule applied to gun tube with a thermal barrier shield. Studies included: (1) solid tube versus air gap, (2) emissivity influences, (3) Air gap versus vacuum barrier, (4) varied boundary conditions, (5) addition of forced air/water, and (6) complex heat loading to replicate live-fire testing. The complex heat load models were set up to directly compare results with live-fire test data. An approximate location to the measurement position was selected for data comparison. A good correlation between the standard barrel test data and the model results for a mixed convection boundary condition case can be observed. Also, the good correspondence between the barrier covered barrel results and the model results for the stagnant air case can be observed. The modeling results presented here provide a reasonable estimation of the thermal conditions that develop with the barrier and with the baseline standard barrel system.

The results of this effort generated a greater understanding of thermal loading and heat mitigation in gun barrels and suppressors and has the potential to drive science and technology-based material solutions for gun barrel/suppressor thermal management and increased maintainability.

RECOMMENDATIONS

Although significant thermal signature was achieved for the firing scenarios tested, a more aggressive firing cadence with high heating loads could result in a less effective thermal barrier and may have other negative system performance impacts (i.e., barrel wear, decreased accuracy, increased dispersion) due to the increased temperatures on the inside of the vacuum barrier. Additional testing and analysis would be necessary to determine recommended operating applications and limitations.

Further modeling should be conducted on varying heating loads/firing conditions to help define potential optimal operating ranges. Outer surface temperatures should be analyzed to determine thermal signature performance, and bore surface temperatures should be monitored. The effects of geometric parameters, placement, and overall barrier configuration should be studied to determine effects on performance. Moreover, the strength and harmonics associated with the barrier configuration and gap spacing should be explored. Surface conditions and materials for the outer barrel surface and the inner bore surface should be studied, including those required for support connections along the tube length.

Although modeled, a basic air gap barrier was not tested. Testing should be conducted to compare an air gap barrier of similar geometry versus the vacuum barrier prototype to further characterize the significance of the vacuum barrier concept.

Finally, additional means for removing heat, particularly from the inside volume of the barrier, should be investigated further. The energy input must still be removed though it may be distributed differently, either through additional conductive pathways, possible phase change materials, or convective cooling enhancements.

REFERENCES

1. FLIR Systems, Retrieved from ttp://www.flir.com/home/.

2. Insulon Technology, Retrieved from https://conceptgroupinc.com/applications/.

3. ANSYS Fluent, V16, 2015.

4. Florio, L. A., “Modeling Heat Transfer due to the Firing of One Round in an M4,” Technical Report ARWSE-TR-08005, U.S. Army ARDEC, Picatinny Arsenal, NJ, December 2008.

5. Florio, L. A., “Thermal Conditions in M4 Barrel Resulting from Repeated Firing,” Technical Report ARWSE-TR-09012, U.S. Army ARDEC, Picatinny Arsenal, NJ, June 2010.

DISTRIBUTION LIST

U.S. Army CCDC AC
ATTN: FCDD-ACE-K
FCDD-ACW-WF, A. Foltz
L. Florio
FCDD-ACE-J, A. Jacob
Picatinny Arsenal, NJ 07806-5000

Defense Technical Information Center (DTIC)
ATTN: Accessions Division
8725 John J. Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

REVIEW AND APPROVAL OF ARDEC REPORTS

THIS IS A:

☑ **TECHNICAL REPORT** ☐ **SPECIAL REPORT**

☐ **MEMORANDUM REPORT** ☐ **ARMAMENT GRADUATE SCHOOL REPORT**

FUNDING SOURCE ARDEC SC&T

[e.g., TEX3; 6.1 (ILIR, FTAS); 6.2; 6.3; PM funded EMD; PM funded Production/ESIP; Other (please identify)]

Thermal Isolation/Barriers for Small Caliber Weapon Applications

Title

Project

Adam L. Foltz

Author/Project Engineer

ARWSE-TR-18051

Report number/Date received (to be completed by LCSD)

x7096

Extension

B2

Building

RDAR-WSW-F

Author's Office Symbol

PART 1. **Must be signed before the report can be edited.**

a. The draft copy of this report has been reviewed for technical accuracy and is approved for editing.

b. Use Distribution Statement A ☑, B ☐, C ☐, D ☐, E ☐, or F ☐ for the reason checked on the continuation of this form. Reason: ______

1. If Statement A is selected, the report will be released to the National Technical Information Service (NTIS) for sale to the general public. Only unclassified reports whose distribution is not limited or controlled in any way are released to NTIS.

2. If Statement B, C, D, E, or F is selected, the report will be released to the Defense Technical Information Center (DTIC) which will limit distribution according to the conditions indicated in the statement.

c. The distribution list for this report has been reviewed for accuracy and completeness.

Kobi O'Malley 30 July 2018

Division Chief (Date)

PART 2. To be signed either when draft report is submitted or after review of reproduction copy.

This report is approved for publication.

Kobi O'Malley

Division Chief (Date)

RDAR-CIS (Date)

LCSD 49 (1 Sept 16)
Supersedes SMCAR Form 49, 20 Dec 06