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SLOW HEATING TEST THERMAL EQUILIBRIUM AND MAXIMUM REACTION TEMPERATURE

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ABSTRACT

STANAG 4382 Slow Heating, Munitions Test Procedures has been reviewed and updated by the AC/326 SG/B Slow Heating Custodial Working Group. As part of this process, questions arose as to guidance for thermal soaking and maximum testing temperature. MSIAC completed analytic thermal equilibrium calculations and NSWCDD completed finite difference thermal equilibrium calculations in order to help provide guidance for appropriate soak times. The analytic and finite difference calculations were in good agreement, providing significant confidence in both sets of calculations. Initially, bounding analytic thermal soak calculations were conducted using one-term approximation solutions for the time required for a cylinder to reach 48ºC and 45ºC using a 50ºC heat soak. Further one-term approximation solutions for the time required for a range of Comp B cylinders to reach 45ºC using a 50ºC heat soak were subsequently conducted. NSWCDD performed 1-D finite difference calculations for a variety of packaged and unpackaged munitions. The results were compared to required soak time tables and formulas contained in the STANAG 4224 Edition 4 (superseded). The results show that the table and formulas in STANAG 4224 match the most conservative maximum time calculations until about 100 mm diameter and then change slope to essentially suggest a one day soak at 203mm. Above 203mm diameter, the formula trend matches fairly well with the nominal times required to reach a 48ºC or 45ºC center temperature. For items with a diameter greater than about ½ meter, the required soak times become quite long (2 days and longer). A 50ºC heat soak duration formula was developed based around the idea that it should provide a conservative heat soak time based on a 45ºC centerline temperature. The resulting preconditioning formula has been incorporated into the new AOP-4382. Finally, MSIAC addressed the issue of maximum testing temperature by conducting a review of maximum experimental reaction temperatures using the MSIAC AIMS database. The review of 29 slow heating test results, which included reaction temperature, indicated that the highest known reaction temperature occurred with the PAC-3 rocket motor where the first reaction was at 260°C at 27.8°C/hr. As the reaction temperature is the oven temperature, it is not surprising that very large items with lower thermal kinetics energetics have higher reaction temperatures.

Keywords:

Slow Heating, STANAG 4382, Temperature Equilibrium, Maximum Reaction Temperature.

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ABBREVIATIONS

AOP	Allied Ordnance Publication
AC/326	NATO Ammunition Safety Group
Comp B	Composition B
CWG	Custodial Working Group
NATO	North Atlantic Treaty Organization
NSWCDD	Naval Surface Warfare Center Dahlgren Division
SG/A	Subgroup A
SCO	Slow Cook-Off
SH	Slow Heating
STANAG	NATO Standardization Agreement
WG	Working Group

INTRODUCTION

The slow heating test is described in STANAG 4382 Slow Heating, Munitions Test Procedures. The purpose of the slow heating test is to assess the reaction, if any, of munitions and weapon systems to a gradually increasing thermal environment. STANAG 4382 and the associated AOP-4382 were recently updated by the AC/326 SG/B Slow Heating (SH) Custodial Working Group (CWG), led by S. Struck, USA. As part of this process, questions arose as to guidance for thermal soaking and maximum testing temperature. The SH CWG had decided that it would be appropriate to do a heat soak of 50°C until reaching thermal equilibrium. STANAG 4224 ED. 4, Large Caliber Artillery and Naval Gun Ammunition Greater than 40 mm, Safety and Suitability for Service Evaluation, contains guidance for heat soak times. However, the origin of this guidance was unknown. For this reason, MSIAC completed analytic thermal equilibrium calculations and NSWCDD completed finite difference thermal equilibrium calculations in order to provide guidance for appropriate soak times. These calculations were compared to the guidance provided in STANAG 4224 ED. 4. Additionally, MSIAC conducted a review of maximum experimental reaction temperatures to help provide guidance for a maximum testing temperature.

1 STANAG 4224 EDITION 4 CONDITIONING DURATIONS

STANAG 4224 Edition 4 (superseded by STANAG 4761) states the following:

When conditioning ammunition, the durations given below shall be used as a minimum:

Calibre (mm)	40	57	76	90	100	105	120	155	165	203
Duration (h)	4	7	8	13	15	18	20	22	23	26

The recommended conditioning durations are not to be extended beyond a total of 36 hours for temperatures above 50ºC without the advice of the developer.

To derive minimum conditioning duration for ammunition of calibre not specified in the table above, the following equation may be used:

a. For calibre ≤ 105mm
$D = 0.1016 + 0.0516*S + .0009946*S^2$

b. For calibre > 105mm.
$D = 16.8414 - 0.0013*S + .0002292*S^2$

D = Duration of Conditioning (hr)
S = Ammunition Calibre (mm)

2 ANALYTIC THERMAL EQUILIBRIUM CALCULATIONS

2.1 BOUNDING CYLINDRICAL THERMAL SOAK CALCULATIONS

Under certain conditions, the temperature profile of a solid cylinder can be calculated, with good accuracy, using a one term equation. Bounding analytic one-term approximation calculations for the time required for a cylinder to reach 48ºC and 45ºC using a 50ºC heat soak were conducted. The computational procedure consists of solving for the Fourier number, τ from the following equation:

$$\frac{T_0 - T_\infty}{T_i - T_\infty} = A_1 e^{-\lambda_1^2 \tau}$$

The time can then be calculated from the Fourier number:

$$t = \frac{\tau r_0^2}{\alpha}, \text{ where } \alpha = \frac{k}{\rho c_p}.$$

The values for A_1 and λ_1 depend on the Biot number, $\mathrm{Bi} = \frac{h r_0}{k}$. h is the heat transfer coefficient. k is the thermal conductivity. c_p is the specific heat and ρ is the density. In all cases the Biot numbers were large (much greater than 0.1) and the Fourier numbers were large (much greater than 0.2). Therefore the one term solutions should be accurate within 2%.

The bounding calculations of maximum time and minimum time were based on a range of expected explosive and propellant properties. Additional calculations were performed using a more nominal maximum and minimum range. These values were based on information found in the LLNL Explosive Handbook [1]. Table 1 presents a listing of the parameters that were varied for the bounding calculations. Table 2 presents the tabular parameters used for the solution procedure [2]. Figures 1 and 2 present graphs for the calculated time for a cylinder center to reach 48ºC compared to the tabular and formula based guidance in STANAG 4224 ED. 4. The STANAG 4224 ED. 4 tabular and formula results are very similar. Figures 3 and 4 present graphs for the calculated time for a cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224 ED. 4. Figures 3 and 4 differ only in the x-axis scale to facilitate comparison for small and very large items.

Table 1. Parameters used for the bounding one-term approximation thermal analysis.

Value	Extreme range	Nominal range
ρ (g/cc)	1.5 – 2.2	1.7 – 1.8
k (W/m·ºC)	0.1 – 0.5	0.2 – 0.3
C_p (J/kg·ºC)	500 – 1500	1200 – 1300
h (W/m^2·ºC)	55 – 120	75 - 100

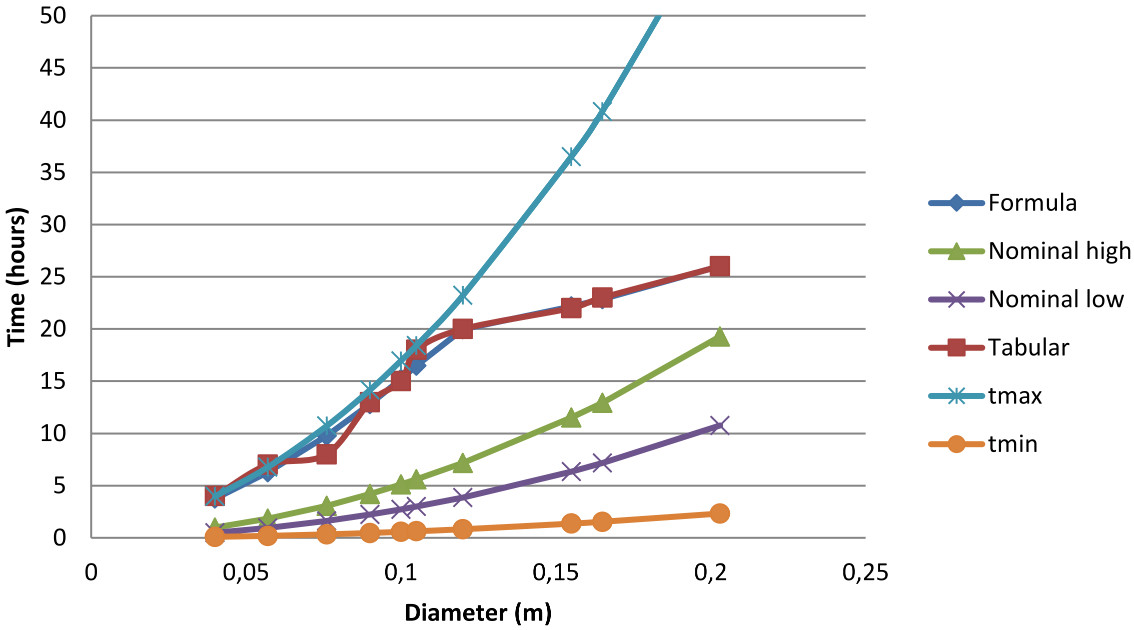

Figure 1. Calculated time for a cylinder center to reach 48ºC compared to the tabular and formula based guidance in STANAG 4224.

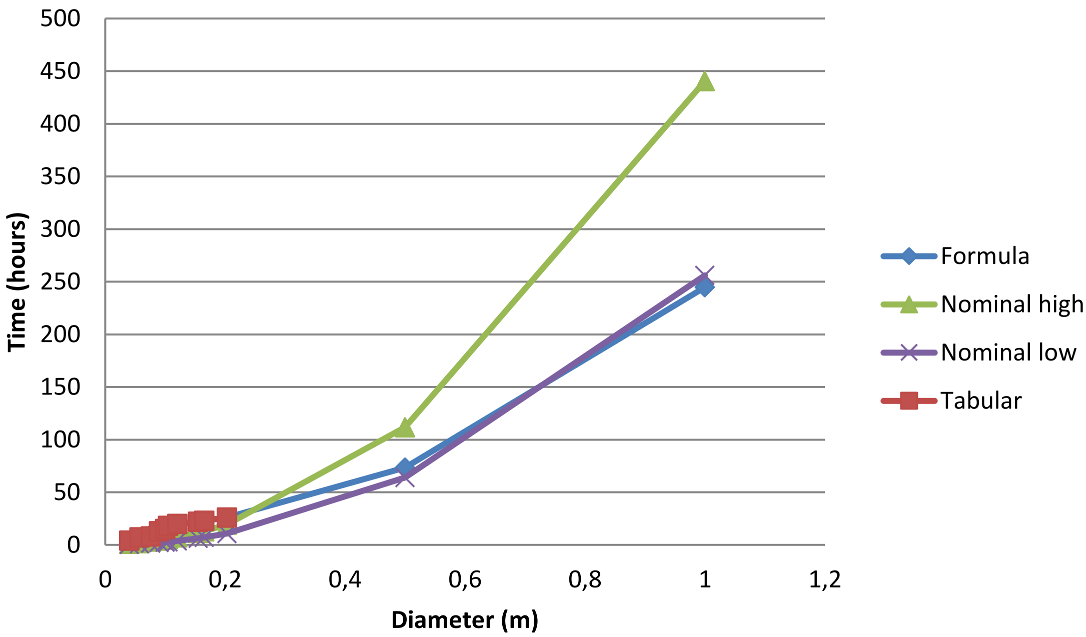

Figure 2. Calculated time for a cylinder center to reach 48ºC compared to the tabular and formula based guidance in STANAG 4224.

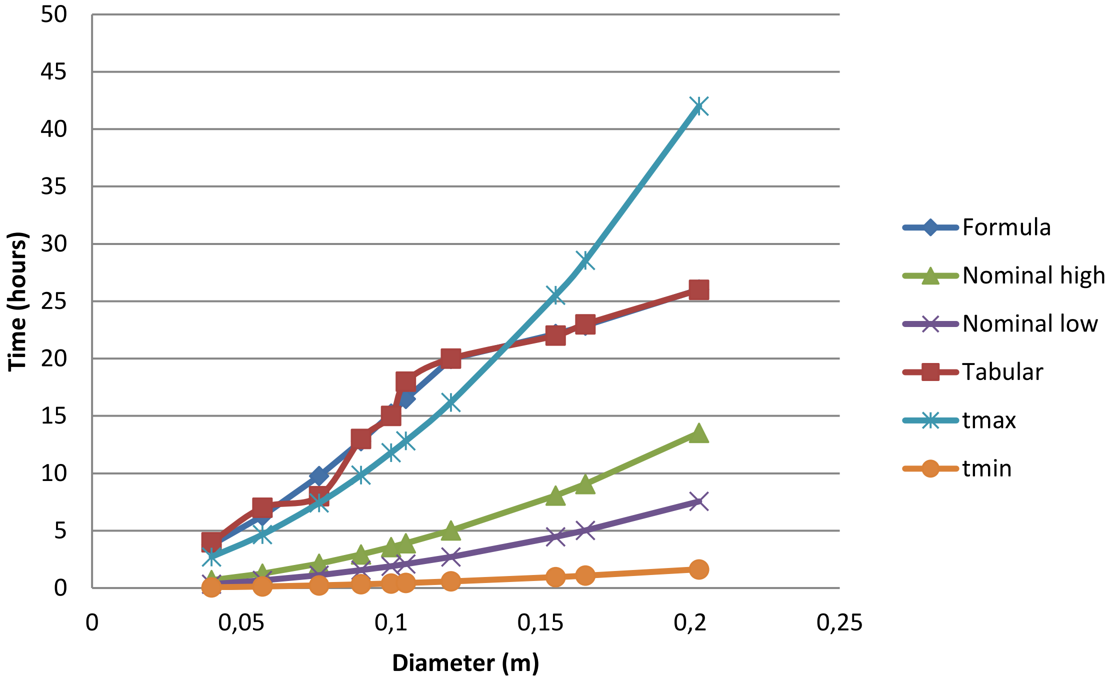

Figure 3. Calculated time for a cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224.

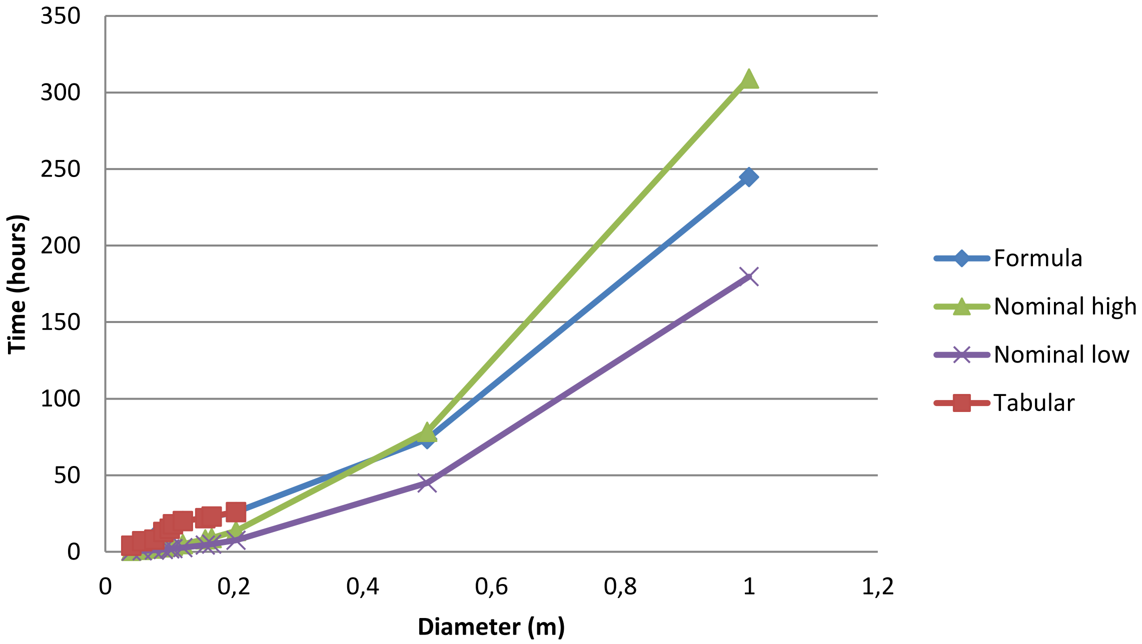

Figure 4. Calculated time for a cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224.

Table 2. Coefficients used in the one-term approximate solution of transient one-dimensional heat conduction in plane walls, cylinders, and spheres.

	Cylinder Geometry	
Bi	λ_1	A_1
0.2	0.6170	1.0483
0.3	0.7465	1.0712
0.4	0.8516	1.0931
0.5	0.9408	1.1143
0.6	1.0184	1.1345
0.7	1.0873	1.1539
0.8	1.1490	1.1724
0.9	1.2048	1.1902
1.0	1.2558	1.2071
2.0	1.5995	1.3384
3.0	1.7887	1.4191
4.0	1.9081	1.4698
5.0	1.9898	1.5029
6.0	2.0490	1.5253
7.0	2.0937	1.5411
8.0	2.1286	1.5526
9.0	2.1566	1.5611
10.0	2.1795	1.5677
20.0	2.2880	1.5919
30.0	2.3261	1.5973
40.0	2.3455	1.5993
50.0	2.3572	1.6002
100.0	2.3809	1.6015
∞	2.4048	1.6021

2.2 COMP B CYLINDRICAL THERMAL SOAK CALCULATIONS

The heat transfer coefficient is oven and item dependent. Dr. D. Hubble provided guidance as to heat transfer coefficients that he had obtained from experiments that were conducted using steel cylinders in the NSWCDD standard oven design [3]. These heat transfer coefficients are somewhat lower than the values previously used in the calculations. Analytic one-term approximation calculations for the time required for a cylinder of Comp B to reach 45ºC using a 50ºC heat soak using these lower values were conducted. Table 3 presents the parameters used for these calculations, including the lower heat transfer coefficients. Figures 5 and 6 present graphs for the calculated time for a Comp B cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224 ED. 4.

Table 3. Parameters used for Comp B one-term approximation thermal analysis.

Value	Comp B
ρ (g/cc)	1.7
k (W/m·ºC)	0.226
Cp (J/kg·ºC)	1130
h (W/m^2·ºC)	11 – 25

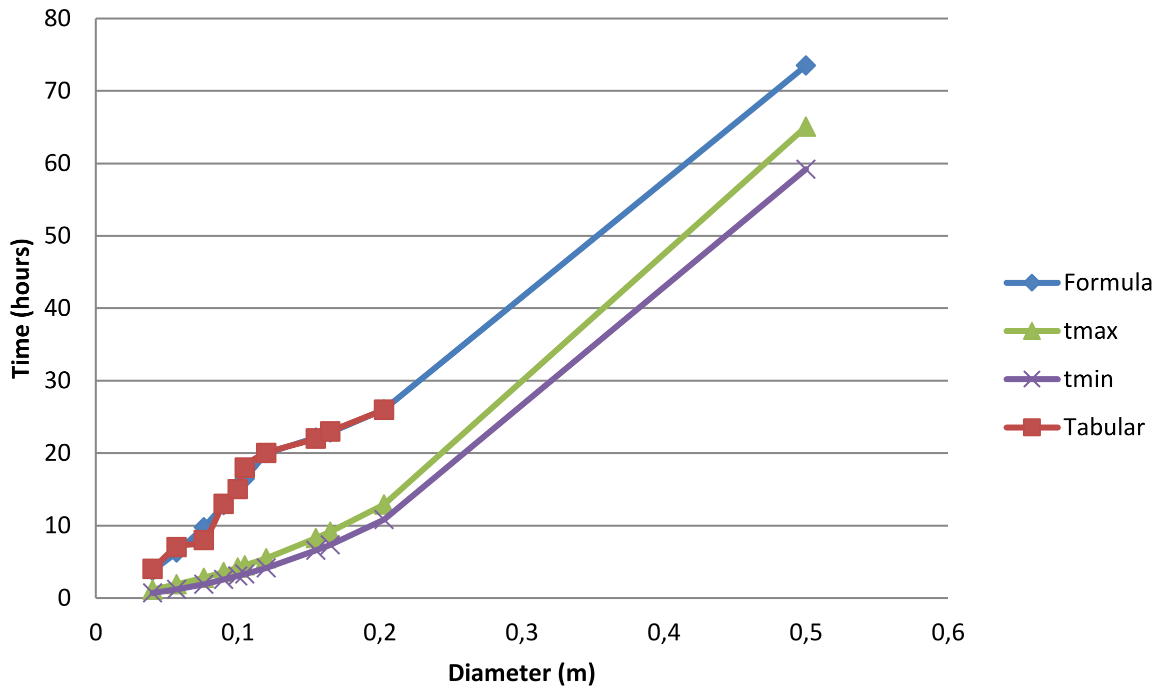

Figure 5. Calculated time for a Comp B cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224.

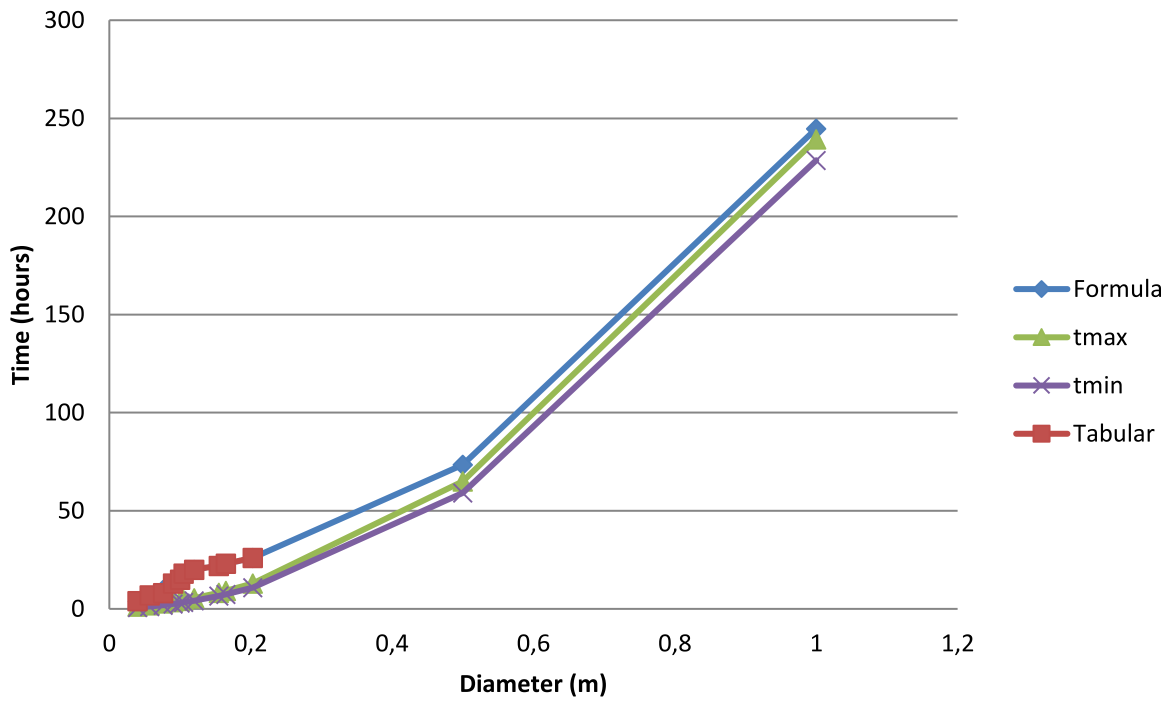

Figure 6. Calculated time for a Comp B cylinder center to reach 45ºC compared to the tabular and formula based guidance in STANAG 4224.

2.3 STANAG 4224 HEAT SOAK GUIDANCE COMPARISON

The analytic results comparison show that the table and formulas in STANAG 4224 match the most conservative maximum time calculations until about 100mm diameters and then change slope to essentially suggest a one day soak at 203mm. Above 203mm diameter, the formula trend matches fairly well with the nominal times required to reach a 48ºC or 45ºC center temperature. For items with a diameter greater than about ½ meter, the required soak times become quite long (2 days and longer). For the Comp B calculations, the required soak time to reach a 45ºC center temperature lies somewhat below the table and formulas in STANAG 4224. This is not particularly surprising, as it is believed that the table and formulas are meant to represent the required soak temperature to reach a 48ºC center temperature. Above 100mm diameter, the Comp B required soak times follow the STANAG 4224 curve quite closely, but with a somewhat lower required soak time.

3	FINITE DIFFERENCE THERMAL EQUILIBRIUM CALCULATIONS

3.1 HEAT SOAK TEMPERATURE DIFFERENTIAL

NSWCDD completed one dimensional finite difference thermal modeling to calculate munitions explosive fill temperatures versus time. The fill centerline temperature is asymptotic to the soak temperature with time. Tightening the fill centerline temperature difference requirement significantly increase the required soak time. To demonstrate this, an example calculation was conducted using a 1000 lb. bomb soaked at 50ºC from a starting temperature of 20ºC. The left plot in Figure 7 presents the 50ºC heat soak temperature profiles for the 1000 lb. bomb example and the right plot in Figure 7 presents the 50ºC heat soak centerline temperature profile as a function of time for the same munition. The explosive fill centerline reaches 40ºC in 19 hours, 45ºC in 27 hours and 48ºC in 38 hours. These results show that it takes nearly twice as long to reach a temperature differential of 2ºC compared to a temperature differential of 10ºC. For this reason, a study was done using different size munitions looking at soak durations required to achieve 10ºC, 5ºC and 2ºC centerline temperature differentials.

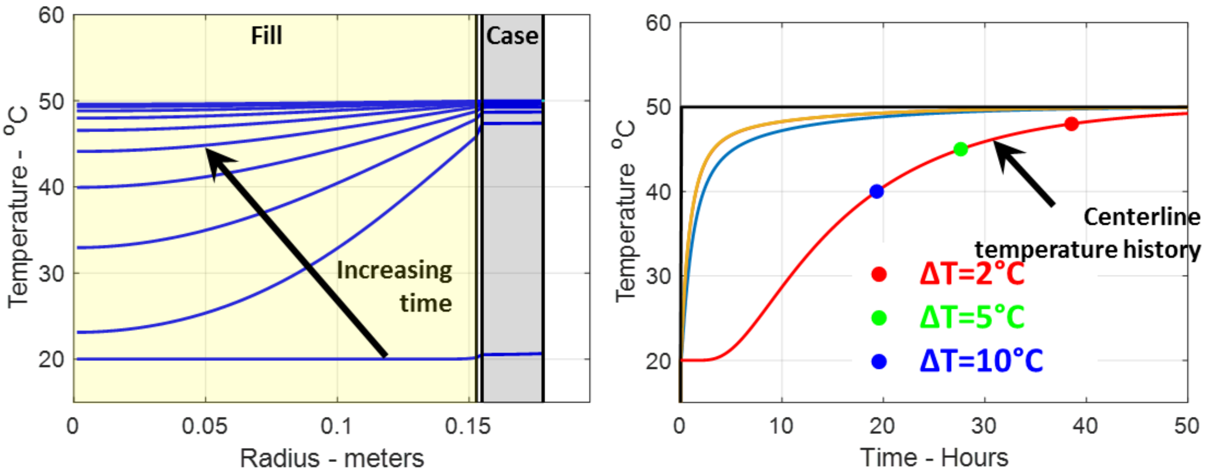

Figure 7. 50ºC heat soak temperature profile as function of time (left) and centerline temperature history (right) for a 1000 lb. bomb starting at 20ºC.

3.2 HEAT SOAK TEMPERATURE DIFFERENTIAL STUDY

Thermal modeling was conducted for a variety of munitions from 105mm up to 1.03m using a 50ºC heat soak and initial temperature of 20ºC. The munitions were modeled bare or in a container depending on the munition. The soak durations required to achieve 10ºC, 5ºC and 2ºC centerline temperature differentials were calculated. The graphed results for the calculated heat soak durations versus munition diameter (caliber) are presented in Figures 8 and 9. Figures 8 and 9 also compare the finite difference results to the tabular and formula based guidance in STANAG 4224. The STANAG 4224 guidance appears quite conservative for smaller diameter munitions.

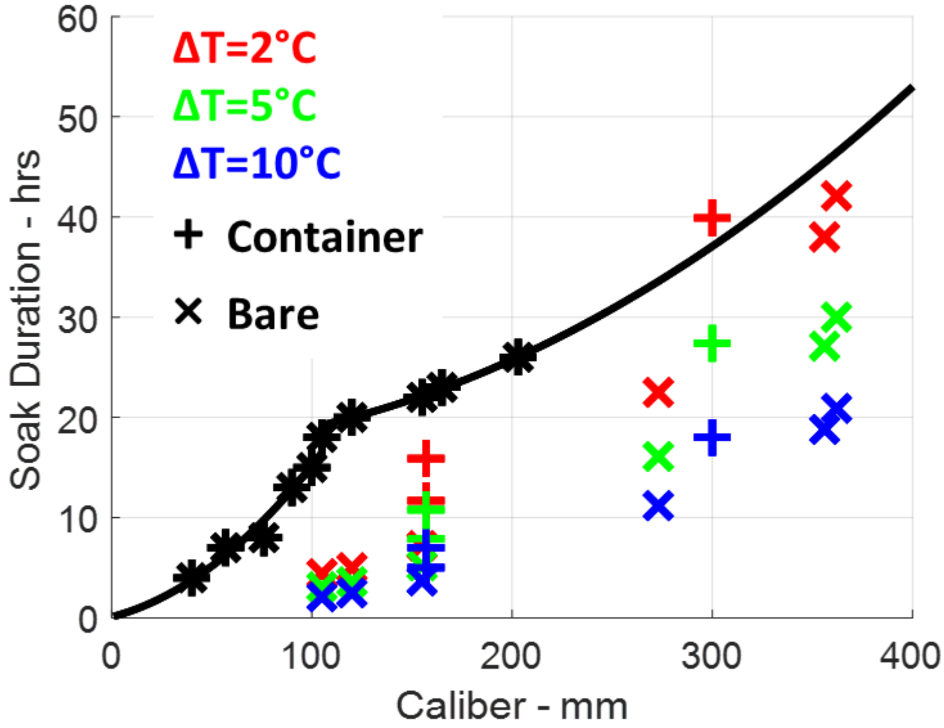

Figure 8. Heat soak duration required to reach 2ºC, 5ºC and 10ºC centreline temperature differentials for a variety of munitions.

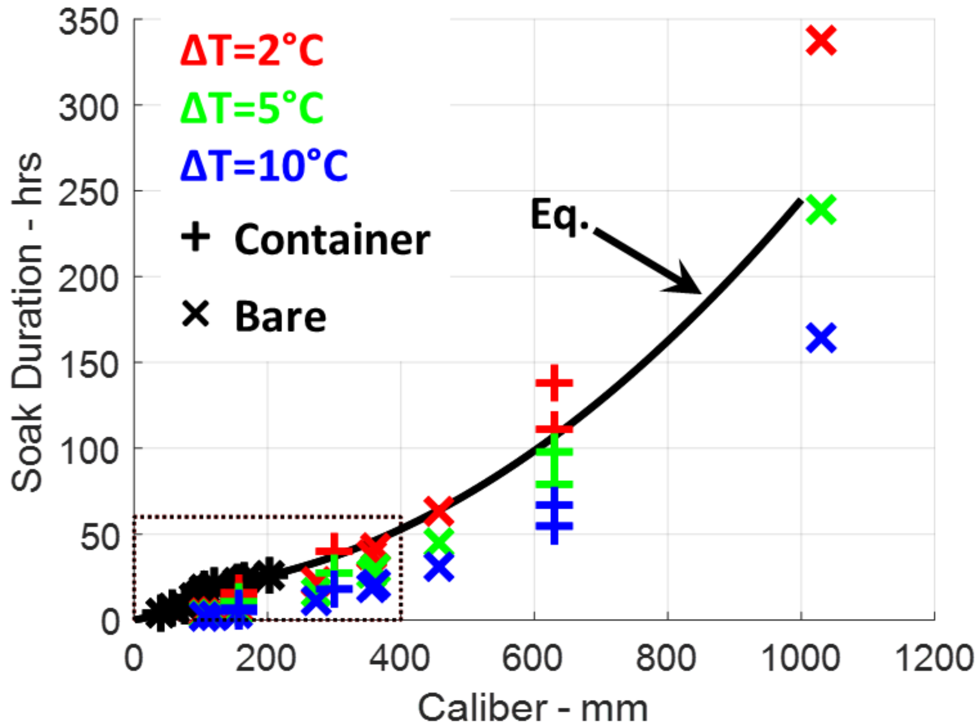

Figure 9. Heat soak duration required to reach 2ºC, 5ºC and 10ºC centreline temperature differentials for a variety of munitions.

4 UPDATED STANAG 4382 HEAT SOAK GUIDANCE

Reviewing Figure 5 and Figure 8, both the analytic calculations and the finite difference calculations show that STANAG 4224 heat soak guidance appears to be extremely conservative for smaller diameter munitions. This is particularly true for the 45ºC centerline temperature. For this reason, it was decided to develop a new guidance that would remain conservative, but less conservative for small munitions than the STANAG 4224 guidance. Additionally, it was decided that a single simple formula would be preferential, instead of having multiple formulas and a table.

Based on the analytic and finite difference calculations, it was decided to create a heat soak duration formula based around the idea that it should provide a conservative heat soak time based on a 45ºC centerline temperature. The resulting preconditioning formula that has been incorporated into the new AOP-4382 is presented in Figure 10. The figure compares the heat soak duration as a function of munition caliber to the STANG 4224 guidance, the 45ºC centerline analytic results, and the finite difference results for 45ºC and 40ºC centerline temperatures. From the figure, it is clear that the 45ºC analytic and finite difference centerline temperature soak durations agree very well. This provides confidence in the thermal calculations and the new AOP-4382 preconditioning formula.

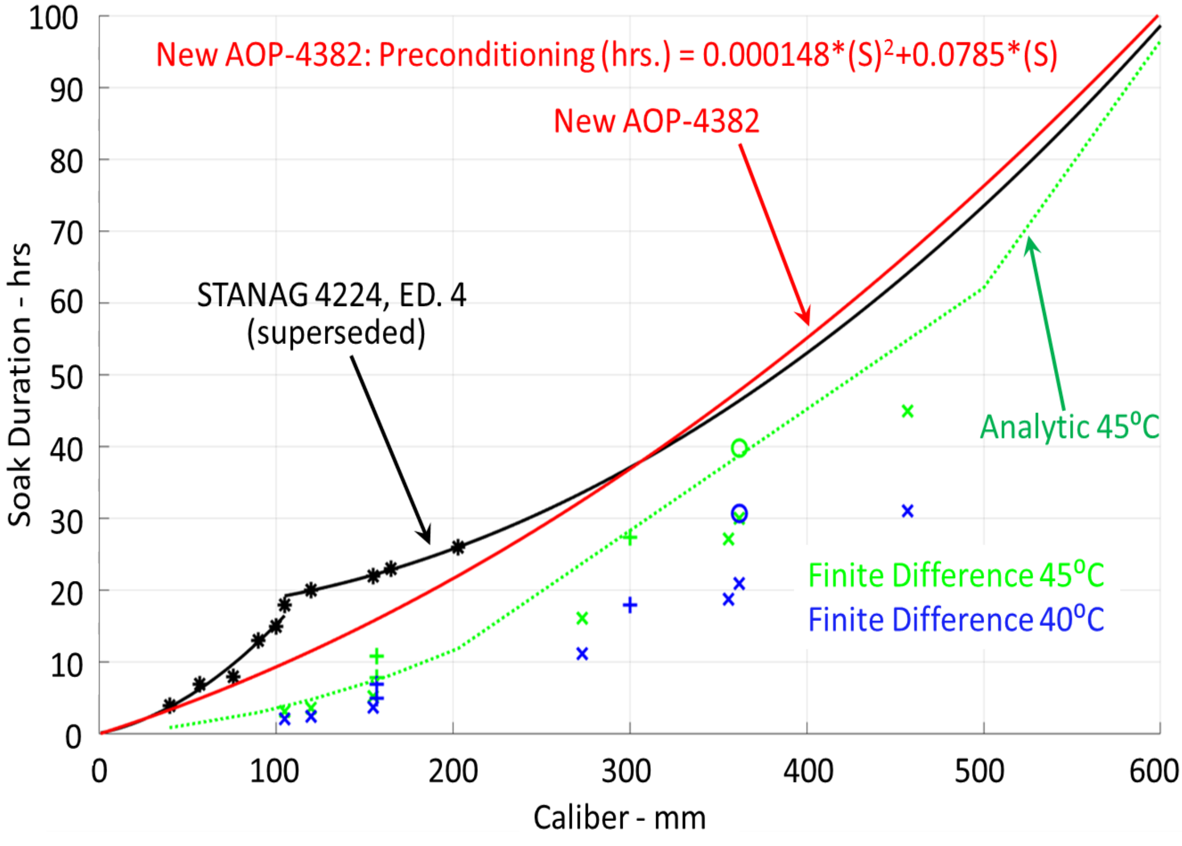

Figure 10. Comparison of the new AOP-4382 preconditioning formula,

As a result of this work, AOP-4382 has been updated. The new AOP-4382 guidance for preconditioning now reads as:

> Precondition the test item in the oven at 50°C (± 3°C) until the test item has reached thermal equilibrium. Annex A provides three methods to determine when a test item is considered to have reached equilibrium: direct measurement, modeling or a calculation based on size. The preconditioning period is not required to exceed 24 hours but can be extended if desired.

The new AOP-4382 preconditioning soak time guidance for calculation based on size is:

> The calculation Preconditioning period (hrs.) = $0.000148*(S)^2+0.0785*(S)$
> • For cylindrical test items, the dimension S (mm) is the diameter.
> • For rectangular prism-shaped test items, e.g., a typical munition or multiple munitions packaged in a typical cuboid-shaped container, the dimension S (mm) is the length of the diagonal between the two shortest sides.

5 MAXIMUM REACTION TEMPERATURE

Using the MSIAC AIMS tool, MSIAC conducted a review of maximum experimental reaction temperatures to help provide guidance for maximum testing temperature. There are 29 first reaction temperatures listed for Slow Cook-Off (SCO) testing results. These temperatures are between 120ºC and 260ºC. Table 4 presents a listing of the highest 25 first reaction temperature results from the review. The result of the review is that the highest known reaction temperature is 260ºC at a heating rate of 27.8°C/hr with the PAC-3 analog rocket motor which contained an HTPB/Al based propellant. The vast majority of munitions react at temperatures well below this value. As the reaction temperature is the oven temperature, it is not surprising that very large items with lower thermal kinetics energetics have higher reaction temperatures.

Table 4. Highest first temperature reaction SCO results from the AIMS database.

Munition	Item	Main Energetic Material	Ext. Dim. (mm)	Config.	Heating Rate (°C/hr)	Reaction Temp. (°C)
PAC-3 Missile - Analog Rocket Motor	Rocket Motor	HTPB/Al Propellant	280	Pack.	27.8	260
PAC-3 Missile - Analog Rocket Motor	Rocket Motor	HTPB/Al Propellant	280	Pack.	27.8	260
PAC-3 Missile - Analog Rocket Motor	Rocket Motor	HTPE/Al Propellant	280	Pack.	27.8	237
2.75 " Rocket - Mk146 Mod 0 Warhead	Warhead	PBXN-110	70	Pack.	22.2	223
105 mm PGU 44/B HE Shell	Warhead	PBXN-109	105	Pack.		218
105 mm M915 DPICM Shell	Warhead	PAX-2A	105	Pack.	27.8	215
Apache Missile	Rocket Motor	HTPB/Al Propellant		Bare	3.3	196
5" HE Shell	Warhead	ARX-4024	127	Bare	3.3	195
ASRAAM Missile	Warhead	PBXP-31		Bare	3.3	195
MU90 Torpedo	Warhead	V-350	324	Bare	3.3	195
105 mm M915 DPICM Shell	Warhead	Comp A-5	105	Pack.	27.8	194
155 mm LU211-M Shell - GEMO 3L GTU	Warhead	XF-13333	143	Bare	3.3	193
60 mm MAPAM Mortar	Warhead	PBXN-110	60	Bare	3.3	189
TOW 2 Bunker Buster Missile	Warhead	PBXN-109	141	Pack.	17.7	188
120 mm IM HE-T	Warhead	OSX-8	120	Pack.	3.3	187
120 mm IM HE-T	Warhead	OSX-8	120	Pack.	3.3	186
155 mm DM 84 Fuze	Fuze	RDX/TNT		Pack.	3.3	180
SMAW-HEDP Rocket	Warhead	PBXIH-18	83	Bare		180
Precision Guided Bomb - PGB	Warhead	PBXN-109 (RS-RDX)		Bare	3.3	177
60 mm MAPAM Mortar	Warhead	Comp B	60	Bare	3.44	176
60 mm MAPAM Mortar	Warhead	Comp B	60	Bare	3.38	175
Penguin Missile	Warhead	DESTEX		Bare	3.3	175
Mk82 Bomb IM-B	Warhead	B-2268 B	273	Bare	3.3	174
JASSM Missile - WDU-042/B Warhead	Warhead	AFX-757	318	Pack.	3.3	173
Penguin Missile	Warhead	PBXN-109		Bare	3.3	172

CONCLUSIONS

STANAG 4382 Slow Heating, Munitions Test Procedures has been reviewed and updated by the AC/326 SG/B SH CWG. MSIAC completed analytic thermal equilibrium calculations and NSWCDD completed finite difference thermal equilibrium calculations in order to help provide guidance for appropriate soak times. NSWCDD provided guidance as to appropriate heat transfer coefficients that were obtained from experiments conducted using steel cylinders in the standard oven design used at the NSWCDD. The analytic and finite difference calculations were in good agreement, providing significant confidence in both sets of calculations.

A 50ºC heat soak duration formula was developed based around the idea that it should provide a conservative heat soak time based on a 45ºC centerline temperature. The resulting preconditioning formula has been incorporated into the new AOP-4382. Finally, MSIAC addressed the issue of maximum testing temperature by conducting a review of maximum experimental reaction temperatures using the MSIAC AIMS database. The review of 29 slow heating test results, which included reaction temperature, indicated that the highest known reaction temperature occurred with the PAC-3 rocket motor. First reaction was at 260°C at 27.8°C/hr. As the reaction temperature is the oven temperature, it is not surprising that very large items with lower thermal kinetics energetics have higher reaction temperatures. STANAG 4382 ED. 3 and AOP-4382 ED. A. V. 1 are currently being ratified by the NATO AC/326. Promulgation of these documents is anticipated in the very near future.

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