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# SWATCH TEST RESULTS OF COMMERCIAL CHEMICAL PROTECTIVE BOOTS TO CHALLENGE BY CHEMICAL WARFARE AGENTS: SUMMARY REPORT

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RESEARCH AND TECHNOLOGY DIRECTORATE

February 2001

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Swatches from nine commercially available chemical protective boots were challenged with liquid droplets of Sarin (GB) and mustard (HD) using modifications of the static diffusion described in TOP 8-2-501. The cumulative mass of each agent that permeated each swatch was determined over time and the results for all swatches were used to determine an average cumulative mass for each boot. From these data, a breakthrough time was calculated for each boot/agent combination for purposes of comparisons.

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## EXECUTIVE SUMMARY

As part of the Domestic Preparedness Program, nine commercially available boot designs were tested to assess their capability to protect in a chemical warfare (CW) agent environment. Swatches of material from each boot design were tested for resistance to permeation for Sarin (GB) and mustard (HD). From this data, the author calculated the estimated time it would take to permeate the boot with sufficient agent to cause physiological effects in a person wearing the boot. The tests are described and the calculated breakthrough times are presented.

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## PREFACE

The work described in this report was authorized under the Expert Assistance (Equipment Test) Program for the U.S. Army Soldier and Biological Chemical Command (SBCCOM) Program Director for Domestic Preparedness.

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The author also acknowledges the technical contributions of the Expert Review Panel for Personal Protective Equipment (PPE) Testing as listed below:

Dr. Jimmy Perkins, University of Texas School of Public Health, San Antonio, TX.
Dr. Annetta Watson, Life Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN.
Dr. Ted Zellers, University of Michigan School of Public Health, Ann Arbor, MI.
Leo F. Saubier, Battelle Memorial Institute, Edgewood, MD.

The panel reviewed and commented on the test procedures, instrumentation, data analysis and presentation. Their guidance was a valuable element in the development of clear and adequate descriptions of the concepts and procedures used in these tests.

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# TEST RESULTS OF COMMERCIAL CHEMICAL PROTECTIVE BOOTS TO CHALLENGE BY CHEMICAL WARFARE AGENTS: SUMMARY REPORT

## 1. INTRODUCTION

In 1996, Congress passed Public Law 104-201 (Defense Against Weapons of Mass Destruction Act of 1996), directing the Department of Defense (DoD) to assist other federal, state, and local agencies in enhancing preparedness for terrorist attacks using weapons of mass destruction. The DoD responded by forming the Domestic Preparedness Program that same year. One of the objectives of the Domestic Preparedness Program is to enhance federal, state and local emergency and hazardous material (HAZMAT) response to nuclear, biological and chemical (NBC) terrorism incidents. As part of an effective response, emergency and HAZMAT personnel who are responding to an incident will use personal protective equipment (PPE) to protect them from exposure to chemical agents or biological agents. The specific PPE that would be used by these federal, state and local emergency and HAZMAT personnel would depend upon the situation encountered and what PPE is held in inventory. In some cases, chemical protective boots may be required to enter a contaminated or potentially contaminated area.

## 2. OBJECTIVES

This study evaluates some commercially available and commonly used chemical protective boots to assess how well they resist vapor permeation from liquid contamination by chemical agents Sarin (GB) and mustard (HD). This information is intended for federal, state and local emergency and HAZMAT personnel as an aid in their evaluation (and possible modification) of current work rules regarding specific chemical protective boots currently in inventory and as an aid in future procurement of appropriate chemical protective boots. This is especially important if these personnel choose to include military chemical agent protection as a

criterion. The information supplements data and information provided by the boot manufacturers. The boots are tested in new, as-received condition. The effects of aging, temperature extremes, laundering, and other factors are beyond the intended scope of this test program. These tests are conducted to assess percutaneous (i.e. skin) protection only.

## 3. TESTING AND DATA ANALYSIS

### 3.1 Testing Overview.

The chemical protective boots that are tested in this test program are listed in Appendix A. Testing consisted of a permeation test of material swatches to measure the permeation of both GB and HD through the swatches.

### 3.2 Liquid Challenge/Vapor Permeation Testing (Agent Swatch Testing)

#### 3.2.1 Liquid Challenge/Vapor Permeation Testing Procedures.

This testing is conducted to measure the vapor permeation of chemical agents GB and HD through boot swatches over a 24-hr period. The test is intended to assess how well the boot materials resist vapor permeation. The amount of agent applied and duration of exposure do not represent any particular threat that responders may encounter, but they do serve as a common point of reference for all test results.

The test methodology was taken from TOP 8-2-501[1] and is described in Appendix B. Twelve swatches were cut from two pairs of each boot design to be tested. Due to limited availability of certain boot designs, the management decision was made to cut swatches from two pairs, rather than the six pairs originally called for, to meet the program schedule. All

[1] Test Operations Procedure (TOP) 8-2-501, Permeation and Penetration of Air-Permeable, Semipermeable and Impermeable Materials with Chemical Agents or Simulants (Swatch Testing). U.S. Army Dugway Proving Ground, UT. 3 March 1997, UNCLASSIFIED Report (AD A322329).

swatches were taken approximately midway up the side of the boot. Six of the swatches were allocated to GB testing and the remainder were allocated to HD testing. Swatches are taken from silicone (M45 military mask formulation) slabs for use as a source of HD or GB vapor after contamination.

Laboratory personnel apply a predetermined liquid agent challenge of 10 $g/m^2$ to the top surface of each swatch.

The permeation test apparatus contains seven test cells. For each test, swatches from one boot design were placed in six of the cells (normal swatch sequence is boot 1, boot 2, boot 1, boot 2, boot 1 and boot 2) and a silicone swatch was placed in the seventh cell. In the analysis, each swatch was assumed to represent the area covered by the boot; the foot and the lower leg.

Agent droplets are applied to the surface of the first swatch at time zero. Agent is then applied to the surface of each succeeding swatch at 3-min intervals. The upper chamber of each test cell is sealed. A 1.0 L/min flow of air, from the test cabinet, is maintained in the lower test cell chamber beneath each swatch.

During the 24-hr test period, gas samples are taken on a sequential basis by a laboratory MINICAMS™ with stream selection system (a miniaturized gas chromatograph with flame photometric detector and sampling system (from OI Analytical, CMS Field Products Group, Birmingham, AL)). Gas sampling by the MINICAMS™ begins for the first swatch approximately 3 min following agent application. Subsequent 3-min cycles of the MINICAMS™ are composed of 2 min of desorption of collected agent vapor from the pre-concentrator tube (PCT) onto the column followed by 1 min of gas sampling (collection of agent

vapor in the PCT). Sampling is sequential through six boot material swatches, the silicone swatch,[2] and three blank gas samples (taken from the test cabinet to purge the sampling line before repeating the sampling sequence). The six boot material swatches, the silicone swatch, and three blanks are all sampled for the first time within the first 30 min of the test. Then the sampling sequence begins anew.

The MINICAMS™ first determines the amount of agent vapor in each gas sample. Using this result, the amount (ng) of agent vapor present in the airstream that passes beneath the swatch over the time from the previous gas sample to the current gas sample is determined by the MINICAMS™ permeation software. The calculations assume that the permeation change with time is a straight line over the 30 min interval. The permeation for each time interval is the average of the permeation rates (flux, ng/cm$^2$/min) for the current and previous gas samples multiplied by 30 min. This amount of agent vapor is presumed to be the amount that has permeated the swatch over that time interval. The cumulative mass of agent permeating the swatch per unit area at any elapsed time during the 24-hr test is defined as $M_f$. It is based on the mass permeated in the time interval over the effective swatch area, which is the opening in the permeation cell (10 cm$^2$), and is determined by the MINICAMS™ permeation software. Over the 24-hr test period, a series of $M_f$ values is calculated for each swatch.

3.2.2 Liquid Challenge/Vapor Permeation Testing Analysis.

Each boot design has $M_f$ data for six swatches for each of the two agents over the

[2]Originally, it was intended to use silicone swatches as references or controls, but it was soon found that permeation through the silicone varies too widely for it to be used for that purpose. Silicone swatches were used anyway, because they serve as a reliable source of agent vapor to assure the tester that the MINICAMS® is responding properly during tests when little or no agent permeates the actual test swatches.

24-hr test period. For this report, the average (of six swatches) cumulative permeation ($M_f$) is calculated for each agent. This average is then presented, at each of the reported elapsed times, as representative of the boot's permeation resistance. The reported elapsed time for each boot design is the sum of the elapsed times for the six swatches divided by six.

To estimate $M_f$ at each elapsed time over an entire boot, the simplifying assumption is made that the exposure is uniform over the entire boot. In the analysis, each swatch was assumed to represent the area covered by the boot; the foot and lower leg. Swatches were taken from approximately the same locations for all boots; roughly midway up the side of the boot. Laboratory personnel visually estimate a location midway up each boot and cut a strip of material, with scissors, from each boot of sufficiently large surface area from which three swatches are then cut.

### 3.2.3 Relationship Between Liquid Challenge/Vapor Permeation Test Results and Skin Exposure.

The permeation test is designed to distinguish among these material swatches according to their vapor permeation resistance to chemical agents. It is not intended to specifically replicate threat scenarios that may be encountered in actual use. As previously reported by Belmonte[3], it is instructive to estimate the agent dosage ($C_i t_{skin}$) that would result from such a standard agent challenge as a relative indication of possible physiological effects. This is done by converting the average $M_f$s to equivalent agent dosages. This relationship was developed by Fedele (written communication, Dr. P. Fedele, R&T Directorate, ERDEC, July 1997) and was reported by

[3] Test Results of Level A Suits to Challenge by Chemical and Biological Warfare Agents and Simulants: Summary Report. U. S. Army Edgewood Research Development and Engineering Center, MD. August 1998, UNCLASSIFIED Report (AD A353013).

Belmonte[3]. For boot materials impermeable to airflow, the only mechanism for removal of agent vapor that permeates the barrier is its permeation through the skin, so the equation is:

$$\text{Agent Dosage (mg - min/m}^3\text{)} = \frac{M_f\ (\text{ng/cm}^2)}{\text{Permeability of skin to agent vapor (cm/min)}} \qquad \textit{Equation 1}$$

where skin permeability is 2 cm/min for HD and 0.1 cm/min for GB. The agent dosage can then be compared to doses that are known to cause certain levels of toxicity. It is assumed that skin permeability to HD and GB are roughly uniform over the entire body.

3.2.4 Evaluation Criteria for Liquid Challenge/Vapor Permeation Test Results.

When analyzing the test results, it is useful to determine whether the data indicate that the chemical protective boot provides percutaneous protection over some period of time. Mustard vapor can produce erythema (reddening of the skin) at localized dosages of approximately 2357 mg-min/m$^3$ on the tops of the feet. It can produce vesication (skin burns and blisters) at 4714 mg-min/m$^3$ on the tops of the feet. It was assumed that the feet were protected by the test boots and challenged uniformly by the liquid dose used on the swatches. The action of mustard is assumed to be local. Using the threshold skin reddening dosage, and the skin permeability for mustard and substituting values in Equation 1, we obtain the HD threshold value for $M_f$.

$$\text{Threshold } M_f = 2 \text{ X } 2357 = 4714 \text{ ng/cm}^2 \qquad \textit{Equation 2}$$

Sarin vapor can produce incapacitation at percutaneous dosages of approximately 8000 mg-min/m$^3$ and can cause lethality at dosages of 15,000 mg-min/m$^3$ where exposed persons are healthy, young, fit and well-nourished males of approximately 70-kg mass. People who are smaller, less fit, etc. may exhibit adverse effects at lower dosages ($C_I t_{skin}$). Unlike mustard, Sarin

acts systemically: the body reacts to the total amount of Sarin absorbed by the body. It was assumed that the boots are incorporated into a full ensemble protecting the entire body, but that only the boots are challenged by the liquid agent. The amount of Sarin agent per unit area (average $M_f$) necessary to permeate boot material covering the feet and lower legs and produce a predetermined systemic effect was estimated by using the whole-body dosage threshold of incapacitation (8000 mg-min/$m^3$), the skin permeability to Sarin vapor (0.1 cm/sec) from Equation 1, and 19.23% as the fractional area (proportion of the total body area represented by the hands and forearms in the BRHA model[4]). The relationship is:

$$\text{Threshold } M_f = (\text{Threshold dose} \times \text{skin permeability})/(\text{fractional area}) \qquad \textbf{Equation 3}$$

Substituting,

$$\text{Threshold Mf} = (8000 \times 0.1)/(0.1923) = 4159 \text{ ng/cm}^2 \qquad \textbf{Equation 4}$$

The breakthrough time is the time at which the average $M_f$ reaches the GB threshold $M_f$.

**Table 1. Agent Breakthrough Criteria**

| Agent | Threshold Dosage (mg-min/$m^3$) | Physiological Effect | Skin Permeability ($P_s$), (cm/min) | Threshold $M_f$, (ng/$cm^2$) |
|---|---|---|---|---|
| HD | 2357 | Erythema | 2 | 4714 |
| HD | 4,714 | Vesication | 2 | 9428 |
| GB | 8,000 | Incapacitation | 0.1 | 4159 |
| GB | 15,000 | Lethality | 0.1 | 7798 |

Breakthrough time should not be interpreted as the time that a boot can be safely worn, either for HD or GB. Breakthrough times should only be used to compare boot materials.

[4] Fedele, Dr. Paul D., Nelson, Douglas, C., *A Method of Assessing Full Individual Protective System Performance Against Cutaneous Effects of Aerosol and Vapor Exposures*, U.S. Army Edgewood Research, Development and Engineering Center, Aberdeen Proving Ground, Maryland, October, 1995; Section 1-3 "Body Region Hazard Analysis Process" included in the report for the JSLIST Program: Cronin, Tracy D., *Final Report for the Development of the Man-In-Simulant Test (MIST) Methodology for Evaluation of Chemical/Biological (CB) Protective Garments*, TECOM Project No. 8-EI-825-ABO-004, U.S. Army Dugway Proving Ground, Dugway, Utah, April 1996.

## ACRONYMS and ABBREVIATIONS

| | |
|---|---|
| Ct | Vapor exposure, product of vapor concentration ($mg/m^3$) and time (minutes) |
| $C_1t_{skin}$ | Vapor exposure to skin |
| $cm^2$ | Square centimeters |
| °F | Temperature in degrees Fahrenheit |
| delta p | Differential pressure |
| DoD | Department of Defense |
| ECBC | U.S. Army Edgewood Chemical Biological Center |
| ERDEC | U.S. Army Edgewood Research, Development and Engineering Center |
| g | Gram |
| GB | Sarin, Isopropylmethylphosphonofluoridate |
| HD | Sulfur Mustard; 2,2'-Dichlorodiethylsulfide |
| L | Liter |
| $M_f$ | Cumulative mass permeation through the material |
| $m^2$ | Square meters |
| $m^3$ | Cubic meters |
| mg | Milligram |
| µL | Microliter |
| ng | Nanogram |
| NBC | Nuclear, Biological and Chemical |
| PCT | Pre-concentrator tube |
| PPE | Personal Protective Equipment |
| $P_s$ | Skin permeability |
| RH | Relative Humidity |
| TOP | Test Operations Procedure |

## Appendix A -
## Boots Chosen for Testing

**Table A- 1: Boots Tested**

| Model | Manufacturer | Address |
|---|---|---|
| Dunlop Hevea Nailstep | Dunlop Hevea LTD | Liverpool, UK |
| Tingley Hazproof 82330 | Tingley Rubber Corp. | Plainfield, NJ |
| LaCrosse Commander 89612 | LaCrosse Footwear Inc. | LaCrosse, WI |
| LaCrosse Monarch 87568 | LaCrosse Footwear Inc. | LaCrosse, WI |
| Bata Polymax 84076 | Bata Shoe Inc. | Belcamp, MD |
| Bata Hazmax 87012 | Bata Shoe Inc. | Belcamp, MD |
| Bata Overbooties 97591 | Bata Shoe Inc. | Belcamp, MD |
| Servus Hazmat HZT 75107 | Norcross Safety Products | Rock Island, IL |
| LaCrosse Chemtrex 24228 | LaCrosse Footwear Inc. | LaCrosse, WI |

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## Appendix B -
## Modified Static Diffusion Test Procedure

**MODIFIED STATIC DIFFUSION TEST**

This test procedure was adapted from Test Operations Procedure (TOP) 8-2-501, Permeation and Penetration of Air-Permeable, Semipermeable and Impermeable Materials with Chemical Agents or Simulants (Swatch Testing). U.S. Army Dugway Proving Ground, UT. 3 March 1997, UNCLASSIFIED Report (AD A322329).

The following procedure will be used:

1.Upon receipt of the boots, all available information concerning the boots will be recorded; date of manufacture, lot number, serial number, materials of construction, etc.

2. From each pair of boots, one each 1 and 15/16 in diameter material swatch will be taken for HD and one like-sized material swatch will be taken for GB. If seams are present and they are flat, one each 1 and 15/16 in diameter seam swatch will be taken for HD and one like-sized seam swatch will be taken from each pair of boots for GB. If soles are flat, one each 1 and 15/16 in diameter sole swatch will be taken for HD and one each like-sized sole swatch will be taken for GB from each pair of boots. Swatches will be taken from at least 6 pairs of boots (a minimum of 6 HD swatches and 6 GB swatches will be tested) for each boot model/style. Thickness measurements will be taken and recorded for each swatch. Each swatch will be placed in an airtight bag and given a unique serial number, which will be placed on the bag. A list of serial numbers will be kept with the swatches.

3. The environmental chamber will be controlled at a temperature of 90 +/- 2 °F (32 +/- 2 °C) and the maximum achievable relative humidity without occurrence of condensation (60% +/- 10% RH). The temperature and RH readings will be checked weekly with a calibrated meter. The test cell air will be drawn from the chamber air. TOP 8-2-501 specifies that a system control and data acquisition system will be used but this system will not be used due to budget constraints. The temperature and RH will be recorded in a computer file. Flow rates will be manually recorded. TOP 8-2-501 specifies that differential pressure monitoring will be done but differential pressure gages will not be used due to budget constraints.

4. The TOP test cell will be used. When assembling, the cell lugs will be tightened by hand to finger tight. The flow rate beneath each swatch will be 1 L/min, which will be controlled by a linear mass flow controller. The flows will be checked with a calibrated test meter weekly. Each test cell will be checked for leaks after assembly by connecting it to the vacuum source and checking that the inlet flow is the same as the outlet flow on the mass flow controller (cell lugs will be retightened if flows don’t match).

5. The swatches will be preconditioned overnight in the environmental chamber. Eighty-mil silicone will be used as an indicator swatch to verify that the MINICAMS can detect agent vapor permeation (one silicone swatch per 6 boot swatches). TOP 8-2-501 specifies that positive control and negative control swatches will be used but they will not be used due to budgetary and schedule limitations.

Appendix B

APPENDIX B

6. Agents GB and HD will be used. The contamination density will be 10 g/m$^2$ (eight 1 µL HD droplets or ten 1 µL GB droplets). The agent will be applied using the click/touch method with a Hamilton repeating dispenser. TOP 8-2-501 specifies that a robotic agent application system will be used for agent application but this will not be done due to budget constraints.

7. Seven swatches will be tested at once. MINICAMS with stream selection system will monitor vapor penetration with a 3-minute cycle per swatch. There will be 3 blank sampling intervals following the indicator swatch. Each swatch will be sampled once every 30 minutes. The MINICAMS will be standardized weekly.

8. The test length will be 24 hours.

9. The test cells and o-rings will be aerated between uses. No other cleaning method will be used.

10. The data to be reported are cumulative permeation (ng/cm$^2$) versus elapsed time from contamination (minutes) for each swatch. All recorded data will be placed in laboratory notebooks and a technical report will be drafted at the conclusion of this effort.

APPENDIX B

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APPENDIX B

**Appendix C -**
**Digital Photographs of Boots Tested**

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APPENDIX C

**Figure C- 1: Dunlop Hevea Nailstep Boot**

**Figure C- 2: Tingley Hazproof Boot**


**Figure C- 3: LaCrosse Commander Boot**

**Figure C- 4: LaCrosse Monarch Boot**

**Figure C- 5: Bata Polymax Boot**

**Figure C- 6: Bata Hazmax Boot**

APPENDIX C

**Figure C- 7: Bata Overbootie**

**Figure C- 8: Servus Hazmat Boot**

**Figure C- 9: LaCrosse Chemtrex Boot**

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**Appendix D -**
**Permeation Results Tables**

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APPENDIX D

**Table D- 1. Average HD Permeation**

| $M_t$, Average HD Cumulative Permeation (ng/cm$^2$) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg Time (min) | Dunlop Hevea Nailstep | Avg Time (min) | Tingley Hazproof | Avg Time (min) | LaCrosse Commander Nitrile/PVC | Avg Time (min) | LaCrosse Monarch PVC | Avg Time (min) | Bata PolyMax | Avg Time (min) | Bata HazMax | Avg Time (min) | Bata Over-booties | Avg Time (min) | Servus HazMat | Avg Time (min) | LaCrosse Chemtrex Neoprene |
| 5 | 3 | 10 | 4 | 8 | 1 | 8 | 2 | 12 | 2 | 8 | 5 | 9 | 3 | 7 | 13 | 10 | 6 |
| 35 | 46 | 40 | 25 | 38 | 14 | 38 | 24 | 42 | 9 | 38 | 43 | 39 | 21 | 37 | 180 | 40 | 36 |
| 65 | 84 | 70 | 44 | 68 | 58 | 68 | 56 | 72 | 16 | 68 | 75 | 69 | 542 | 67 | 500 | 70 | 57 |
| 95 | 117 | 100 | 63 | 98 | 131 | 98 | 97 | 102 | 23 | 98 | 104 | 99 | 1424 | 97 | 885 | 100 | 77 |
| 125 | 148 | 130 | 81 | 128 | 221 | 128 | 143 | 132 | 30 | 128 | 133 | 129 | 2050 | 127 | 1267 | 130 | 117 |
| 155 | 176 | 160 | 98 | 158 | 316 | 158 | 193 | 162 | 39 | 158 | 160 | 159 | 2489 | 157 | 1636 | 160 | 319 |
| 185 | 205 | 190 | 113 | 188 | 411 | 188 | 246 | 192 | 50 | 188 | 188 | 189 | 3169 | 187 | 1990 | 190 | 920 |
| 215 | 234 | 220 | 129 | 218 | 503 | 218 | 300 | 222 | 61 | 218 | 215 | 219 | 4017 | 217 | 2326 | 220 | 2040 |
| 245 | 267 | 250 | 144 | 248 | 598 | 248 | 355 | 252 | 73 | 248 | 242 | 249 | 4628 | 247 | 2643 | 250 | 3601 |
| 275 | 312 | 280 | 158 | 278 | 691 | 278 | 411 | 282 | 91 | 278 | 269 | 279 | 5231 | 277 | 2947 | 280 | 5451 |
| 305 | 378 | 310 | 172 | 308 | 776 | 308 | 469 | 312 | 122 | 308 | 296 | 309 | 5706 | 307 | 3243 | 310 | 7474 |
| 335 | 473 | 340 | 185 | 338 | 853 | 338 | 526 | 342 | 175 | 338 | 324 | 339 | 6120 | 337 | 3533 | 340 | 9616 |
| 365 | 608 | 370 | 198 | 368 | 925 | 368 | 583 | 372 | 257 | 368 | 351 | 369 | 6755 | 367 | 3828 | 370 | 11831 |
| 395 | 791 | 400 | 211 | 398 | 992 | 398 | 641 | 402 | 374 | 398 | 379 | 399 | 7300 | 397 | 4143 | 400 | 14078 |
| 425 | 1031 | 430 | 223 | 428 | 1055 | 428 | 700 | 432 | 534 | 428 | 407 | 429 | 7855 | 427 | 4495 | 430 | 16331 |
| 455 | 1327 | 460 | 235 | 458 | 1115 | 458 | 760 | 462 | 736 | 458 | 434 | 459 | 8493 | 457 | 4898 | 460 | 18587 |
| 485 | 1682 | 490 | 247 | 488 | 1172 | 488 | 823 | 492 | 980 | 488 | 462 | 489 | 9047 | 487 | 5363 | 490 | 20850 |
| 515 | 2098 | 520 | 259 | 518 | 1230 | 518 | 892 | 522 | 1264 | 518 | 490 | 519 | 9609 | 517 | 5897 | 520 | 23109 |
| 545 | 2569 | 550 | 270 | 548 | 1288 | 548 | 967 | 552 | 1580 | 548 | 520 | 549 | 10169 | 547 | 6509 | 550 | 25360 |
| 575 | 3096 | 580 | 282 | 578 | 1347 | 578 | 1053 | 582 | 1903 | 578 | 551 | 579 | 10761 | 577 | 7203 | 580 | 27570 |
| 605 | 3675 | 610 | 294 | 608 | 1406 | 608 | 1149 | 612 | 2258 | 608 | 583 | 609 | 11424 | 607 | 7983 | 610 | 29785 |
| 635 | 4299 | 640 | 305 | 638 | 1466 | 638 | 1258 | 642 | 2667 | 638 | 620 | 639 | 12274 | 637 | 8844 | 640 | 32048 |
| 665 | 4959 | 670 | 316 | 668 | 1529 | 668 | 1381 | 672 | 3103 | 668 | 660 | 669 | 13236 | 667 | 9778 | 670 | 34310 |
| 695 | 5656 | 700 | 328 | 698 | 1596 | 698 | 1524 | 702 | 3561 | 698 | 705 | 699 | 14110 | 697 | 10784 | 700 | 36532 |
| 725 | 6335 | 730 | 339 | 728 | 1669 | 728 | 1688 | 732 | 4010 | 728 | 756 | 729 | 14791 | 727 | 11856 | 730 | 38751 |
| 755 | 6971 | 760 | 351 | 758 | 1745 | 758 | 1877 | 762 | 4441 | 758 | 814 | 759 | 15517 | 757 | 12993 | 760 | 40972 |
| 785 | 7624 | 790 | 363 | 788 | 1828 | 788 | 2094 | 792 | 4803 | 788 | 880 | 789 | 16426 | 787 | 14194 | 790 | 43193 |
| 815 | 8436 | 820 | 376 | 818 | 1920 | 818 | 2340 | 822 | 5173 | 818 | 954 | 819 | 17216 | 817 | 15457 | 820 | 45345 |
| 845 | 9390 | 850 | 388 | 848 | 2020 | 848 | 2618 | 852 | 5624 | 848 | 1038 | 849 | 17975 | 847 | 16774 | 850 | 47495 |
| 875 | 10271 | 880 | 401 | 878 | 2130 | 878 | 2935 | 882 | 6088 | 878 | 1132 | 879 | 18895 | 877 | 18133 | 880 | 49740 |
| 905 | 11053 | 910 | 414 | 908 | 2252 | 908 | 3299 | 912 | 6529 | 908 | 1236 | 909 | 19835 | 907 | 19527 | 910 | 51950 |
| 935 | 11912 | 940 | 429 | 938 | 2386 | 938 | 3717 | 942 | 6928 | 938 | 1355 | 939 | 20651 | 937 | 20956 | 940 | 54101 |
| 965 | 12915 | 970 | 444 | 968 | 2544 | 968 | 4194 | 972 | 7366 | 968 | 1488 | 969 | 21469 | 967 | 22418 | 970 | 56291 |
| 995 | 13939 | 1000 | 460 | 998 | 2730 | 998 | 4725 | 1002 | 7904 | 998 | 1630 | 999 | 22334 | 997 | 23909 | 1000 | 58514 |
| 1025 | 14879 | 1030 | 478 | 1028 | 2947 | 1028 | 5311 | 1032 | 8490 | 1028 | 1784 | 1029 | 23257 | 1027 | 25429 | 1030 | 60732 |
| 1055 | 15798 | 1060 | 496 | 1058 | 3196 | 1058 | 5957 | 1062 | 9055 | 1058 | 1952 | 1059 | 24259 | 1057 | 26973 | 1060 | 62972 |
| 1085 | 16851 | 1090 | 517 | 1088 | 3477 | 1088 | 6662 | 1092 | 9644 | 1088 | 2135 | 1089 | 25257 | 1087 | 28535 | | |
| 1114 | 17852 | 1120 | 541 | 1118 | 3793 | 1118 | 7427 | 1122 | 10284 | 1118 | 2331 | 1119 | 26254 | 1117 | 30111 | | |
| 1141 | 18792 | 1150 | 566 | 1148 | 4134 | 1148 | 8246 | 1152 | 10935 | 1148 | 2543 | 1149 | 27250 | 1147 | 31704 | | |
| 1168 | 19823 | 1180 | 595 | 1178 | 4504 | 1178 | 9123 | 1182 | 11594 | 1178 | 2774 | 1179 | 28243 | 1177 | 33310 | | |
| 1193 | 20822 | 1210 | 627 | 1208 | 4904 | 1208 | 10062 | 1212 | 12131 | 1208 | 3020 | 1209 | 29222 | 1207 | 34924 | | |
| 1219 | 21833 | 1240 | 663 | 1238 | 5330 | 1238 | 11067 | 1242 | 12538 | 1238 | 3281 | 1239 | 30201 | 1237 | 36551 | | |
| 1243 | 22804 | 1270 | 702 | 1268 | 5786 | 1268 | 12121 | 1272 | 13060 | 1268 | 3554 | 1269 | 31189 | 1267 | 38187 | | |
| 1267 | 23783 | 1300 | 746 | 1298 | 6266 | 1298 | 13205 | 1302 | 13663 | 1298 | 3841 | 1299 | 32170 | 1297 | 39829 | | |
| 1291 | 24772 | 1330 | 793 | 1328 | 6771 | 1328 | 14323 | 1330 | 14217 | 1328 | 4142 | 1329 | 33144 | 1326 | 41325 | | |
| 1315 | 25767 | 1360 | 846 | 1358 | 7294 | 1358 | 15404 | 1359 | 14808 | 1358 | 4456 | 1359 | 34111 | 1354 | 42827 | | |
| 1339 | 26776 | 1390 | 905 | 1388 | 7836 | 1388 | 16508 | 1387 | 15436 | 1388 | 4784 | 1389 | 35075 | 1383 | 44333 | | |

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APPENDIX D

**Table D- 2. Average GB Permeation**

| $M_f$ Average GB Cumulative Permeation (ng/cm$^2$) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg Time (min) | Dunlop Hevea Nailstep | Avg Time (min) | Tingley Hazproof | Avg Time (min) | LaCrosse Commander Nitrile/PVC | Avg Time (min) | LaCrosse Monarch PVC | Avg Time (min) | Bata PolyMax | Avg Time (min) | Bata HazMax | Avg Time (min) | Bata Over-booties | Avg Time (min) | Servus HazMat | Avg Time (min) | LaCrosse Chemtrex Neoprene |
| 10 | 1 | 9 | 3 | 11 | 3 | 8 | 1 | 9 | 1 | 10 | 1 | 7 | 0 | 11 | 2 | 8 | 1 |
| 40 | 19 | 39 | 26 | 41 | 37 | 38 | 15 | 39 | 12 | 40 | 10 | 37 | 5 | 41 | 22 | 38 | 20 |
| 70 | 46 | 69 | 49 | 71 | 89 | 68 | 38 | 70 | 23 | 70 | 25 | 67 | 320 | 71 | 42 | 68 | 37 |
| 100 | 71 | 99 | 65 | 101 | 139 | 98 | 65 | 100 | 29 | 100 | 41 | 97 | 3754 | 101 | 51 | 98 | 43 |
| 130 | 92 | 130 | 80 | 131 | 183 | 128 | 93 | 130 | 35 | 130 | 55 | 127 | 10305 | 131 | 58 | 128 | 48 |
| 160 | 110 | 160 | 94 | 161 | 223 | 158 | 117 | 160 | 40 | 161 | 69 | 157 | 17157 | 161 | 65 | 158 | 52 |
| 190 | 127 | 190 | 110 | 192 | 261 | 188 | 140 | 190 | 45 | 191 | 81 | 187 | 24022 | 192 | 72 | 188 | 56 |
| 220 | 142 | 220 | 126 | 222 | 296 | 218 | 161 | 220 | 49 | 221 | 92 | 217 | 30908 | 222 | 78 | 218 | 59 |
| 250 | 157 | 250 | 142 | 252 | 330 | 248 | 180 | 251 | 54 | 251 | 102 | 247 | 37799 | 252 | 84 | 248 | 62 |
| 280 | 170 | 280 | 157 | 282 | 362 | 278 | 198 | 281 | 58 | 281 | 112 | 277 | 44692 | 282 | 90 | 278 | 65 |
| 310 | 184 | 311 | 171 | 312 | 392 | 308 | 214 | 311 | 63 | 311 | 121 | 307 | 51589 | 312 | 96 | 308 | 68 |
| 340 | 200 | 341 | 185 | 342 | 420 | 338 | 230 | 341 | 66 | 342 | 130 | 337 | 58492 | 342 | 101 | 338 | 70 |
| 370 | 218 | 371 | 198 | 373 | 447 | 368 | 246 | 371 | 70 | 372 | 138 | 367 | 65406 | 373 | 107 | 368 | 73 |
| 400 | 243 | 401 | 211 | 403 | 472 | 398 | 261 | 401 | 73 | 402 | 146 | 397 | 72333 | 403 | 112 | 398 | 75 |
| 430 | 277 | 431 | 224 | 433 | 496 | 428 | 276 | 432 | 77 | 432 | 153 | 427 | 79251 | 433 | 117 | 428 | 78 |
| 460 | 324 | 461 | 236 | 463 | 519 | 458 | 291 | 462 | 81 | 462 | 160 | 457 | 86143 | 463 | 122 | 458 | 80 |
| 490 | 390 | 492 | 248 | 493 | 541 | 488 | 306 | 492 | 86 | 492 | 166 | 487 | 93014 | 493 | 126 | 488 | 82 |
| 520 | 482 | 522 | 259 | 523 | 562 | 518 | 320 | 522 | 91 | 523 | 174 | 517 | 99865 | 523 | 131 | 518 | 85 |
| 550 | 606 | 552 | 270 | 554 | 582 | 548 | 333 | 552 | 96 | 553 | 181 | | | 554 | 136 | 548 | 87 |
| 580 | 770 | 582 | 281 | 584 | 601 | 578 | 346 | 582 | 103 | 583 | 189 | | | 584 | 140 | 578 | 89 |
| 610 | 983 | 612 | 292 | 614 | 619 | 608 | 359 | 613 | 110 | 613 | 197 | | | 614 | 145 | 608 | 91 |
| 641 | 1257 | 642 | 302 | 644 | 636 | 638 | 372 | 643 | 118 | 643 | 204 | | | 644 | 150 | 638 | 93 |
| 671 | 1604 | 673 | 313 | 674 | 653 | 668 | 386 | 673 | 127 | 673 | 211 | | | 674 | 154 | 668 | 96 |
| 701 | 2027 | 703 | 323 | 704 | 669 | 698 | 401 | 703 | 138 | 704 | 217 | | | 704 | 158 | 698 | 98 |
| 731 | 2530 | 733 | 333 | 735 | 684 | 728 | 418 | 733 | 151 | 734 | 223 | | | 735 | 163 | 728 | 101 |
| 761 | 3116 | 763 | 343 | 765 | 699 | 758 | 436 | 763 | 167 | 764 | 230 | | | 765 | 167 | 758 | 103 |
| 791 | 3795 | 793 | 353 | 795 | 714 | 788 | 455 | 794 | 183 | 794 | 236 | | | 795 | 172 | 789 | 105 |
| 821 | 4566 | 823 | 362 | 825 | 728 | 818 | 477 | 824 | 203 | 824 | 242 | | | 825 | 176 | 819 | 107 |
| 851 | 5423 | 854 | 372 | 855 | 742 | 848 | 502 | 854 | 225 | 854 | 248 | | | 855 | 181 | 849 | 109 |
| 881 | 6377 | 884 | 382 | 885 | 755 | 878 | 530 | 884 | 250 | 885 | 254 | | | 885 | 185 | 879 | 112 |
| 911 | 7423 | 914 | 391 | 916 | 768 | 908 | 562 | 914 | 278 | 915 | 260 | | | 916 | 189 | 909 | 114 |
| 941 | 8561 | 944 | 401 | 946 | 781 | 938 | 598 | 944 | 310 | 945 | 266 | | | 946 | 193 | 939 | 116 |
| 971 | 9802 | 974 | 411 | 976 | 794 | 968 | 640 | 975 | 345 | 975 | 272 | | | 976 | 197 | 969 | 118 |
| 1001 | 11143 | 1004 | 420 | 1006 | 806 | 998 | 687 | 1005 | 383 | 1005 | 278 | | | 1006 | 201 | 999 | 120 |
| 1032 | 12576 | 1035 | 430 | 1036 | 819 | 1028 | 740 | 1035 | 425 | 1035 | 283 | | | 1036 | 206 | 1029 | 122 |
| 1062 | 14109 | 1065 | 439 | 1066 | 831 | 1058 | 800 | 1065 | 472 | 1066 | 289 | | | 1066 | 210 | 1059 | 124 |
| 1092 | 15740 | 1095 | 448 | 1097 | 843 | 1088 | 866 | 1095 | 522 | 1096 | 294 | | | 1097 | 214 | 1089 | 126 |
| 1122 | 17467 | 1125 | 457 | 1127 | 855 | 1118 | 939 | 1125 | 577 | 1126 | 300 | | | 1127 | 218 | 1119 | 128 |
| 1152 | 19283 | 1155 | 466 | 1157 | 867 | 1148 | 1020 | 1156 | 636 | 1156 | 305 | | | 1157 | 222 | 1149 | 130 |
| 1182 | 21183 | 1185 | 475 | 1187 | 879 | 1178 | 1109 | 1186 | 699 | 1186 | 311 | | | 1187 | 226 | 1179 | 132 |
| 1213 | 23158 | 1216 | 484 | 1217 | 892 | 1208 | 1207 | 1216 | 768 | 1216 | 316 | | | 1217 | 230 | 1209 | 134 |
| 1243 | 25215 | 1246 | 493 | 1247 | 904 | 1238 | 1314 | 1246 | 840 | 1247 | 321 | | | 1247 | 234 | 1239 | 136 |
| 1273 | 27367 | 1276 | 502 | 1278 | 916 | 1268 | 1432 | 1276 | 917 | 1277 | 327 | | | 1278 | 238 | 1269 | 138 |
| 1303 | 29597 | 1306 | 511 | 1308 | 929 | 1298 | 1559 | 1306 | 998 | 1307 | 332 | | | 1308 | 242 | 1299 | 140 |
| 1333 | 31894 | 1336 | 520 | 1338 | 942 | 1328 | 1697 | 1337 | 1084 | 1337 | 337 | | | 1338 | 246 | 1329 | 142 |
| 1364 | 34251 | 1367 | 528 | 1368 | 955 | 1358 | 1846 | 1367 | 1175 | 1367 | 342 | | | 1368 | 250 | 1359 | 144 |

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**Appendix E -**
**Permeation Results Plots**

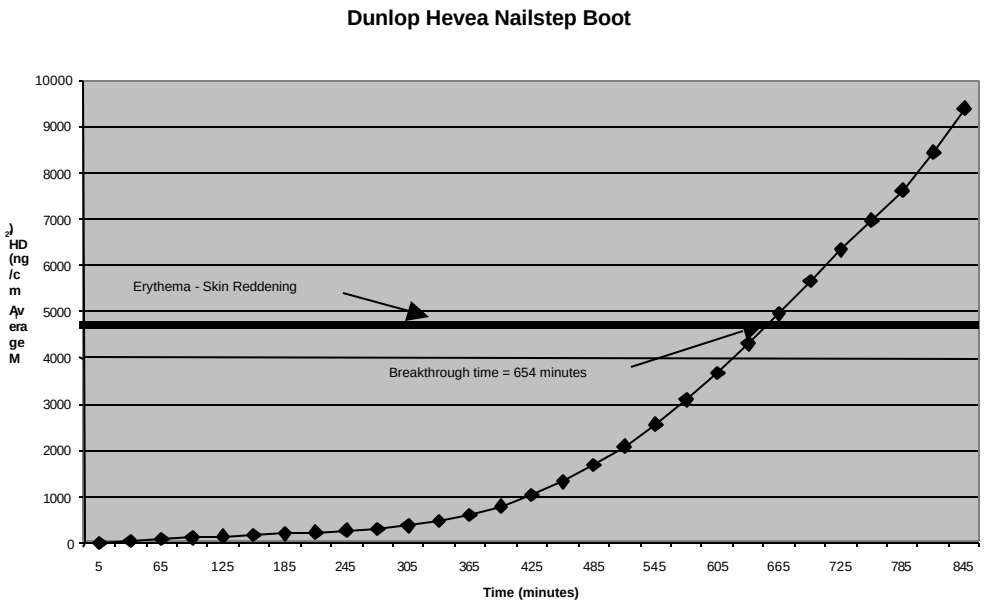


**Figure E- 1: Dunlop Hevea Nailstep - Average HD Cumulative Permeation**

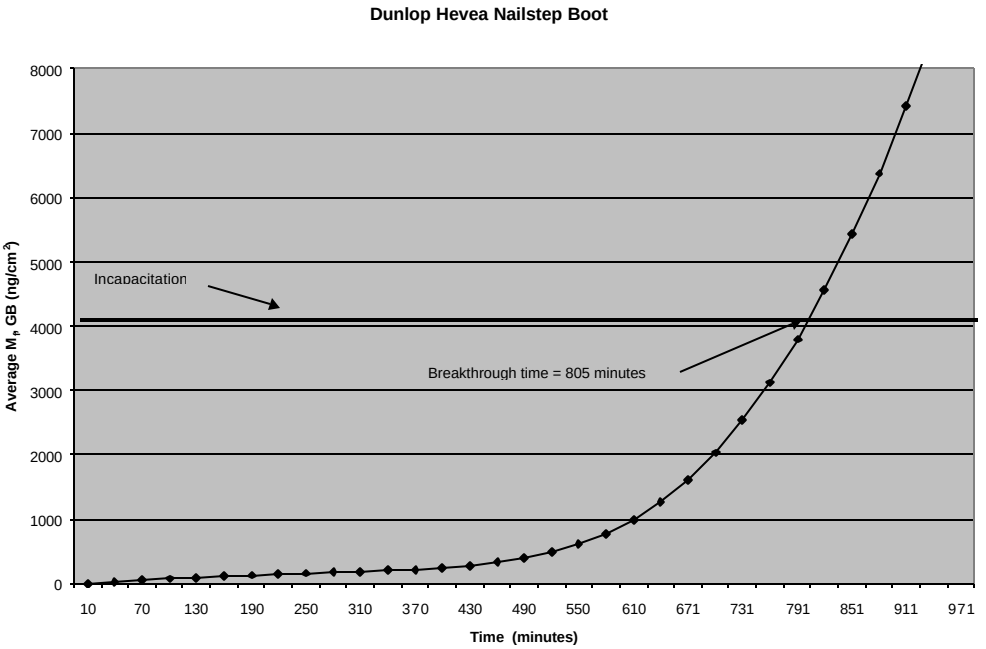


**Figure E- 2: Dunlop Hevea Nailstep - Average GB Cumulative Permeation**

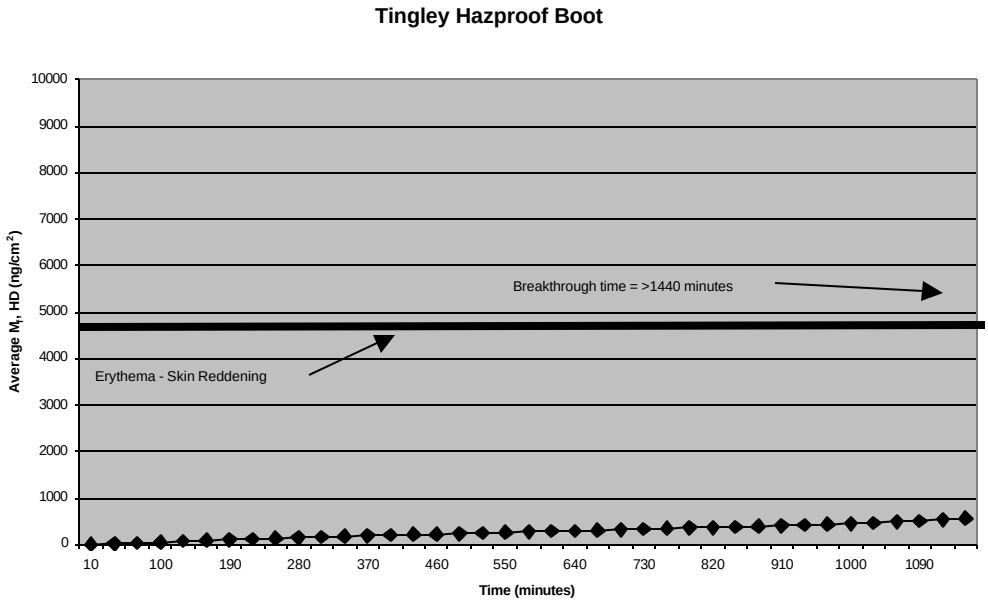


**Figure E- 3: Tingley Hazproof: Average HD Cumulative Permeation**

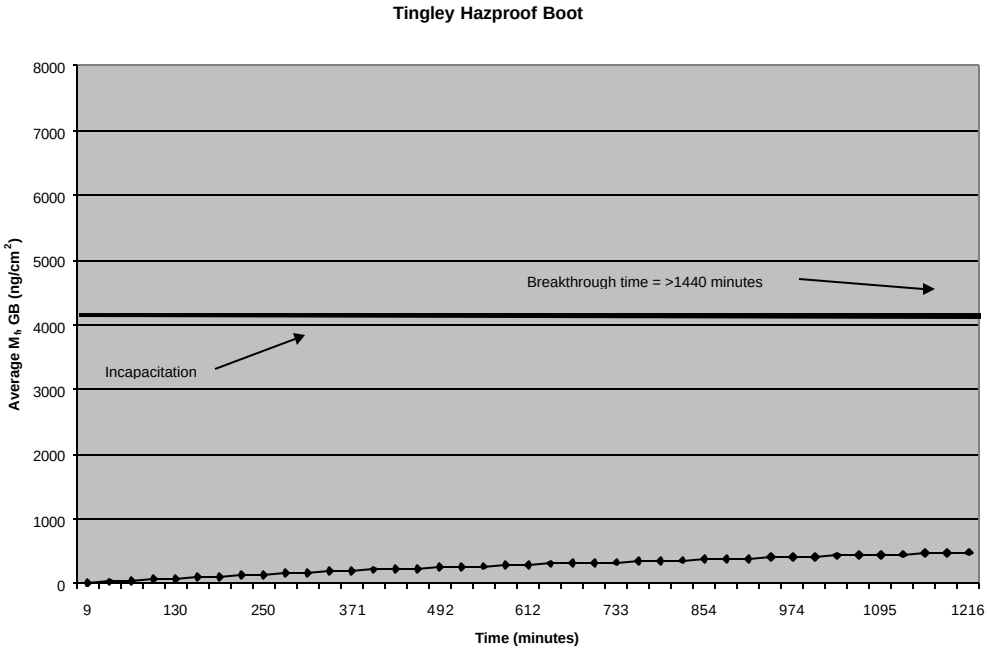


**Figure E- 4: Tingley Hazproof: Average GB Cumulative Permeation**

APPENDIX E

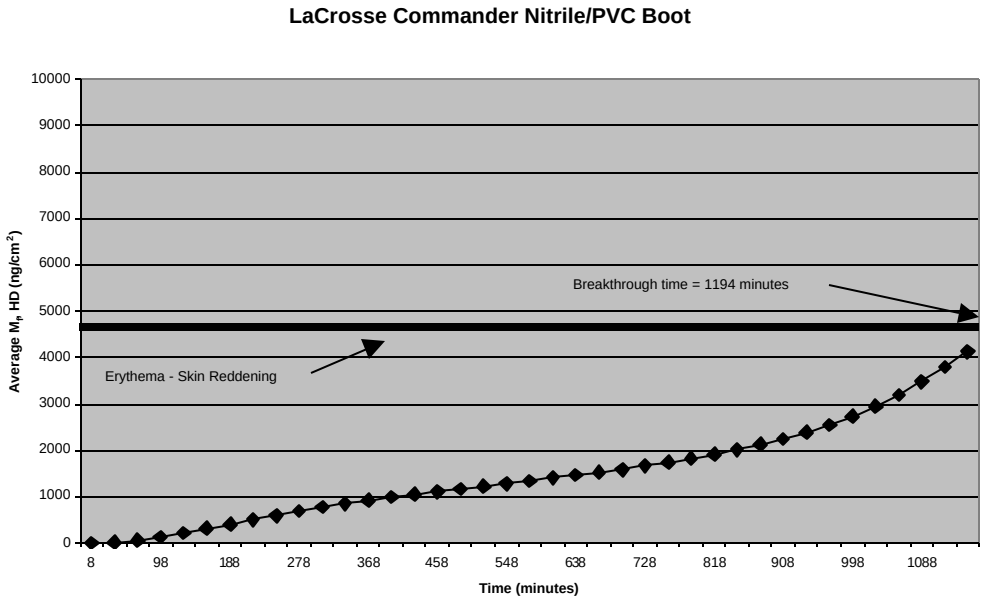


**Figure E- 5: LaCrosse Commander: Average HD Cumulative Permeation**

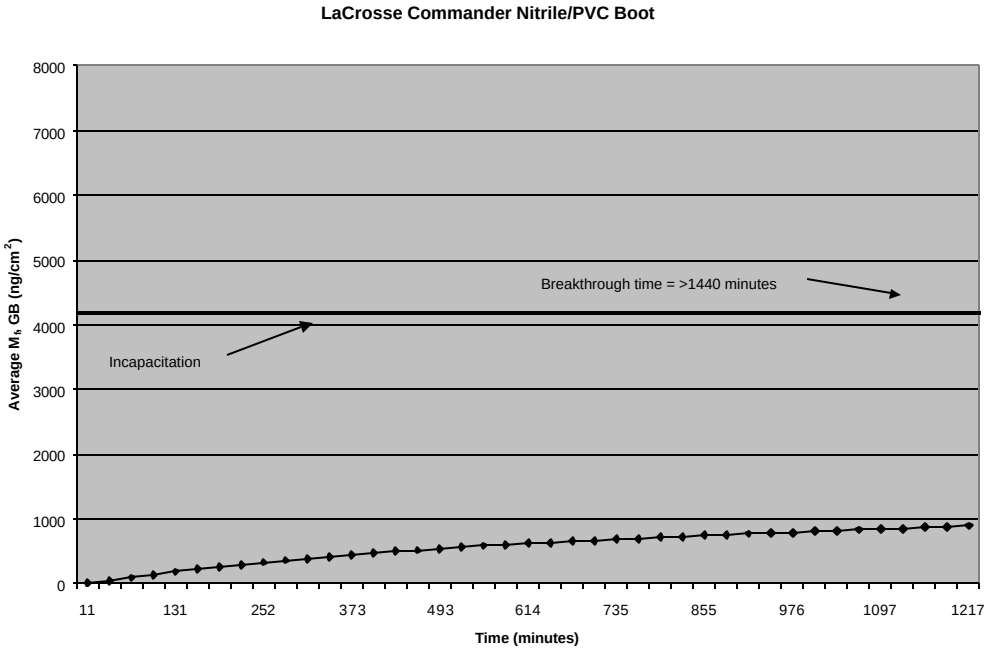


**Figure E- 6: LaCrosse Commander: Average GB Cumulative Permeation**

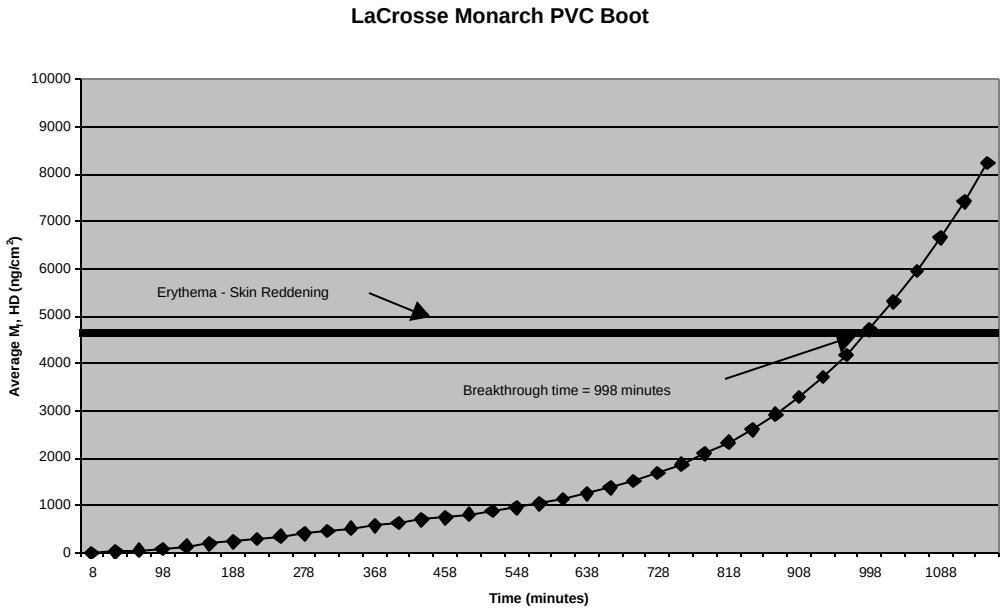


**Figure E- 7: LaCrosse Monarch: Average HD Cumulative Permeation**

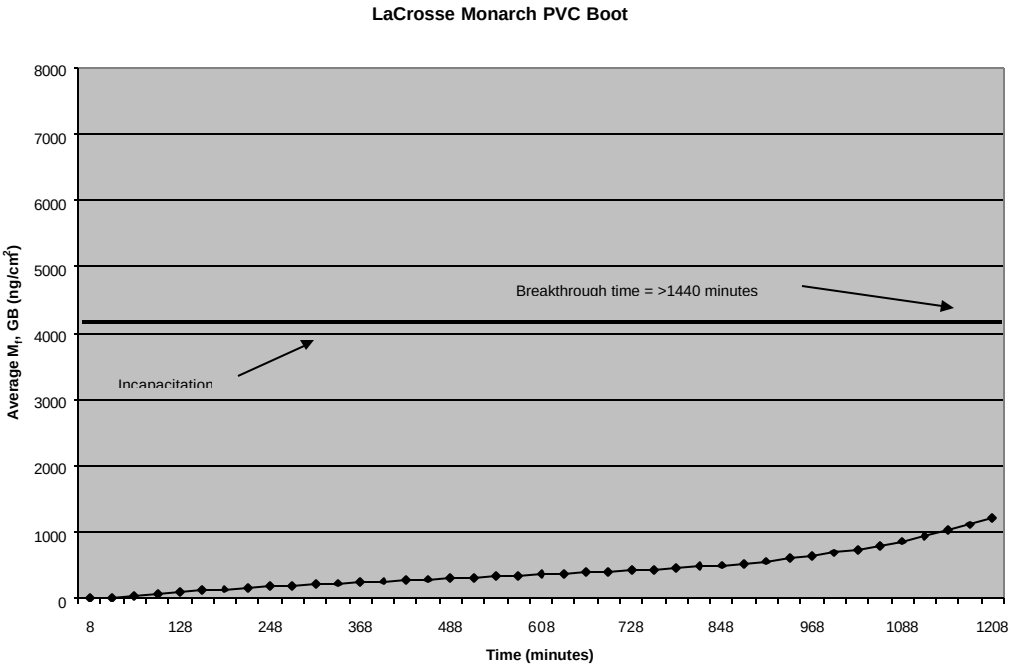


**Figure E- 8: LaCrosse Monarch: Average GB Cumulative Permeation**

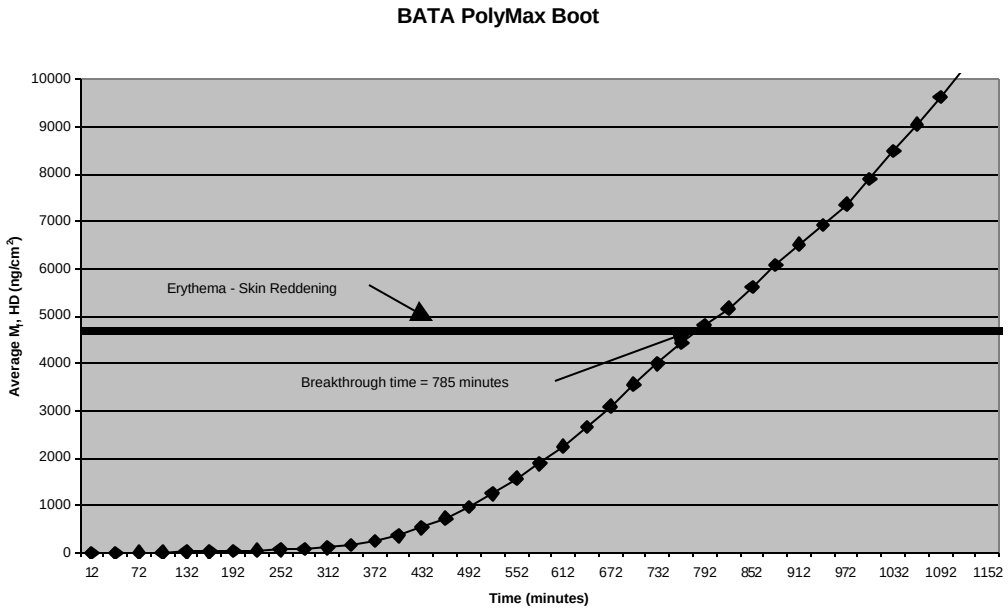


**Figure E- 9: Bata Polymax: Average HD Cumulative Permeation**

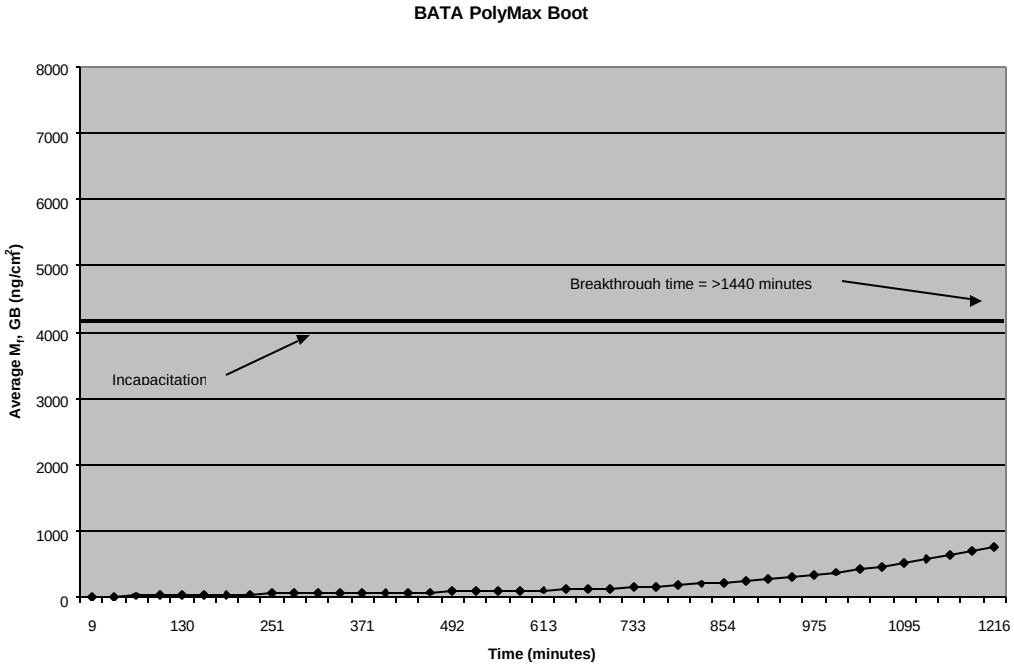


**Figure E- 10: Bata Polymax: Average GB Cumulative Permeation**

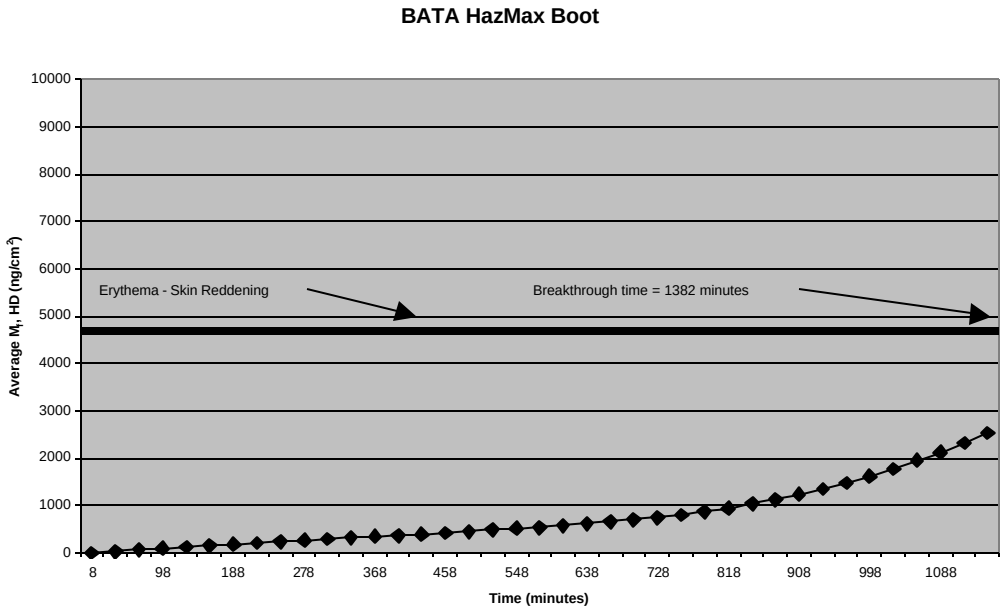


**Figure E- 11: Bata Hazmax: Average HD Cumulative Permeation**

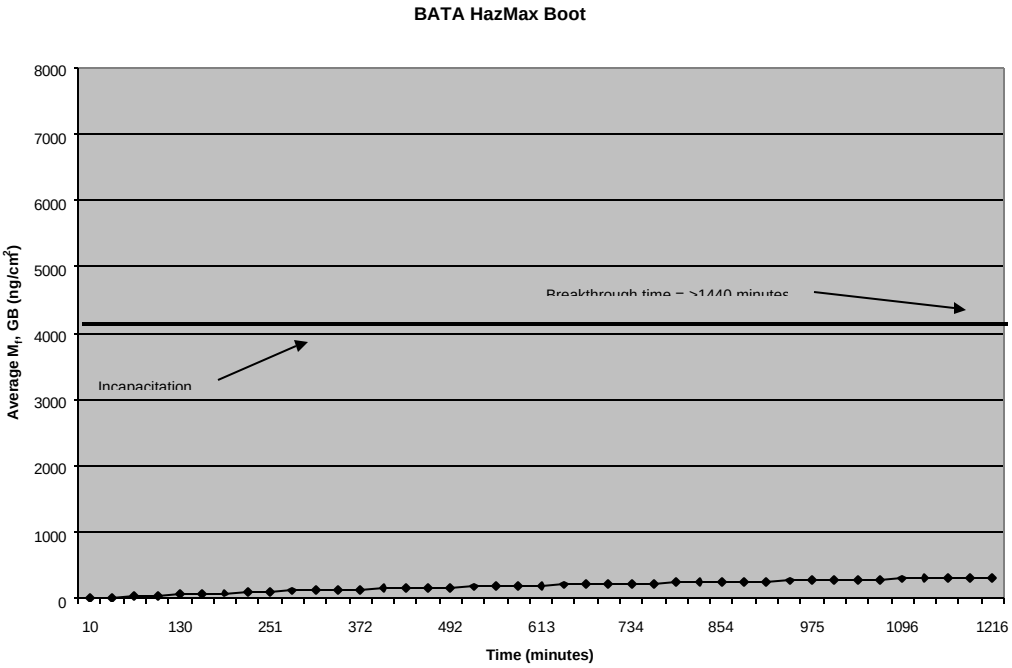


**Figure E- 12: Bata Hazmax: Average GB Cumulative Permeation**

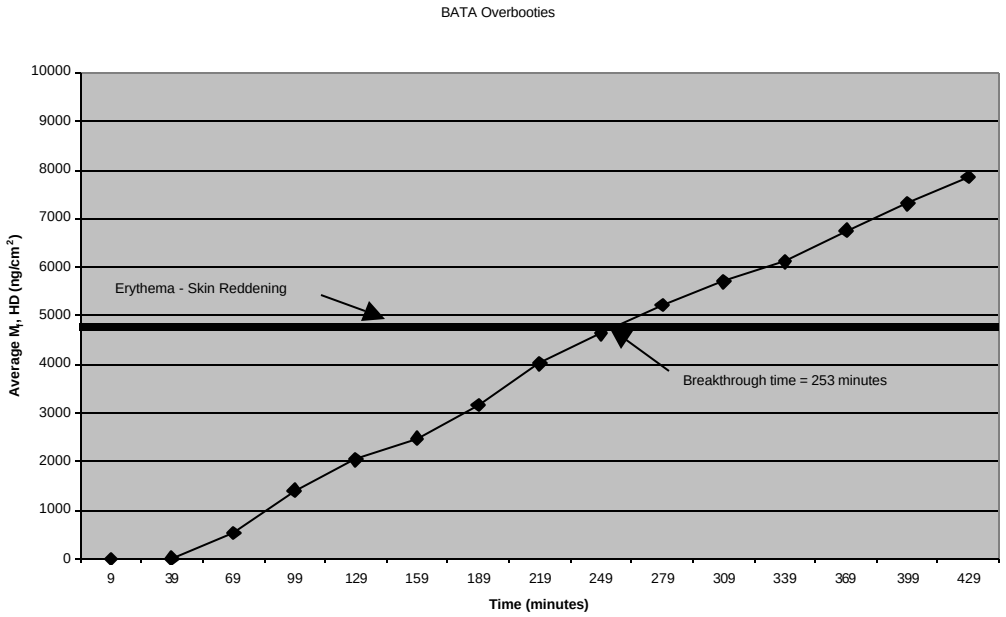


**Figure E- 13: Bata Overbooties: Average HD Cumulative Permeation**

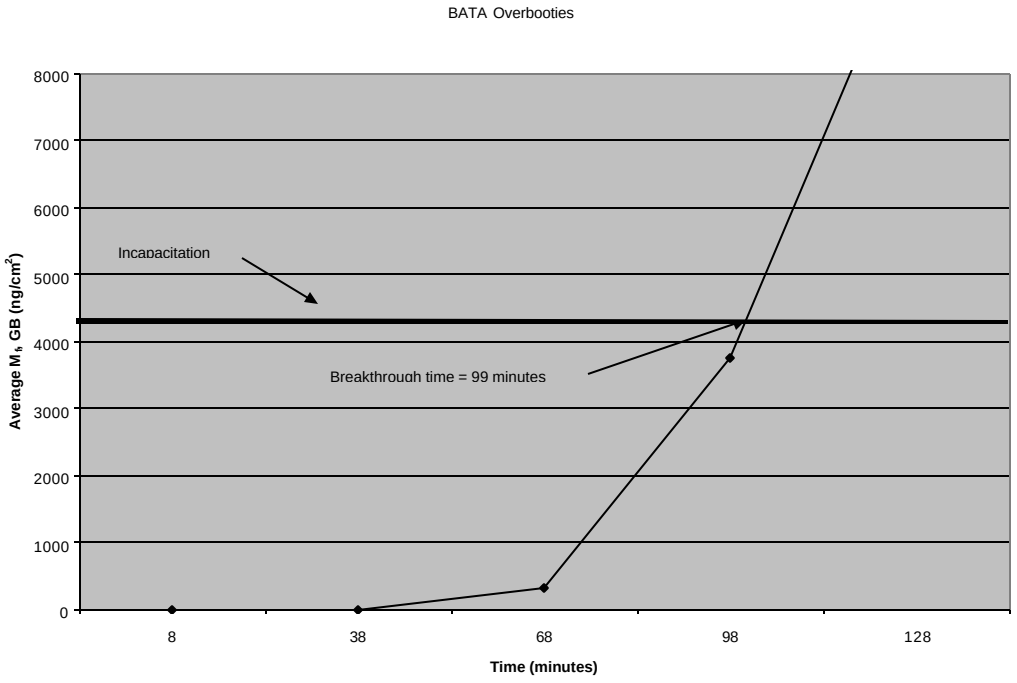


**Figure E- 14: Bata Overbooties: Average GB Cumulative Permeation**

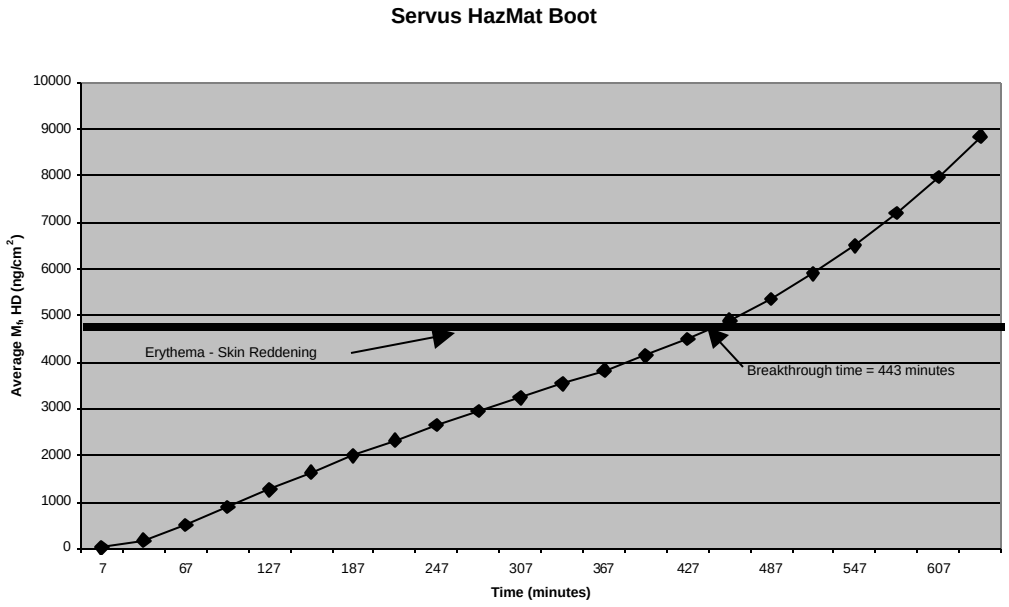


**Figure E- 15: Servus Hazmat: Average HD Cumulative Permeation**

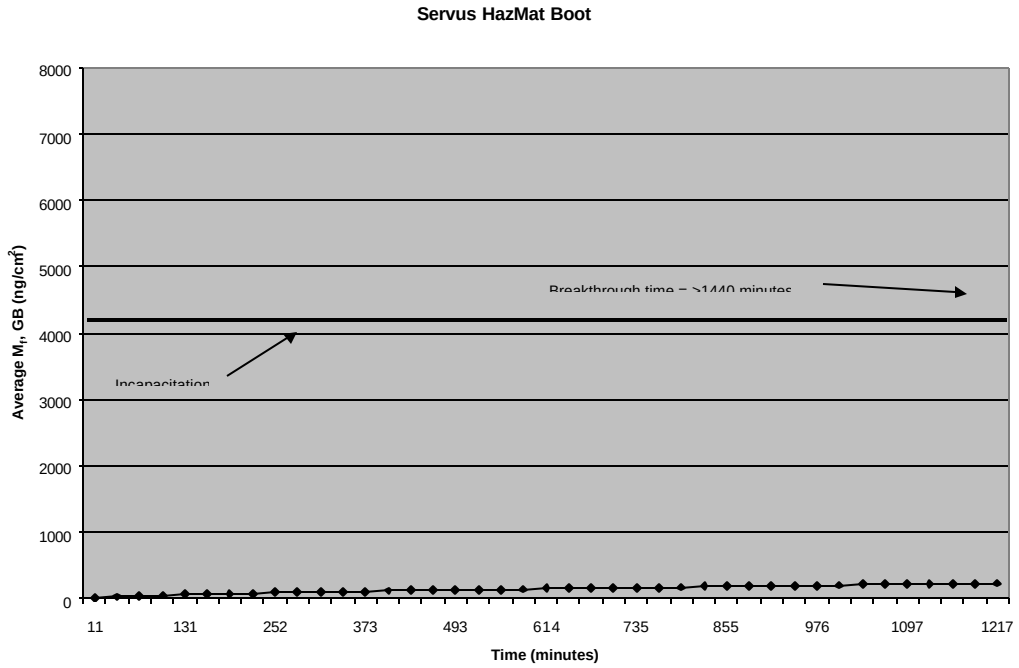


**Figure E- 16: Servus Hazmat: Average GB Cumulative Permeation**

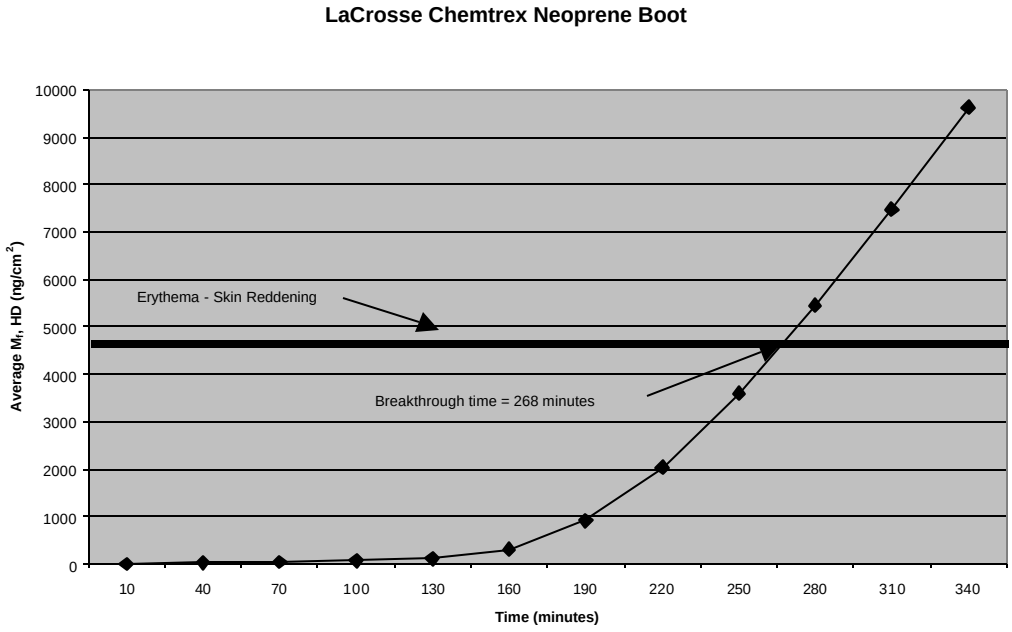


**Figure E- 17: LaCrosse Chemtrex: Average HD Cumulative Permeation**

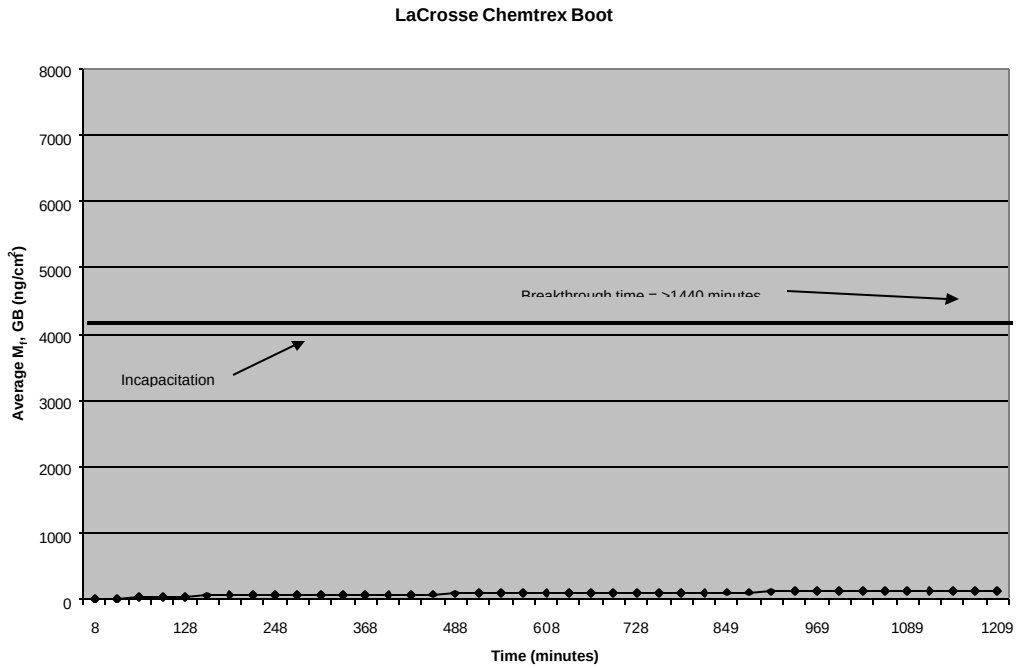


**Figure E- 18: LaCrosse Chemtrex: Average GB Cumulative Permeation**

## Appendix F -
## Overall Test Results

**Table F- 1. Overall Test Results**

| Boot Model | Breakthrough Time (min) | |
|---|---|---|
| | HD | GB |
| Dunlop Hevea Nailstep | 654 | 805 |
| Tingley Hazproof 82330 | >1440 | >1440 |
| LaCrosse Commander 89612 | 1194 | >1440 |
| LaCrosse Monarch 87568 | 998 | >1440 |
| Bata Polymax 84076 | 785 | >1440 |
| Bata Hazmax 87012 | 1382 | >1440 |
| Bata Overbooties 97591 | 253 | 99 |
| Servus Hazmat HZT 75107 | 443 | >1440 |
| LaCrosse Chemtrex 24228 | 268 | >1440 |