ABSTRACT

Title of Document: IGNITION TESTING OF U.S. ARMY ROCKET LAUNCH TUBES WITH COMPARATIVE HEAT TRANSFER ANALYSIS

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The objective of this research was to determine the time to ignition of U.S. Army fiberglass epoxy rocket tubes in various conditions. Experiments were conducted using an oxygen calorimeter and a propane burner for determining the ignition time. The Biot number and heat transfer coefficient was determined. A lumped capacitance method was used to calculate the energy input.

The energy input from the rocket plume into the tube was calculated using a semi-infinite solid with surface convection.

The two energy calculations were compared indicating that approximately 1.4 rockets must be fired in rapid succession to lead to ignition conditions. Tube condition was found to have no affect on ignition time.

IGNITION TESTING OF U.S. ARMY ROCKET LAUNCH TUBES WITH COMPARATIVE HEAT TRANSFER ANALYSIS

By

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Nomenclature

A	Area	(m^2)
Bi	Biot Number	
h_c	Convective heat transfer coefficient	($W/m^2\ K$)
ρ	Density	($kg/\ m^3$)
D	Diameter	(m)
θ^*	Dimensionless temperature difference	
x	Distance	(m)
ε_t	Emissivity (Tube)	
ε	Emissivity	
ε_{CO2}	Emissivity (Carbon dioxide)	
ε_f	Emissivity (Flame)	
ε_g	Emissivity (Gas)	
ε_s	Emissivity (Soot)	
ε_{H2O}	Emissivity (Water)	
E_g	Energy generated	(J)
E_{in}	Energy In	(J)
Q	Energy input	(J/m^2)
E_{out}	Energy out	(J)
E_{st}	Energy stored	(J)
q"	Heat flux	(W/m^2)
d	Material thickness	(m)
Nu_D	Nusselt Number	
S	Pathlength	(m)
Pr	Prandtl Number	
h_r	Radiative heat transfer coefficient	($W/m^2\ K$)
κ_s	Radiative property of soot	(m^{-1})
Re_D	Reynolds Number	
c	Specific heat	(J/kg K)
σ	Stefan-Boltzmann constant	($W/m^2\ K^4$)
T	Temperature	(K)
T_a	Temperature (Ambient)	(K)
T_f	Temperature (Flame)	(K)
T_∞	Temperature (Fluid)	(K)
T_{ig}	Temperature (Ignition)	(K)
T_i	Temperature (Initial)	(K)
T_s	Temperature (Surface)	(K)
θ	Temperature difference	(K)
k	Thermal conductivity	(W/m K)
α	Thermal diffusivity	(m^2/s)
δ_T	Thermal thickness	(m)
L	Thickness (tube)	(m)

t	Time	(s)
t_{chem}	Time for flammable mixture to reach thermal runaway	(s)
t_{py}	Time for fuel to begin to pyrolysis	(s)
t_{mix}	Time for pyrolysis products to mix	(s)
t_{ig}	Time to piloted ignition	(s)
h	Total heat transfer coefficient	(W/m^2 K)
u	Velocity	(m/s)
M	Viscosity	(kg/s m)
V	Volume	(m^3)

Chapter 1: Introduction

1.1 Overview

This report addresses ignition of U.S. Army rocket tubes which house the rocket for storage, transportation and firing. HIMARS, M270 and M270A1 launchers comprise the Multiple Launch Rocket System (MLRS) of the United States Army. The launchers have been used by the United States Army for many years both in battle and in training. Available data to date indicate over 80,000 rockets have been fired. [1] Thirteen tube fires have been reported occurring within the 80,000 launches. [2] Each rocket tube houses one rocket and is clustered into pods of six rockets. The plume of a single rocket is sufficient in size to completely engulf the other five tubes.

The occurrence of a tube fire subsequent to MLRS rocket firings, while infrequent, has a possibility of severe consequences affecting troop safety. The fires have on occasion resulted in extensive damage to launchers and launch equipment. [2] These occurrences demonstrate the need to modify the procedures and training in the event of a rocket tube fire.

The Department of Fire Protection Engineering at the University of Maryland is providing assistance to the Precision Fires Rocket and Missile Systems Project Office to investigate tube fires on the Multiple Launch Rocket System launchers. The feasibility of several automatic detection devices is reviewed. Analysis of the ignition and sustained combustion of the tubes is performed. Evaluation and testing of extinguishing agents on tube fires is conducted and preliminary MLRS tube fire training suggestions are made.

This report is focused solely on research into the ignition of the rocket tubes. A series of tests on MLRS tube sections are conducted to determine the time to achieve tube ignition of empty MLRS rocket tube sections under various conditions. An attempt to quantify the number of rockets that must be fired in rapid succession to lead to tube ignition conditions is conducted based on experimentation and analysis. The experiments include using an oxygen calorimeter apparatus for testing small samples and a 44 kW propane burner for testing 0.6 m tube sections to determine the time to ignition.

1.2 Objective

The objective of this report is to provide information concerning the conditions surrounding ignition of empty MLRS tubes. Engineering analysis is conducted to determine the average temperature of the rocket plume and the amount of time the plume impinges on the tube. The rocket plume data is used to obtain an estimate of the amount of energy that the rocket plume imparts to the tube. The experiments provide the time to ignition for various tube conditions.

The cone calorimeter experiment is used to determine the time to ignition of tube samples when exposed to a predetermined, well-controlled incident radiant heat flux. The apparatus is also used to search for variances in time to ignition for tubes of various conditions. The two tube conditions to be tested with the cone apparatus are an un-fired tube and a fired tube. An un-fired tube is a tube which has not had a rocket fired from it. A fired tube is a tube which has had a rocket fired from it.

The propane burner experiments provide an alternative heating condition to replicate the repeated heat exposure from a series of rockets being launched in rapid succession. The heat exposure from the burner is compared to that from the rocket plume through in a heat transfer analysis using the exit gas temperature and external tube wall temperature, discussed later in this report. The lumped heat transfer model is verified with the experimental data. A result of this analysis is to determine an approximate amount of energy the propane burner (or rocket plume) imparts to the tube. An estimate of how many rockets must be fired in rapid succession can be identified which will generate a level of energy equal to the ignition energy of the tubes.

In addition, the propane burner experiments are performed to compare the time to ignition for tubes of various conditions. The conditions investigated include undamaged tubes, punctures of the wall and abrasion of the interior surface.

All of the experiments are devised to achieve the goal of obtaining ignition time data using a relatively repeatable test procedure. The experiments use small samples of the full length tubes which affects the length over diameter ratio used in the heat transfer calculations. The size of the facilities and test apparatus prohibit full size tube tests. The experiments are also further limited to relatively readily available heat sources, rocket motors are not used to test the tubes for ignition. The rocket plume creates different heating of the tube as compared to the propane burner. The rocket plume subjects the tube to extremely high temperatures over a short period of time, while the propane burner heats the tube at lower temperatures over a longer period of time.

1.3 Background

1.3.1 MLRS Overview

Three vehicular platforms are included in the U.S. Army's multiple launch rocket system (MLRS). The current production model is the High Mobility Artillery Rocket System (HIMARS) launcher. The older M270 and M270-A1 both remain in service. Pictures and the main characteristics of the three launchers are listed below; see Figure 1, Figure 2, and Table 1.

Figure 1: HIMARS [1]

Figure 2: M270-A1 [1]

Table 1: Information on the individual MLRS launchers [1, 3, and 4]

Vehicle	HIMARS	M270A1	M270
Platform	FMTV truck	Full track (Self-propelled)	Full track (Self-propelled)
Crew	3 Man/Man rated cab	3 Man/Man rated cab	3 Man/Man rated cab
Payload	1 Rocket/Missile pod	2 Rocket/Missile pods	2 Rocket/Missile pods
Munitions	Entire MLRS/ATACMS family	MLRS/ATACMS family	Selected MLRS family
Munitions Range	15-70 plus km	15-70 plus km	15-70 km
Fire Control	On board fire control, Pos-Nav/Reload systems	M270 improved diagnostics w/ greater memory & speed	On-board fire control system (Digital)
Time Between Launches	7-9 seconds	5 seconds	5 seconds
Range	300 plus miles	N/A	N/A

The MLRS platform is versatile and capable of firing a wide range of munitions. The most common munitions used are the M26 series of unguided tactical rockets. [1] The full range of munitions include the M26, M26A2, M28 and, M28A1/A2 rockets and the ATACMS BLK I missiles. The HIMARS and M270A1 are also capable of firing the M30 GMLRS, ATACMS BKL 1A, ATACMS BLK 1A QR Unitary and ATACMS BLKII missiles. [4] The MLRS's main targets are personnel sites, counter battery, and enemy air defense. The maximum range of the M26 series is 32 km. [4]

The rocket pods themselves contain 6 tubes, each approximately 4 meters long and 0.3 meters in diameter. The tubes are in two rows of three. The pod structure is slightly longer than the tubes, approximately 4.2 m long, 1 m wide, and 0.8m tall with skids, see Figure 3. [5]

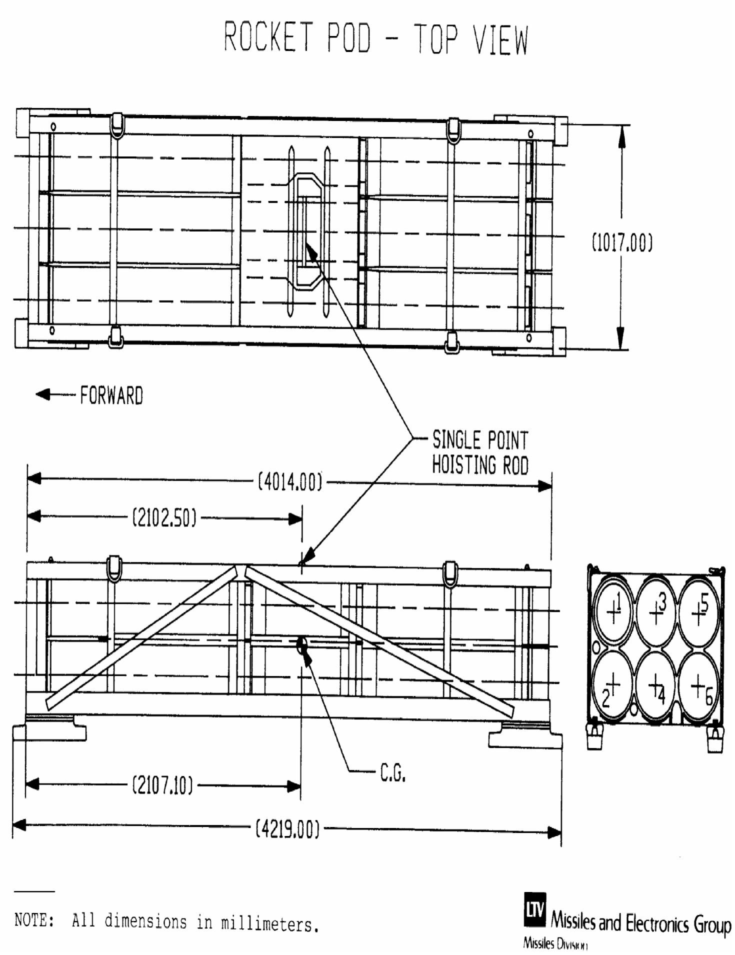

Figure 3: Diagram of M26 Rocket Pod [5]

The tubes themselves are made from fiber glass and epoxy. The interior of the tube contains four spin rails, rifling, that begin at the rear end of the tube and are 1.8 m long. [5] The tube is constructed using hoop and helical layers of fiber glass and epoxy, see Figure 4 [6]

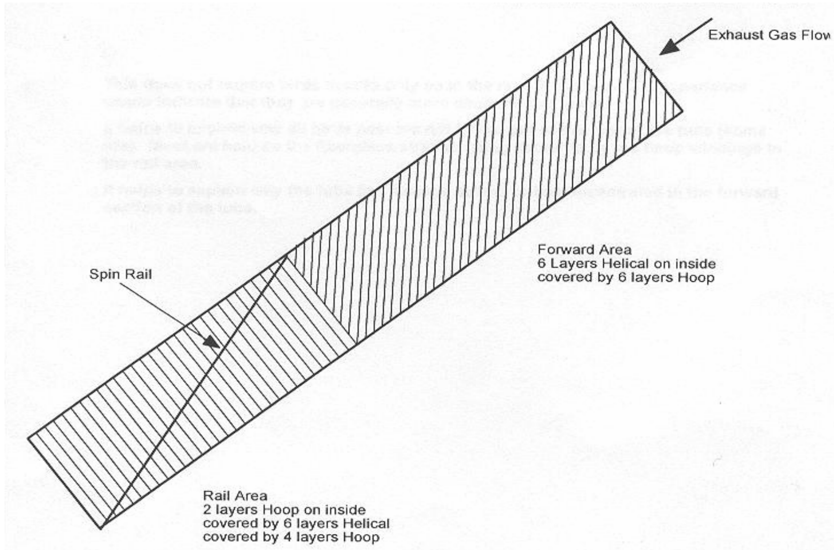

Figure 4: Rocket tube construction diagram, courtesy of Bobby Richardson.

The interior of the tube is coated with an additional coat of special epoxy called a gel coat. [1] The exterior of the pods are painted with a metallic (non-lead) based paint to match camouflage schemes and serve as an additional protective layer against the elements. [1]

The HIMARS carries one pod while the M270 and M270A1 carry two pods. A typical sequence of events begins with a full pod of rockets on a launcher. All the rockets are fired from the tubes. The empty pod is then unloaded and a new loaded pod is placed on the launcher. The empty pods and tubes are not reused. [1]

Tube damage is of concern and is considered to be a possible factor in ignition of tubes. It is possible that the tubes are damaged during transport, storage, or launch. The common damage scenarios suggested by the sponsor are forklift punctures caused by the tines during improper pod handling. The potential for dropping pods in a manner that results in a puncture is also considered. Another source of possible damage is interior abrasion caused by the fins of the rocket scoring the inside of the tube during loading or firing of the rocket. The tubes burn as a thermoset, do not melt, where the epoxy burns as a type A combustible and the fiber glass winding remains.

The thirteen reported tube fire cases are summarized in Table 2. [2] However, during the research study, several anecdotes were related of additional, unreported minor scale tube fires. [1] Since 1982, an average of one reported tube fire occurs every two years. Although reported tube fires are not a common event, the consequences are considered to be severe enough to research.

Table 2: MLRS tube fire history

Date	Location	Conditions	Results
Fall 1982	Ft. Bliss	NA	Additions: Two cab mirrors, fire extinguishers, additional epoxy coat to tube, modified crew training
6-Jul-89	Ft. Riley	Forklift damage	NA
8-Aug-91	Ft. Sill	Damage to tube 3	Fire truck was needed for extinguishment
7-Dec-92	Ft. Sill	NA	Extensive damage to tube
14-Dec-95	NA	NA	NA
1998	Ft. Bragg	Forklift damage *	NA
22-Aug-01	Ft. Sill	NA	Minimal tube damage
19-Feb-03	Italy	Dropped pod	Some damage to LLM
Spring 2003	Iraq	High winds	Extinguisher ineffective, Launcher destroyed
31-Jul-03	Ft. Sill	NA	Pod destroyed
22-Jun-05	Ft. Chaffe	NA	Pod destroyed, Launcher damaged
17-Aug-05	Ft. Hood	NA	Launcher destroyed
Spring 2006	Iraq	NA	NA

* [7]

The density of the supplied sections is measured using small test samples cut from selected tube sections. The test samples are weighed using a scale. The volume is determined using water displacement in a graduated cylinder. The average density of the tube is found to be 1875 kg/m^3 with a standard deviation of approximately 65 kg/m^3.

The specific heat and thermal conductivity of the tubes are approximated using as a guide rigid fiber glass values. A more accurate way to determine the material properties of the tube is to use the rule of mixtures. The rule of mixtures in the case of specific heat of the rocket tube is $c_{p_{mix}} = c_{p_{glass}} \times \%_{glass} + c_{p_{epoxy}} \times \%_{epoxy}$. In the case of the rocket tube limited data is provided regarding the composition of the tube and the epoxy. The limited data prohibits using the rule of mixtures to determine material properties. The variable analysis is used to account for the uncertainty in the tube material properties.

1.3.2 Overview of Ignition of Solids

The focus of the ignition testing conducted in this research is time to ignition. The time to ignition of the solid is used to determine the amount of energy put into the tube at ignition.

The time to ignition of materials is used to better understand the time-line of events in a fire. [8] It is possible that piloted ignition of solids under surface heating conditions demonstrate the phenomena of 'flash point' and 'fire point.' [9] Flash point is considered the minimum condition where pyrolysis products close to the surface reach the lower flammability limit. [9] The lower flammability limit corresponds to the minimum fuel concentration for ignition to occur. [8] The fire point is where conditions near the surface are approximately at the stoichiometric mixture. [9] Researchers use tests to associate the flash point and fire point to rates of pyrolysis and mass fluxes. [9]

The classical analysis for piloted ignition does not have the flames actually touching the surface. The rocket plume and propane burner experiments have flames impinging on the surface. When there is direct flame impingement, the flame is a source of energy and ignition. [9] It is difficult to analyze the heat flux imposed by the flame and the magnitude of the convective component based on first principles. [9] The classical interpretation of piloted ignition is considered for this discussion of solid ignition as well as the analysis of the data.

The total time to piloted ignition in solids is described in three steps.

$$t_{ig} = t_{py} + t_{mix} + t_{chem} \tag{1}$$

The first step involves raising a solid's temperature by heating to produce pyrolysis products, containing gaseous fuel. [8] Step two consists of the transportation of the fuel vapor through the fluid boundary layer. [8] The transportation allows for the evolved fuel vapor to mix with air. The third step includes the time from the flammable mixture reaching the pilot to the point where the chemical reaction reaches 'thermal runaway.' [8] The dominating step is usually the time to pyrolysis. [8]

The time to pyrolysis is a problem of heat conduction into the solid and is dominated by the thermal inertia of the solid, kρc. [8] The larger a solid's thermal inertia the more difficult it is to raise its temperature. [8]

The two types of heating conditions discussed in the literature are continuous and discontinuous heat flux. [9] Continuous heat flux conditions are discussed in this review. The continuous heat flux condition characterizes the fire point as the minimum surface temperature that produces sufficient volatiles to allow for a flame to be maintained at the surface. [9] When the heat flux is continuous, a number of factors may be identified as contributing to the solid reaching the fire point, including the chemical reaction at and below the surface, the transport of volatiles through the surface and the heat transfer to the surface. [9] To simplify the ignition problem a solid is considered inert, where only the heat transfer to a surface through one dimensional heat conduction is considered. [9] Various initial and boundary conditions are used to change the configuration of the solid ignition condition.

Solids may be considered thermally thin or thermally thick. A thermally thin solid has approximately no internal temperature gradient. [8] The thermally thin criteria is represented by a material of thickness 'd' insulated on one side or of thickness '2d' and heated on both sides. [8] The thermally thin solid has a thickness that is less than the thermal penetration depth as indicated in equation (2). [8]

$$d << \delta_T \approx \sqrt{\alpha t} \approx \frac{k(T_s - T_i)}{\dot{q}''} \tag{2}$$

The boundary conditions for a thermally thin solid are for the surface and the center or insulated face of the solid. [8]

$$\dot{q}'' = \left(-k\frac{\partial T}{\partial x}\right)_{x_s} \qquad \text{(Surface)} \tag{3}$$

$$\left(\frac{\partial T}{\partial x}\right)_{x_i} = 0 \qquad \text{(Center or insulated face)} \tag{4}$$

The thermally thick theory is further explained using a semi-infinite solid model where the conditions on the back surface of the solid have a negligible effect on the solution. [8] The semi-infinite solid case results in ignition before the thermal penetration depth reaches the back surface of the solid. The criteria for a semi-infinite solid is estimated by [8]

$$d \geq \delta_T \approx \sqrt{\alpha t_{ig}} \quad \textbf{(5)}$$

The boundary conditions for a thermally thick solid are for the surface and the back face of the solid. [8]

$$x = 0,\ T = T_s,\ \text{constant} \quad \textbf{(6)}$$

$$x \rightarrow \infty,\ T = T_a \quad (7)$$

At time equal to zero the temperature throughout the solid is at ambient conditions. [8]

Solid ignition focuses on the time to ignition of a solid when it is exposed to a well characterized heat flux. Using a well characterized heat flux and time to ignition the critical heat flux to ignite a solid may be identified. The critical heat flux is the lowest heat flux where the temperature just reaches T_{ig} after an infinitely long exposure duration. Below this critical heat flux, no ignition is possible through the conduction model. [8] The equation for the critical heat flux is represented by [8]

$$\dot{q}''_{ig,crit} = h_c(T_{ig} - T_a) + \sigma\varepsilon(T_{ig}{}^4 - T_a{}^4) \quad \textbf{(8)}$$

The results of the experimental data for ignition are used to determine the minimum heat flux needed to cause ignition. The data is often plotted for the ignition time versus the incident radiative heat flux. That plot may show a critical heat flux as the asymptote of the curve. [8] It should be noted that the critical heat flux value is not necessarily a pure material property but also depends on the heat transfer boundary conditions associated with the test. [9]

The present study focuses on the experimental time to reach ignition of the tube material. The experimental data is used to determine if different tube conditions and tube damage affect the time to ignition. The time to ignition is also used to determine the amount of input energy into the tube that is needed to cause it to ignite. The objective is to approximate the number of rockets that must be fired in a rapid sequential burst to impart enough energy to lead to possible tube ignition. The theory behind the energy and heat input calculations are presented in the following section.

1.3.3 Biot Number

The Biot number is defined as a dimensionless parameter that provides a measurement of the solid's temperature gradient relative to the temperature difference between the same solid's surface and the fluid. [10] Mathematically the Biot number is represented as follows:

$$Bi = \frac{hL}{k} \tag{9}$$

The thermal conductivity in the Biot number equation is that of the solid.

The experimental Biot number is determined from a series of temperature measurements taken from the experiments. The temperature measurements are made dimensionless and plotted versus time where the best fit curve represents the Biot number. The results of the experiments are shown in later sections. Determining the Biot number enables the calculation of the propane burner heat transfer coefficient.

A Biot number less than 0.1 also allows for the lumped capacitance method to be used when determining the energy input to the tube from the propane burner.

1.3.4 Dimensionless Temperature

The dimensionless temperature must also be defined in order to calculate the Biot number. The dimensionless temperature that is used in this thesis corresponds to a maximum dimensionless temperature associated with the burner flame temperature, the initial temperature and the temperature of the exterior tube surface. The technique used to measure the temperature and location of the measurements is described below. The equation for the dimensionless temperature is: [10]

$$\theta^* = \frac{T_\infty - T}{T_\infty - T_i} \tag{10}$$

1.3.5 Lumped Capacitance Method

The use of the lumped capacitance method is allowed when the Biot number is less than 0.1. The lumped capacitance method is used to determine the net energy input from the propane burner to the tube at the time tube ignition, 't', occurs.

$$Q = \rho c L (T_\infty - T_i)\left[(1 - \exp\left(\frac{-ht}{\rho c L}\right)\right] \tag{11}$$

The lumped capacitance method begins with the energy rate equation. [10]

$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st} \tag{12}$$

Simplifying the energy rate equation by eliminating the generation term and assuming the system is adiabatic the equation takes the form of

$$\dot{E}_{in} = \dot{E}_{st} \tag{13}$$

Substituting terms the equation becomes [10]

$$Ah(T_\infty - T) = V\rho c \frac{dT}{dt} \tag{14}$$

Introducing a temperature difference

$$\theta = T_\infty - T \tag{15}$$

It is recognized that $d\theta/dt = dT/dt$. Separating variables and integrating equation 14 using the following initial conditions is done.

Initial Condition: $t = 0$ and $T(0) = T_i$

The integral becomes [10]

$$\frac{hA}{\rho c V}\int_{\theta_i}^{\theta}\frac{d\theta}{\theta} = \int_0^t dt \tag{16}$$

The θ_i term is equivalent to T_∞-T.

Integrating equation 16 the solution yields the following equation. [10]

$$\theta^* = \frac{T_\infty - T}{T_\infty - T_i} = \exp\left(-\frac{ht}{\rho c L}\right) \tag{17}$$

The above equation may be used to determine the temperature a solid reaches at some point in time. The θ^* term is the same term described above with the discussion of the Biot number.

However, the energy put into the tube at some time is desired, not the temperature at that same point in time. To determine the total energy transfer to the solid occurring up to a point in time the integral must be taken. [10]

$$Q = \int_0^t q\,dt = hA\int_0^t \theta\,dt \tag{18}$$

Taking the integral for both sides, where 't' in the case of this thesis is equal to the time to ignition, yields the following equation. [10]

$$Q = \rho c L (T_\infty - T_i)\left[(1 - \exp\left(\frac{-ht}{\rho c L} \right) \right] \quad \textbf{(19)}$$

Equation 19 represents the total energy transfer to the tube from the propane burner up to a certain time. The time frame this thesis is concerned with is how much energy is put into the tube from the start of the test until ignition occurs. It is noted that the thermal conductivity term is not present in the lumped heat capacitance method.

1.3.6 Heat Transfer Coefficient

The heat transfer coefficient of the propane burner must also be calculated. A similar method is used in the calculation of the rocket plume heat transfer coefficient shown later in Chapter 2. The major difference is that the emissivity of the propane flame from the burner may more accurately be calculated using previously published methods.

The heat transfer coefficient calculated using the below method is separate from the heat transfer coefficient calculated from the Biot number determined experimentally.

1.3.6.1 Total Heat Transfer Coefficient

The heat transfer coefficients for the propane burner flame are calculated. Approximate solutions for the convective and radiative heat transfer coefficients are used to form a total heat transfer coefficient. The total heat transfer coefficient is used to calculate energy input into the tubes from the rocket plume discussed in Chapter 2 and the propane burner discussed in Chapter 4. The total heat transfer coefficient is represented by equation 20.

$$h = h_c + h_r \quad \textbf{(20)}$$

1.3.6.2 Convective Heat Transfer Coefficient

The convective heat transfer coefficient is calculated using convective correlations of turbulent flows in circular tubes. [10]

$$h_c = Nu_D \left(\frac{k}{D} \right) \quad \textbf{(21)}$$

The commonly referred Dittus-Boelter equation is used to calculate the Nusselt number. [10]

$$Nu_D = 0.023\, Re_D^{\;4/5}\, Pr^n \quad \textbf{(22)}$$

The value ‘n’ corresponds to the heating condition within the fluid. For the case of a hot fluid and cold tube ‘n’ is 0.3 for cooling. ($T_s < T_\infty$). [10]

The Reynolds number is used as a check to ensure the flow of the propane burner flame is turbulent and should be greater than 10,000. The Reynolds’s number is defined as [10]

$$Re = \frac{\rho u D}{\mu} \quad \textbf{(23)}$$

1.3.6.3 Radiative Heat Transfer Coefficient

The radiative heat transfer coefficient is also calculated. The high temperatures involved with the rocket plume necessitate that radiation be included in the calculations. For consistency the radiative term is included with the propane burner calculations. The net radiation heat transfer coefficient is calculated using the following formula. [10]

$$h_r = \frac{\sigma T_f^{\;3}}{\frac{1-\varepsilon_f}{\varepsilon_f} + 1 + \frac{1-\varepsilon_t}{\varepsilon_t}} \quad \textbf{(24)}$$

The emissivity of the flame fluid, ε_f, must first be calculated. The pressure of the fuel and the type of fuel is needed to determine the emissivity of the flame fluid.

The emissivity of the fluid with soot present is defined as [11]

$$\varepsilon_f = \varepsilon_g + \varepsilon_s - \varepsilon_g \varepsilon_s \qquad \textbf{(25)}$$

The emissivity of the soot is determined from equation (26) [8] The radiative property of soot particles is determined from the type of fuel. [12].

$$\varepsilon_s = 1 - \exp(-\kappa_s S) \qquad \textbf{(26)}$$

The emissivity of the gas in the case of a well defined fuel is determined using the following equation and assuming stoichiometric burning for the fuel in air where the only products are carbon dioxide, water and nitrogen gas. [11]

$$\varepsilon_g = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \varepsilon_{CO_2}\varepsilon_{H_2O} \qquad \textbf{(27)}$$

The partial pressures are required to determine the emissivity of each gas from plots in published material. [12] The physical pathlength, 'S', or diameter of the fluid, is also needed. Dalton's law of partial pressure is used to determine the partial pressure of the water and carbon dioxide that are needed. [8]

$$P = \sum_{i=1}^{N} P_i \qquad \textbf{(28)}$$

The above equation is simplified for the specific case of interest to become

$$P_i = P\left(\frac{n_i}{n}\right) \qquad \textbf{(29)}$$

The temperature of the fluid, i.e. the propane flame, is also required to complete the calculations. The temperature of the fluid is determined by averaging the measured front propane flame temperature values over all the tests.

The tube is estimated to have near black body emissivity of 0.9. A variance analysis is conducted for both the rocket plume and propane burner variables to account for the uncertainties in developing the emissivities that lead to the radiative heat transfer coefficient.

Chapter 2: Rocket Plume Analysis

2.1 Introduction

The MLRS rocket plume exposes the tubes to extremely high temperatures over a short period of time. The MLRS rocket uses a solid propellant as fuel. The limited amount of information about the MLRS rocket plume is provided by the United States Army. The temperature versus time plot of the rocket plume is analyzed to determine an approximate average temperature for the rocket plume exposure. The amount of energy the rocket plume imparts to the tube is determined in order to design an experiment which provides a similar energy level (the experiment is described in Chapter 4). The energy from the rocket plume is calculated using a simplified version of the heat equation for a semi-infinite solid with constant surface convection. The derivative of the temperature distribution through the solid is calculated after applying Fourier's law to obtain the heat flux from the rocket plume to the tube. The integral of the heat flux over the exposure time is then calculated to determine the energy imparted to the tube from the rocket plume. The rocket plume energy supplied to the tube is finally compared to the experimental results discussed later in this report. This comparison will be used to approximate how many rockets must be fired in rapid succession to lead to possible tube ignition.

2.2 Semi-Infinite Solid Calculation

2.2.1 Governing Equation

The semi-infinite solid assumption for a transient condition is used to determine the energy input from the rocket plume into the tube. The solution to the semi-infinite solid with constant surface convection begins with the simplified version of governing equation for heat conduction. Rectangular coordinates are used for a simplified analysis assuming that only one spatial coordinate (thickness) is needed to represent the solid's internal temperature distribution. The simplified equation presented as equation (30) also assumes no internal generation which is consistent with the physical reality of the rocket tube problem. [10]

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{30}$$

The initial condition represents the uniform temperature distribution prior to the exposure. [10]

$$T(x,0) = T_i \tag{31}$$

2.2.2 Boundary Conditions

The exterior boundary condition applies regardless of the heating condition: [10]

$$T(x \rightarrow \infty, t) = T_i \tag{32}$$

The interior boundary condition depends on which closed form of the heat equation is used. The closed form solution has three possible cases. The three cases are constant surface temperature, constant surface heat flux, and surface convection.

[10] The case selected to represent the rocket plume heat transfer to the tube is surface convection. [10]

$$-k\frac{\partial T}{\partial x}\bigg|_{x=0} = h[T_\infty - T(0,t)] \quad \textbf{(33)}$$

2.2.3 Diagram of Semi-Infinite Solid with Surface Convection

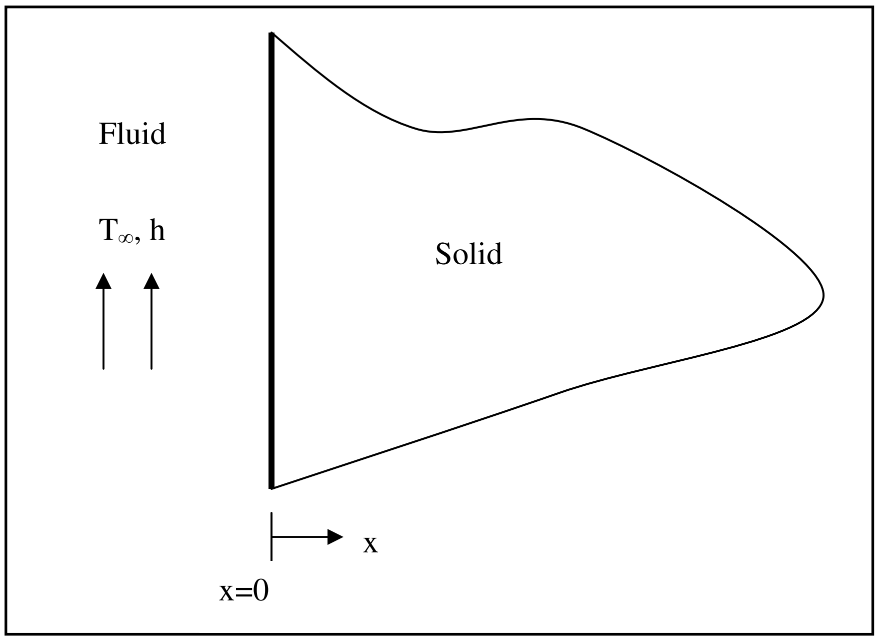

Figure 5: Diagram of semi-infinite solid with surface convection [10]

2.2.4 Solution: Energy Imparted by the Rocket Plume to the Tube

The solution for the amount of energy imparted to the tube by a single rocket plume is determined from the simplified heat equation. Fourier's law is applied to the temperature distribution of the heat equation to obtain the heat flux. The derivative of the heat flux is calculated to obtain the heat flux rate. The integral of the heat flux rate equation is calculated to solve for energy. The solution for the amount of energy imparted to the tube by the rocket plume is

$$Q=(T_{\infty}-T_i)\left(\frac{k\rho c}{h}\right)\left[\exp\left(\frac{h^2}{k\rho c}t\right)erfc\left(\sqrt{\frac{h^2}{k\rho c}t}\right)-1+\frac{2}{\sqrt{\pi}}\left[\sqrt{\frac{h^2}{k\rho c}t}\right]\right] \quad \textbf{(34)}$$

The steps that are used to calculate the energy from the rocket plume to the tube are presented in the following section.

2.2.5 Temperature Distribution

The temperature distribution through the solid may be expressed in the following manner. [10]

$$\frac{T(x,t)-T_i}{T_{\infty}-T_i}=erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)-exp\left(\frac{hx}{k}+\frac{h^2\alpha t}{k^2}\right)erfc\left(\frac{x}{2\sqrt{\alpha t}}+\frac{h\sqrt{\alpha t}}{k}\right) \quad \textbf{(35)}$$

2.2.6 Heat Flux for Semi-Infinite Solid

The heat flux is determined by applying Fourier's law at x=0 to the temperature distribution.

$$q''=-k\frac{dT}{dx}=-kdT\frac{d}{dx}\left[\begin{matrix}erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)\\ -exp\left(\frac{hx}{k}+\frac{h^2\alpha t}{k^2}\right)erfc\left(\frac{x}{2\sqrt{\alpha t}}+\frac{h\sqrt{\alpha t}}{k}\right)\end{matrix}\right] \quad \textbf{(36)}$$

The derivative of the above equation is calculated to obtain the heat flux rate for the semi-infinite solid with surface convection.

2.2.7 Complementary Error Function and Its Derivative

It must be noted that the complementary error function, erfc, is defined as [10]

$$erfc(\omega)=1-erf(\omega) \quad \textbf{(37)}$$

The derivative of the error function is [13]

$$\frac{d}{dz}erf(z) = \frac{2}{\sqrt{\pi}}e^{-z^2}dz \tag{38}$$

2.2.8 Derivation of the Heat Flux Rate Equation

The derivation of the heat flux rate equation begins with substituting the error function expression for the complementary error function.

$$q'' = -k\Delta T\frac{d}{dx}\left[\begin{matrix} 1 - erf\left(\frac{x}{2\sqrt{\alpha t}}\right) - exp\left(\frac{hx}{k} + \frac{h^2\alpha t}{k^2}\right) \\ + exp\left(\frac{hx}{k} + \frac{h^2\alpha t}{k^2}\right)erf\left(\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{k}\right)\end{matrix}\right] \tag{39}$$

Where Δ T is the difference between the fluid temperature and the initial temperature:

$$\Delta T = (T_\infty - T_i) \tag{40}$$

The derivative is taken and evaluated at the surface, x=0, to simplify the expression. The surface x=0 in the below equation physically represents the interior surface of the rocket tube.

$$q'' = -k\Delta T\left[\begin{matrix} -\frac{2}{\sqrt{\pi}}\frac{1}{2\sqrt{\alpha t}} - \frac{h}{k}exp\left(\frac{h^2\alpha t}{k^2}\right) + \frac{h}{k}exp\left(\frac{h^2\alpha t}{k^2}\right)erf\left(\frac{h\sqrt{\alpha t}}{k}\right) \\ + exp\left(\frac{h^2\alpha t}{k^2}\right)\frac{2}{\sqrt{\pi}}exp\left(-\frac{h^2\alpha t}{k^2}\right)\frac{1}{2\sqrt{\alpha t}}\end{matrix}\right] \tag{41}$$

Further simplification of the equation results in:

$$q'' = -k\Delta T\left[-\frac{1}{\sqrt{\pi}}\frac{1}{\sqrt{\alpha t}} - \frac{h}{k}exp\left(\frac{h^2\alpha t}{k^2}\right)\left[1 + erf\left(\frac{h\sqrt{\alpha t}}{k}\right)\right] + \frac{1}{\sqrt{\pi}}\frac{1}{\sqrt{\alpha t}}\right] \tag{42}$$

The error function is replaced with the complementary error function and terms are canceled.

$$\dot{q}'' = -k\Delta T\left[-\frac{h}{k}exp\left(\frac{h^2\alpha t}{k^2}\right)erfc\left(\frac{h\sqrt{\alpha t}}{k}\right)\right] \quad \textbf{(43)}$$

The equation is further simplified through distribution and arranged into the final form, providing a solution for the heat flux of a semi-infinite solid with surface convection.

$$\dot{q}'' = h(T_\infty - T_i)exp\left(\frac{h^2\alpha t}{k^2}\right)erfc\left(\frac{h\sqrt{\alpha t}}{k}\right) \quad \textbf{(44)}$$

The objective of the semi-infinite solid calculation remains to determine the energy input, 'Q.'

2.2.9 Energy of Semi-Infinite Solid with Surface Convection

To obtain the amount of energy the integral of the heat flux, equation 44, is determined. [10]

$$Q = \int_0^t \dot{q}''\,dt \quad \textbf{(45)}$$

For the specific problem discussed, the integral of the heat flux becomes:

$$Q = \int_0^t h(T_\infty - T_i)exp\left(\frac{h^2\alpha t}{k^2}\right)erfc\left(\frac{h\sqrt{\alpha t}}{k}\right)dt \quad \textbf{(46)}$$

The energy equation is simplified to assist in integration.

$$Q = h(T_\infty - T_i)\int_0^a e^{at}\,erfc(\sqrt{at})dt \quad \textbf{(47)}$$

Where 'a' is

$$a = \frac{h^2\alpha}{k^2} \quad \textbf{(48)}$$

The simplified integral is used to obtain the solution through more general means in published material. [14]

$$\int_0^x \exp(Bt)erfc(\sqrt{bt+C})dt = \frac{1}{B}\left[\exp(Bx)erfc(\sqrt{bx+C}) - erfc(\sqrt{C}) + \phi(x)\right] \tag{49}$$

Where

$$B = b = a \tag{50}$$

$$C = 0 \tag{51}$$

$$\phi(x) = \frac{2}{\sqrt{\pi}}\exp(-C)\left[\sqrt{bx+C} - \sqrt{C}\right] \quad for\_B = b \tag{52}$$

The solution to the particular problem addressed for the semi-infinite solid becomes the following by substitution.

$$Q = h(T_\infty - T_i)\left(\frac{k\rho c}{h^2}\right)\left[\exp\left(\frac{h^2}{k\rho c}t\right)erfc\left(\sqrt{\frac{h^2}{k\rho c}t}\right) - 1 + \frac{2}{\sqrt{\pi}}\left[\sqrt{\frac{h^2}{k\rho c}t}\right]\right] \tag{53}$$

Further simplification yields an equation for energy, 'Q,' for a semi-infinite solid with surface convection.

$$Q = (T_\infty - T_i)\left(\frac{k\rho c}{h}\right)\left[\exp\left(\frac{h^2}{k\rho c}t\right)erfc\left(\sqrt{\frac{h^2}{k\rho c}t}\right) - 1 + \frac{2}{\sqrt{\pi}}\left[\sqrt{\frac{h^2}{k\rho c}t}\right]\right] \tag{54}$$

Equation 54 is used to determine the amount of energy a single rocket plume imparts to the tube. The thermal conductivity term is that of the solid.

2.2.10 Heat Transfer Coefficient

2.2.10.1 Total Heat Transfer Coefficient

The heat transfer coefficients for the rocket plume are also calculated. Approximate solutions for the convective and radiative heat transfer coefficients are used to form a total heat transfer coefficient. The total heat transfer coefficient is used to calculate the energy input into the tubes from the rocket plume represented by equation 54. The high temperatures of the rocket plume demonstrate that radiative heating is the principal factor and must be included. The total heat transfer coefficient is represented in Chapter 1 by equation 20.

2.2.10.2 Convective Heat Transfer Coefficient

The convective heat transfer coefficient is calculated using correlations of turbulent flows in circular tubes, see section 1.3.6.2. [10]

2.2.10.3 Radiative Heat Transfer Coefficient

The radiative heat transfer coefficient is also calculated. The large temperatures involved with the rocket plume necessitate that radiation be included in the calculations. The net radiation heat transfer coefficient is calculated using equation 24 for Chapter 1.

However, the emissivity of the rocket plume is estimated instead of calculated as it is for the propane flame. The emissivity of the rocket plume is estimated to be 0.9. The rocket plume is at an extremely high temperature with elevated pressures, both of which increase the emissivity of the flame. Determining the emissivity of gases at high temperatures from first principles is difficult. The tube is estimated to have the same near black body emissivity of 0.9. A variance analysis is conducted below to account for the uncertainties in developing the emissivities that lead to the radiative heat transfer coefficient.

2.3 Rocket Plume Baseline Values

2.3.1 Temperature Calculation

The calculation of the rocket plume temperature is made possible by a graph provided by the U.S. Army that plots the rocket plume temperature versus time, see Figure 6. [10]

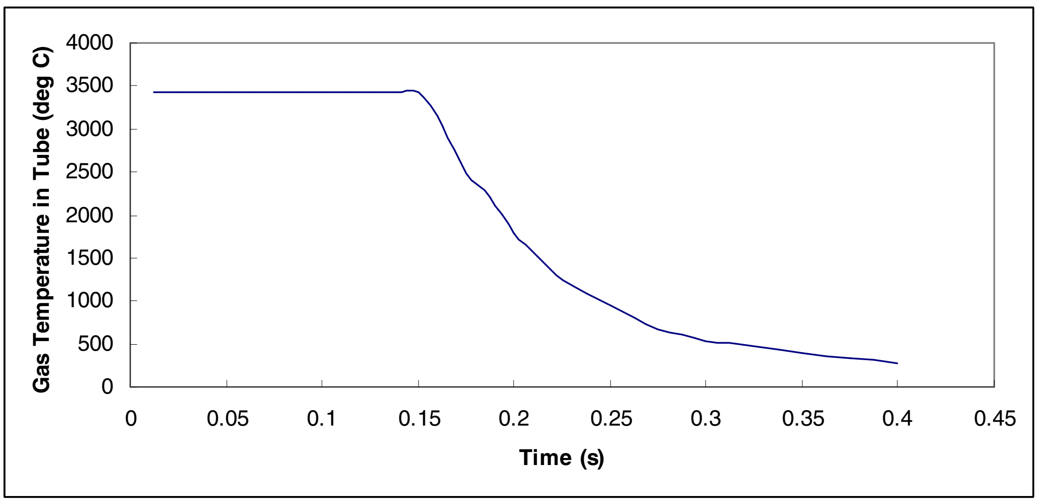

Figure 6: U.S. Army Supplied Rocket Plume Temperature v Time Plot.
Reproduced for clarity and consistency of units.

Due to the high temperatures of the rocket plume over a short period of time, the temperature of the plume at select points is first raised to the third power and then averaged. Temperature values of the plume are taken every 0.0125 s to recreate the plot in Figure 6. The temperature is raised to the third power before obtaining the average in order to consider the larger radiation value at higher temperatures. The average rocket plume temperature that is obtained by the above method is approximately 2773 K for 0.348 seconds.

2.3.2 Rocket Plume Impingement Time

The time the rocket plume is in contact with the tube and velocity of the plume is obtained from information provided by the U.S. Army courtesy of Bobby Richardson [15].

The ambient temperature is assumed to be 300 K for simplicity when selecting properties for air used in the engineering analysis. All benchmark values used in the engineering analysis are provided in Table 3.

Table 3: Benchmark values used in rocket plume analysis

Property	Value	Unit
Velocity	300	m/s
Plume Temperature	2774	K
Ambient Temperature	300	K
Tube Density	1875	kg/m^3
Tube Specific Heat	900	J/kg K
Thermal Conductivity	1	W/m K
Rocket Plume Time	0.348	s

Using equation 54 and the benchmark values in Table 3, the amount of energy one rocket plume imparts to the tube is determined to be 756 kJ/m^2.

2.4 Rocket Plume Variable Variance Analysis

2.4.1 Introduction

The variable variance analysis below is used to determine key variables and assist in understanding the uncertainty in the rocket plume energy calculation due to a lack of information about the benchmark variables. The variables are adjusted by plus or minus thirty percent. The physical reality represented by each variable may suggest using values other than a thirty percent difference. Where different variations are used, they are noted in the subsequent section.

2.4.2 Variance Analysis

An analysis is conducted of the benchmark values used in the engineering calculations. Only one benchmark value is altered at a time, the calculation is then repeated. The thermal conductivity is altered by a factor of ten to take into consideration greater uncertainty in the value. The ambient temperature term is adjusted to represent the lower and upper bounds of the safe operating temperature of the MLRS. The rocket plume temperature is not increased by thirty percent due to limited data on air temperatures above 3000K. The results of the benchmark variable variance analysis are presented in Table 4.

Table 4: Engineering Analysis: Benchmark variance analysis

Property	Values	Values Units	h_c W/m² K	h_r W/m² K	Q kJ/m²
Benchmark			286	990	756
Velocity		m/s			
	210		215		727
	390		352		782
Plume Temperature		K			
	1942		181	340	252
	3000		326	1253	948
Ambient Temperature		K			
	240				774
	333				746
Tube Density		kg/m³			
	2438				787
	1313				711
Tube Specific Heat		J/kg K			
	630				711
	1170				787
Thermal Conductivity		W/m K			
	0.1				439
	10				964
Plume Time		s			
	0.244				558
	0.452				940
Tube Emissivity					
	0.6			681	621
	1			1089	794
Flame Emissivity					
	0.6			681	621
	1			1089	794

The variable variance analysis indicates that there are three key variables that affect the amount of energy the rocket plume imparts to the tube by more than 20 percent. These three variables are the rocket plume temperature, the rocket plume time and the thermal conductivity of the tube. The variance in the thermal conductivity of the tube was selected to be a factor of ten to consider substantial errors. Although the thermal conductivity affects the solution when the value is adjusted by a factor of ten it is assumed that actual error due to uncertainty in the thermal conductivity is much less than the variance tested. When the thermal conductivity term is adjusted by 30% to 1.3 the energy from the rocket plume becomes 787 kJ/m^2. When the thermal conductivity is adjusted downward by 30% to 0.7 the energy form the rocket plume becomes 711 kJ/m^2. Calculating the energy with only a 30% variance in the thermal conductivity greatly reduces the impact that the conductivity has on the overall result. Furthermore, variances in the plume temperature create the greatest variance in the calculation of the amount of energy the rocket plume imparts to the tube.

Chapter 3: Cone Calorimeter

3.1 Introduction

3.2 Overview

This section outlines the experimental protocol for the oxygen consumption calorimeter (cone) experiment. [16] In addition, this section outlines hardware requirements, test item description, test criteria, and instrumentation requirements.

The cone that is used for the experiments is a type CS-237 manufactured by Custom Scientific Instruments. The cone is located in Glenn L. Martin Hall on the University of Maryland's College Park campus. The cone is used to supply a well characterized incident heat flux to a specimen in order to determine the time to piloted ignition.

3.3 Test Samples

The test samples required to conduct the tests are provided as Government Furnished Equipment (GFE). The main focus of tube testing is conducted with cut sections of the forward end of MLRS rocket tubes obtained from rocket pods deemed unsuitable for production. The supplied tube sections have an approximate length of 0.6 m. The tubes are a fiberglass composite, approximately 0.3 m in diameter, and a 3 mm minimum wall thickness. Two types of forward sections are supplied; tubes that have had a rocket previously fired from them, i.e. fired tubes, and new tubes that are deemed unsuitable for production, i.e. un-fired tubes. The interior of the un-fired tubes possess a protective gel coat. The protective gel coat is no longer present on the previously fired tubes.

3.4 Test Objective

The objective of the cone experiment is to determine a time to ignition for tube samples with a well characterized incident heat flux. The incident heat flux and time to ignition is plotted to determine any differences in ignition conditions between a fired tube and un-fired tube sample.

3.5 Experimental Protocol

The cone experiment protocol generally follows ASTM E 1354 – 03 [16], but deviations from the standard are noted. The cone is used to provide a well characterized incident heat flux to the sample. Analysis of the cone set temperature to the applied heat flux is also conducted.

Special specimen mounting techniques of the sample are used. The specimen tray is lined with one layer of aluminum foil. A border of 6.35 mm thick insulation board is placed inside the specimen tray. The insulation board is cut and arranged in the tray to create an air gap under the majority of the specimen. The insulation board effectively raises the top edge of the specimen to the height of the top edge of the specimen tray. One sheet of aluminum foil is used to line the inside of the specimen tray and insulation board. The aluminum foil liner is used to protect the insulation board from any specimen residue. An edge retainer frame is placed over the specimen and specimen tray.

The distance between the top of the specimen tray and the bottom of the cone heater is fixed at 25 mm.

3.6 Hardware

Hardware requirements for the cone experiments are the GFE samples cut into 100 mm by 100 mm squares. An oxygen consumption calorimeter with electric ignition spark plug, specifically type CS-237 Ref#: NBSIR 82-2611, is used to supply the well characterized incident heat flux. A stop watch is used to obtain the time to ignition.

3.7 Experimental Procedure

The ASTM E 1354 – 03 testing procedure is used for the cone experiments. The cone heater is turned on and an input temperature is selected to achieve the desired heat flux condition. A new GFE specimen is placed in a cold specimen tray in such a manner that the inside surface of the tube is placed face up in the specimen tray, Figure 7.

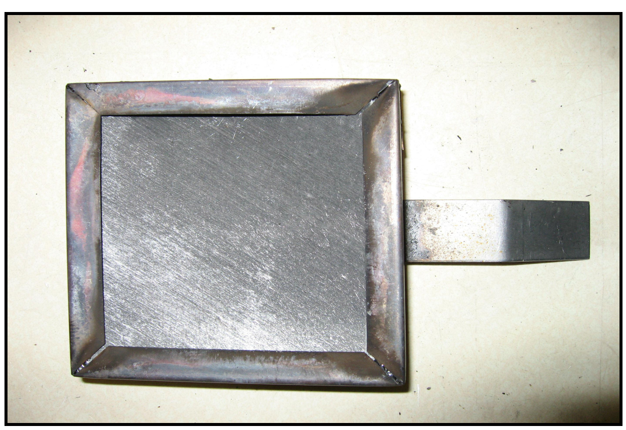

Figure 7: Cone specimen tray with previously fired rocket tube sample and edge retainer frame

An edge retainer frame is then applied to prevent unrepresentative edge burning. The cone heater is allowed to reach a steady state by waiting at least 30 min from the initial temperature setting before testing is begun. [16]

The date and time of the test along with the specimen type, number, mass, set temperature and applied heat flux are pre-recorded. The test begins when the specimen tray with specimen is placed on the load cell and initially exposed to the cone heat flux. The piloted ignition time is recorded at the completion of the test. Three samples are tested at six different heat fluxes and piloted ignition times are recorded for each sample.

3.8 Cone Calorimeter Calibration Curve

The cone calorimeter calibration curve is conducted to obtain the heat flux at several user selected temperatures on the apparatus. The incident heat flux during each test is not measured due to testing constraints. Instead, a temperature is selected on the apparatus that equates to a specific heat flux through a calibration curve. To start each calibration point a set temperature on the apparatus is selected at intervals of 20 °C between 320 °C and 740 °C. The temperature range selected indicates a safe range for the cone from information provided to the author. [17] At each selected temperature the cone heating element is allowed to stabilize for 30 minutes before measurements are taken. A heat flux gage is then placed at the would be sample location and measurements are taken every second for two minutes. The set temperature is then adjusted to the next value and the procedure is repeated again. An average heat flux is obtained from each two minute test; results of the cone calibration are presented in Figure 8.

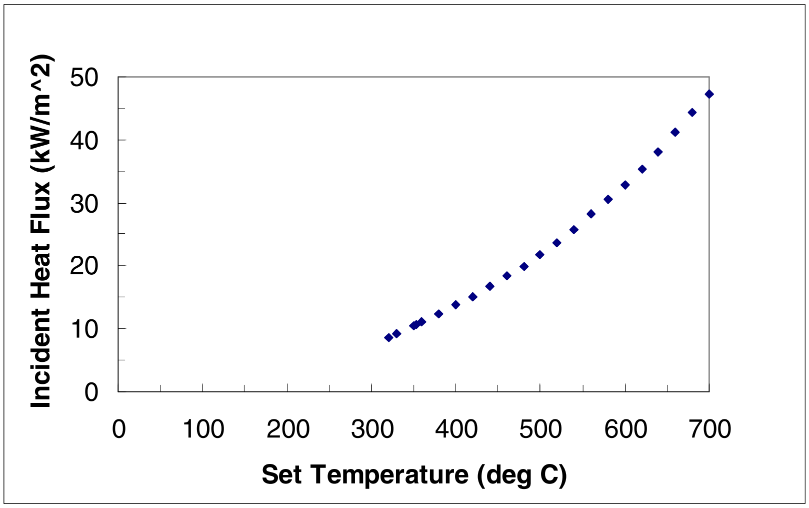

Figure 8: Cone calorimeter heat flux calibration curve

3.9 Cone Calorimeter Heat Flux Variance

The heat flux supplied to each sample during actual testing is not measured due to testing constraints as outlined in the standard. To ensure that the cone supplies a well characterized heat flux to the test sample at the desired heat fluxes further analysis of the heat flux calibration data is conducted. Standard deviations of the two minute heat flux measurements for each desired heat flux are calculated. The analysis of each desired heat flux is presented in Figure 9. The error bars in Figure 9 represent plus and minus one standard deviation from the average measured heat flux.

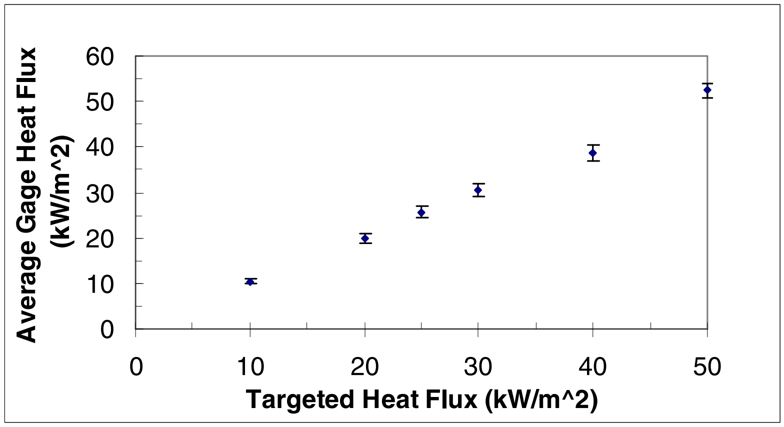

Figure 9: Cone Calorimeter: Average measured heat flux

The calibration curve is used to obtain a set temperature that would equate to the desired heat flux exposing each sample. The above analysis indicates that the cone calorimeter supplies a well characterized heat flux to each sample with an average standard deviation of 1.4 kW/m^2. [18]

3.10 Test Data

The time to piloted ignition along with the test conditions for the cone calorimeter are compiled in Table 5.

Table 5: Time to ignition for cone calorimeter test

Test Number	Damage	Condition	Applied Heat Flux kW/m^2	Time to Flamelets s
16	No	Un-Fired	10	NI
17	No	Un-Fired	10	NI
18	No	Fired	10	NI
4	No	Un-Fired	20	191
14	No	Un-Fired	20	205
15	No	Fired	20	173
5	No	Un-Fired	26	91
12	No	Un-Fired	26	112
13	No	Fired	26	115
3	No	Un-Fired	31	81
10	No	Un-Fired	31	82
11	No	Fired	31	91
2	No	Un-Fired	39	58
8	No	Un-Fired	39	62
9	No	Fired	39	60
6	No	Un-Fired	52	36
1	No	Un-Fired	52	42
7	No	Fired	52	42

NI: No Ignition

The three test samples with a targeted applied heat flux of 10 kW/m^2 labeled with NI in the above table do not ignite. The criterion for no ignition is obtained from the ASTM E1354 indicating after 30 min of exposure with no visible signs of material degradation, the test may be terminated. [16]

3.11 Test Results

The individual cone test results of the measured incident heat flux and time to ignition are presented in Figure 10. The test results display a trend suggesting that an un-fired tube ignites under the same criteria as a fired tube, Figure 10.

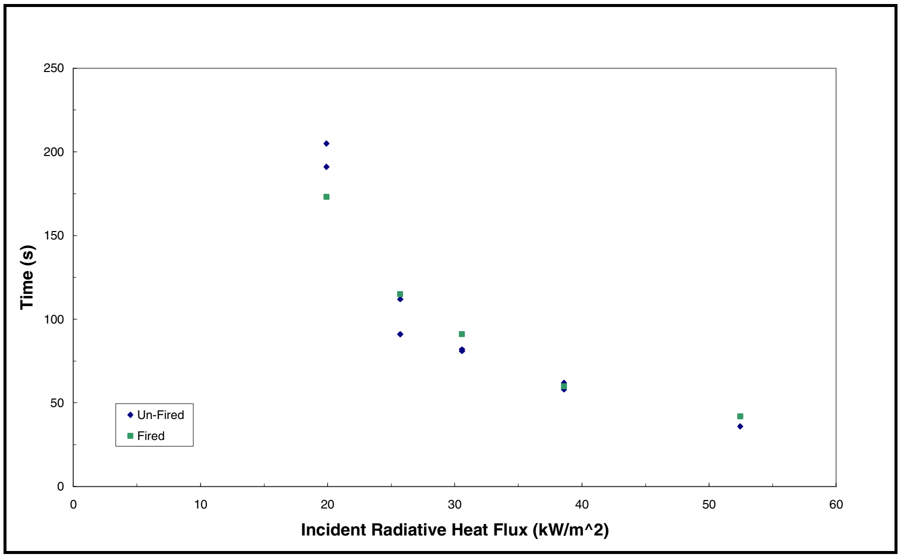

Figure 10: Cone calorimeter test
Three tests at 10kW/m^2 did not ignite within 30 min of exposure.

The average time to ignition for the three samples at each incident heat flux is also examined. The error bars in Figure 11 represent the difference between the average time to ignition and the range in ignition times measured.

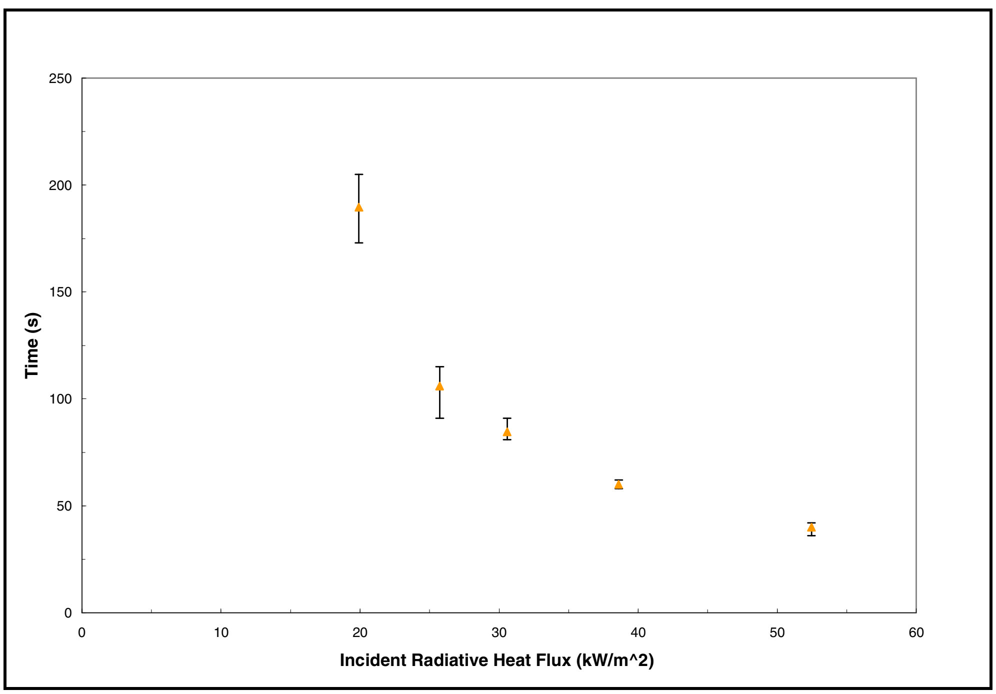

Figure 11: Cone calorimeter test: Average time to ignition

The plot of the average time to ignition with the small error bars further indicating that there is little difference between the time to ignition of a fired and un-fired tube within the limits of the test.

3.12 Cone Calorimeter Summary

The cone calorimeter experiment is conducted to test the tube samples using a well characterized heat flux. The cone allows for the samples to be tested under controlled conditions that eliminate some variables that are present in the larger propane burner experiments. The cone experiment is used to test for discrepancies in the ignition characteristics of a tube that has had a rocket fired from it and an un-fired tube. The limited number of tests that are conducted indicate that no difference in ignition characteristics of the fired and un-fired tubes exist as shown in Figure 10, and Figure 11.

Chapter 4: Propane Flame Experiments

4.1 Introduction

The propane flame experiments are conducted in the Fire Dynamics Laboratory on the University of Maryland's College Park campus. A 44 kW propane burner is used to supply a flame through the center of a tube specimen in order to determine the time to ignition. The propane flame experiments are of a larger scale than the cone experiment and have similar heating characteristics to the rocket plume. In addition the propane flame experiments are broken into two different test protocols with different objectives. The propane experiments provide a continuous exposure and a multiple cycle exposure which will be described in detail below.

4.2 Test Objective

The propane flame experiments are devised to test sections of the rocket tubes for initiation of tiny flames, i.e. flamelets, on the interior surface of the tube. The total exposure time of the tube section to the propane flame is recorded. The objective of recording time to flamelets and the propane flame temperatures is to obtain the experimental Biot number. The recorded data is further used to test ignition conditions of tubes in various conditions including tube damage. The Biot number is used to determine the method of heat transfer analysis used to calculate the amount of energy the propane burner imparts to the tube. The Biot number and the method for determining it is explained in Chapter 1.

4.3 Experimental Protocol

The first task of this research effort is to formulate an experimental protocol and identify hardware and instrumentation requirements. While the intent is to explore the ignition of tubes due to an exposure from a rocket plume, this experimental program is limited to providing an exposure to tubes resulting from a propane flame. Engineering analyses are conducted to develop an experimental protocol with a propane fire which captures the essential aspect of ignition behavior in an analogous fashion to that provided by the rocket plume. The actual tests measure the time length duration for small flames, i.e. flamelets, to propagate on the inner tube wall.

The propane burner that is used has a lag time between initial ignition and full ignition. Due to safety issues there is no feasible way to avoid subjecting the test specimen to the flame during the lag time. All subsequent times that are selected for the burner remaining on are long enough to limit the effect of the burner lag time.

The tubes are tested in three conditions, no damage, simulated forklift damage, and abrasion damage. The types of damage are selected based on what the U.S. Army indicates as possible conditions that may increase the risk of fire.

The first tube condition tested is no damage. The tube sections without damage are tested in the condition the University received them and assumed to be in the condition production tubes would be in. An undamaged tube section does not have any punctures, holes, abrasion or any other type of damage created by the author.

The U.S. Army indicates that when the pods are transported it is possible, through incorrect actions, for the tubes to be punctured by forklift tines. Access to a forklift to recreate the tube damage is not available. To recreate the forklift damage, holes are drilled through the tube in a set pattern. The simulated forklift damage is created by drilling four 19.05 mm diameter holes. The holes are positioned with the center of the hole located at the corners of a 102 by 102 mm square. The square is inset from one edge of the tube by 70 mm, Figure 12.

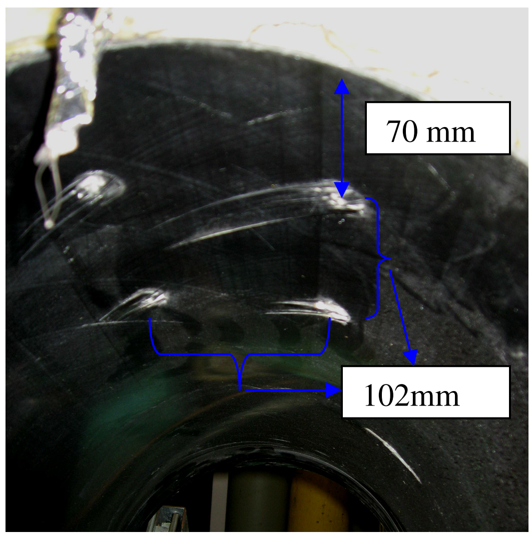

Figure 12: Diagram of simulated forklift tube damage

The U.S. Army also indicates that the fins of the rocket may scratch the interior of the tube, either in loading or firing. Scratching of the interior of the tube is tested to investigate any increased propensity to ignition. Scoring the interior of the tube is conducted by using an abrasive drill bit. The abrasion is approximately 25 mm wide, and is continuous for 1/4 the circumference of the tube, Figure 13.

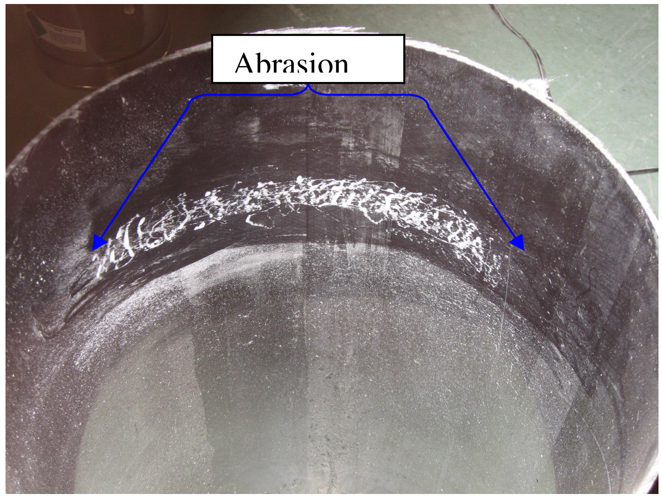

Figure 13: Diagram of abrasion tube damage

The burner and tube supports are at a 45° angle for all tests except where otherwise noted. The 45° angle is selected to represent one of many possible orientations of the rocket pod during firing. The 45° angle also simplifies the construction of the burner and tube supports due to the preproduction of 45° angle support fittings.

4.4 Hardware Requirements

The propane flame experiments are based around the Eclipse category 200 JIBC-2 44 kW burner [19] to ignite the 0.6 m long forward fiber glass epoxy tube sections supplied by the U.S. Army, GFE. The remaining equipment that is used in the test process is listed in Table 6.

Table 6: Hardware requirements for propane tests

Component	Content
Fuel Bottles	Propane bottle & Fixtures
Burner & Tube Stand	Steel support structure to mount burner and tube section
Propane Burner	Eclipse 44 kW burner Cat.# 200 JIBC-2
Insulation	R25 type insulation (0.20 m thick, 0.38 m wide), reduce heat loss from outer tube wall to surroundings
Stopwatch	Time pieces to record relevant test times
Thermocouples	Type K 24 gage thermocouple wire for flame, insulation and exterior tube temperature measurements
Wire Mesh	Support structure to hold thermocouples in place around tube section at pre-set locations
Data Acquisition Unit	Fluke 20 channel unit to acquire thermocouple readings
Computer	Record and analyze data
Video Camera & Tripod	Camcorder for motion picture record of tests
Digital Camera	Record still pictures of tests

4.5 Experimental Procedure

The tube to be tested is instrumented and prepared for testing. The tube condition to be tested dictates the tube set-up. The wire mesh has a thermocouple attached to it to ensure the location of the thermocouple from test to test remains constant. The thermocouple is affixed to the wire mesh approximately 0.07 m from one edge of the wire mesh. The thermocouple is used to measure the exterior surface temperature of the tube. The wire mesh is wrapped into a cylinder slightly larger in diameter than the tube samples. The wire mesh with the thermocouple is slid over the tube so that the thermocouple is also 0.07 m from the edge of the tube.

For tubes with simulated forklift damage a double layer of aluminum foil is placed between the outside surface of the tube and wire mesh at the location of the four drilled holes. The aluminum foil acts as a barrier to prevent flame from directly impinging on the insulation. The thermocouple is placed above the aluminum foil

Before the insulation is placed around the tube the thermocouple is checked to ensure contact with the outside surface of the tube. One layer of insulation is then wrapped around the tube and fastened using a threaded metal hose clamp. The insulation is used to create an approximate adiabatic surface. The adiabatic surface is needed to maintain a similar condition to that of the rocket plume. The hose clamp is tightened enough to ensure that the inside surface of the insulation stays in contact with the wire mesh and the external surface of the tube, but not tight enough to pinch down and significantly reduce the thickness of the insulation.

The instrumented tube with insulation attached is placed on the burner/tube setup and fastened down using a threaded metal hose clamp. All tubes are tested with the thermocouple on the top front portion of the tube, where front corresponds to the tube end farthest away from the propane burner, Figure 15. Damaged tubes are tested with the damaged portion on the top front, farthest away from the burner flame inlet. The purpose of strapping the instrumented tube down is to prevent movement during testing.

One thermocouple is used to measure the flame temperature at the exit of the flame from the front of the tube. The front thermocouple measurements are used in all the propane burner calculations. One additional thermocouple is used to measure the top surface of the insulation at the center of the tube, lengthwise. The whole test set-up is presented in Figure 14 and Figure 15.

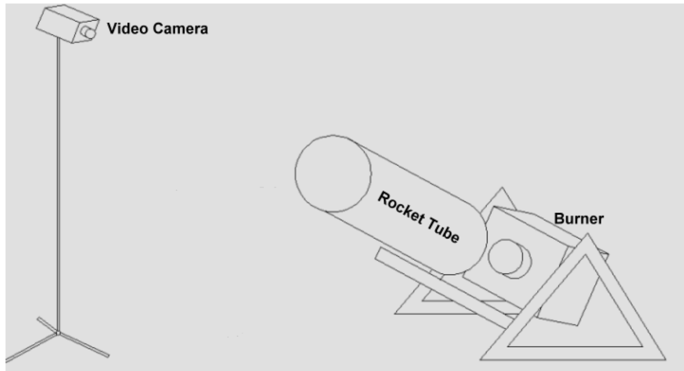

Figure 14: Propane burner experimental set-up (not to scale)

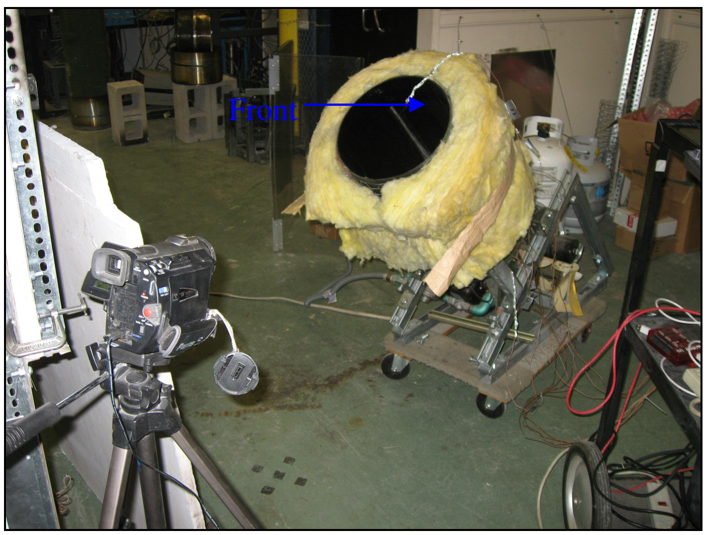

Figure 15: Photograph of propane burner test setup with instrumented tube

The instrumentation, time piece and camera are all started at the same time. The thermocouples and video camera are left to record the ambient conditions for 60 s before the start of each test.

The propane tank valve is opened. The burner valves are opened and the throttle is adjusted to ½. The burner is turned on and the valves on the propane flow system are opened. The time when the burner starts and the time when the burner reaches full power is recorded. The propane pressure decreases when the burner is on full. The pressure from the propane regulator is visually inspected and manually set at 470 Pa throughout the test.

The interior of the tube wall is observed for flamelets, the time of initial occurrence is recorded.

The recording devices are terminated at the completion of each test. The completion of each test is determined to be the conclusion of all scheduled tube exposures to the propane flame if no tube combustion is present. With sustained tube combustion, the test is terminated at the completion of the current flame exposure or when deemed unsafe. A record is made for the interior tube self-extinguishment. Scheduled tube exposures to the propane flame are terminated if the smoke from the tube combustion begins to overwhelm the hood or pose an unacceptable safety risk to the testers. Tests that are terminated early due to safety considerations are deemed completed and noted.

4.6 Continuous Propane Flame Experiments

4.6.1 Introduction

The propane flame experiments are separated into two different protocols. The continuous propane flame experiment is used to test the different tube sections by exposing them to the flame for a predetermined period of time. The continuous propane flame experiments are also used to collect time to ignition and flame temperature data. Time to piloted ignition of the inner tube wall is recorded. The experimental results are also used to calculate the Biot number. From the Biot number the amount of energy the propane flame imparts to the tube is also calculated.

The data is used in the burner energy calculations that are later compared to the rocket plume input energy calculations.

4.6.2 Test Objective

The purpose of this test series is to provide the data necessary for the determination of the ignition parameters (duration) and tube configuration (damaged versus undamaged) by ensuring tube ignition. The individual experiments are analyzed to determine the Biot number which can be used to calculate the experimental value of the net energy input. Results are then compared by plotting the time to ignition versus the net energy input. Of specific interest are the threshold parameter values that result in ignition for the various tube conditions.

4.6.3 Burner Flame Baseline Values

The average fluid temperature for the propane flame is found to be 666 K. In order to begin the emissivity calculation, equation 25, it must be noted that the fuel for the flame is propane at approximately atmospheric pressure, or approximately 101 kPa. The radiative property of soot particles from the propane fuel is 13.32 m^{-1}. [12] The stoichiometric equation for propane burning in air is as follows.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 4H_2O + 3CO_2 + 18.8N_2$$

The stoichiometric equation is used to determine the partial pressures through Dalton's law, equation 29. The physical pathlength, 'S', of the fluid in the case of the propane burner flame is approximately 0.1 m. Substituting the average fluid temperature into equation 24 the emissivity of the fluid is 0.77.

The burner flame velocity is measured when the propane fuel is shut off and only the blower remains on. The air velocity is measured using a Hot Wire Thermo-Anemometer (L584886) made by Extech Instruments.

The specific heat and thermal conductivity of the tube material remains the same as discussed in the tube background and rocket plume sections above. The values and methodology behind the quantities remain the same.

4.6.4 Benchmark Variables

The benchmark variables that are used in the energy calculation are determined from the values above. Table 7 lists the benchmark values used in the energy calculation in equation 11.

Table 7: Propane burn benchmark values

Property	Value	Unit
Velocity	4.3	m/s
Flame Temperature	666	K
Ambient Temperature	300	K
Tube Density	1875	kg/m3
Tube Specific Heat	900	J/kg K
Thermal Conductivity	1	W/m K
Time to Ignition	180	s
Tube Emissivity	0.9	
Flame Emissivity	0.77	

4.6.5 Benchmark Values Variance Analysis

The variable variance analysis below is used to determine key variables and assist in understanding the uncertainty in the propane flame energy calculation due to a lack of information about the benchmark variables. The variables are adjusted on average by plus and minus thirty percent. Variations are noted.

An analysis is conducted of the benchmark values used in the engineering calculations. Only one benchmark value is altered at a time, the calculation is then redone. The ambient temperature is only adjusted to represent Army supplied operating temperature ranges for the vehicle. The results of the benchmark variable variance analysis are in Table 8.

Table 8: Propane burner variable variance analysis

		Values	h_c	h_r	Q
Property	Values	Units	W/m^2 K	W/m^2 K	kJ/m^2
Benchmark			9.8	11.8	1026
Velocity		m/s			
	3.0		7.4	11.8	943
	5.6		12.1	11.8	1098
Flame Temperature		K			
	466		12	4.1	375
	866		8.4	26	2115
Ambient Temperature		K			
	240				1194
	333				933
Tube Density		kg/m^3			
	1313				902
	2438				1103
Tube Specific Heat		J/kg K			
	630				902
	1170				1103
Time to Ignition		s			
	126				789
	234				1218
Tube Emissivity					
	0.6			8.5	910
	1			12.9	1058
Flame Emissivity					
	0.5			7.9	890
	1			15.1	1126

The variable variance analysis indicates that there are two key variables that affect the amount of energy the propane burner imparts to the tube by more than twenty percent. The two variables are the propane flame temperature and the time to ignition. The thermal conductivity term is not in the lumped capacitance energy calculation.

4.6.6 Hardware Requirements

The hardware is previously outlined in Table 6. The GFE is altered to create an experimental test matrix that addresses issues of concern to the sponsor, Table 9. The GFE supplied to the University consists of the forward end of MLRS fiber glass epoxy rocket tubes cut into sections.

Table 9: Hardware requirements for the continuous propane flame exposure tests, specific breakout of GFE

Damage	Tube Type	Damage Type	Number of Tubes
No	Un-fired	N/A	2
No	Previously Fired	N/A	2
Yes	Un-fired	Simulated Forklift Puncture	2
Yes	Previously Fired	Simulated Forklift Puncture	2
Yes	Un-fired	Interior Abrasion	2
Yes	Previously Fired	Interior Abrasion	2

4.6.7 Experimental Procedure

The experimental procedure follows the same set-up and basic test procedure outlined above in section 4.5. Prior to the beginning of the test the tube reference number is recorded along with date, time, ambient temperature, humidity.

The continuous propane exposure experiments expose each tube to the propane flame for a maximum of 240 s. The time at which visual inspection on the interior surface of the tube develops flamelets is recorded. For safety reasons some experiments are terminated prior to the 240 s of continuous propane flame exposure. In those cases the burner shut-off time is also recorded. Further observations are recorded along with still photographs. A test matrix is below.

Table 10: Continuous propane flame exposure test matrix

Test #	Damage	Tube Type	Damage Type	Flame Source	Exposure	# Of Tests
1	No	Un-fired	N/A	Propane	Max. 240 s	2
1	No	Previously Fired	N/A	Propane	Max. 240 s	2
2	Yes	Un-fired	Simulated Forklift Puncture	Propane	Max. 240 s	2
2	Yes	Previously Fired	Simulated Forklift Puncture	Propane	Max. 240 s	2
3	Yes	Un-fired	Interior Abrasion	Propane	Max. 240 s	2
3	Yes	Previously Fired	Interior Abrasion	Propane	Max. 240 s	2

4.6.8 Temperature Profile of the Continuous Propane Exposure

The temperature profile of a single representative test of the continuous propane burner test is plotted in Figure 16.

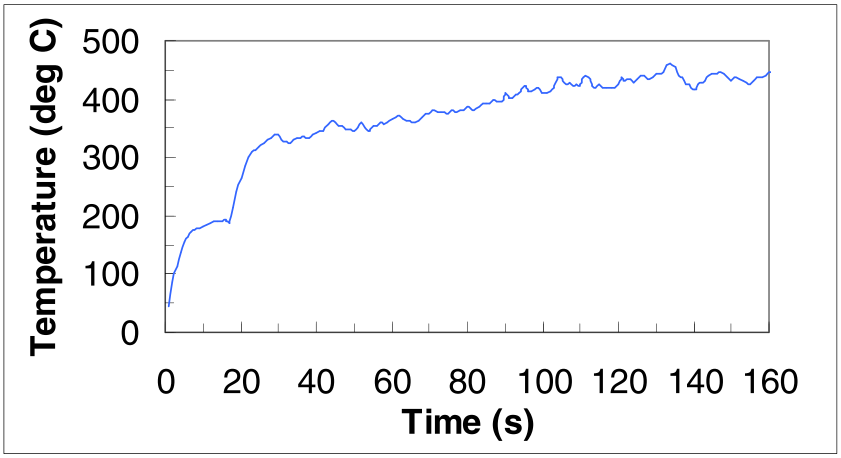

Figure 16: Continuous Exposure Test: Propane burner front temperature profile

The representative test plotted in Figure 16 corresponds to test six for the continuous test. Approximately the first 15 s of each test represent the time that the propane burner is on but has not reached its peak temperature. The first time period is described as a burner pre-heat time. During the pre-heat time the propane flame is shorter, resulting in a lower measured average downstream flame temperature. The line on the above plot abruptly ends as it corresponds to the burner being turned off.

The continuous propane flame exposure test provides an average temperature profile of a relatively smooth curve that levels off when the burner reaches its peak temperature.

4.6.9 Front Propane Flame Temperatures

The front plume temperature of each test is obtained and plotted to show that the test conditions are repeatable. The front temperatures provide further insight into the conditions during each test. An average front downstream plume temperature as measure by the thermocouple for each continuous propane flame exposure test is presented in Figure 17.

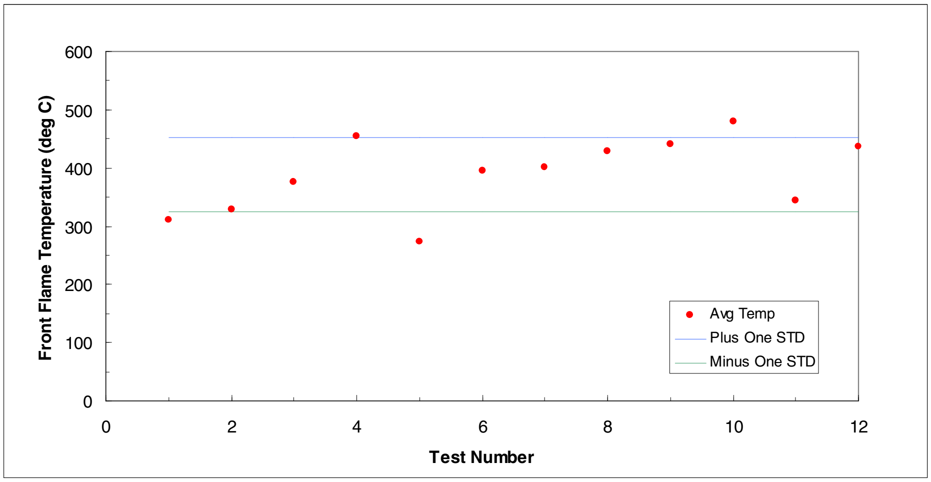

Figure 17: Continuous propane flame exposure test: Front flame temperatures

The horizontal lines on the above plot correspond to the average temperature plus and minus one standard deviation. The range between the lower standard deviation line and upper standard deviation line is 128 °C.

4.6.10 Time to Ignition Data

The data that is collected from the continuous propane flame exposure test is presented below. The main variables of the damage type and condition are listed below along with time to flamelets/ignition. Table 11 indicates that the time to flamelets occur on average with 180 s of propane flame exposure. The similarities in the time to flamelets among the different tests indicate that a damaged tube regardless of type ignites at roughly the same time as an undamaged tube. Further information supporting this idea is described below.

Table 11: Time to ignition for continuous propane flame exposure test

Test Number	Damage	Condition	Time to Flamelets S
4	Abrasion	Un-Fired	201
8	Abrasion	Un-Fired	227
12	Abrasion	Fired	141
6	Abrasion	Fired	229
7	Forklift	Un-Fired	146
3	Forklift	Un-Fired	180
5	Forklift	Fired	151
10	Forklift	Fired	167
2	No	Un-Fired	144
1	No	Un-Fired	159
11	No	Fired	186
9	No	Fired	230

An observation of the propane exposure is that the flamelets first begin on the interior surface of the tube. After time in some instances the flamelets do progress to the edge of the tube section.

4.6.11 Dimensionless Temperature

The dimensionless temperature calculations described above are conducted for the continuous propane burner experiments. These are important for the determination of the Biot number associated with these experiments.

The dimensionless temperature is obtained from the front flame temperature, the external tube temperature and ambient temperature thermocouple measurements. The dimensionless temperature is defined in equation (10). The dimensionless temperature and Biot number lines are presented in Figures 17 and 18. The Biot number lines are included through curve fitting. The Biot number lines form a range encompassing the most extreme experimental results. The experimental dimensionless temperature lines are off-set by 15 s to correspond to the pre-heat time the burner experiences. The off-set allows for a more realistic Biot number line by only considering the time period when the burner is fully on. Figure 18 plots each experiment along with the boundary Biot numbers. The average Biot number is 0.085 which is less than 0.1. The experimental values determine that the Biot number is less than 0.1 indicating the lumped capacitance method may be used to calculate the energy input.

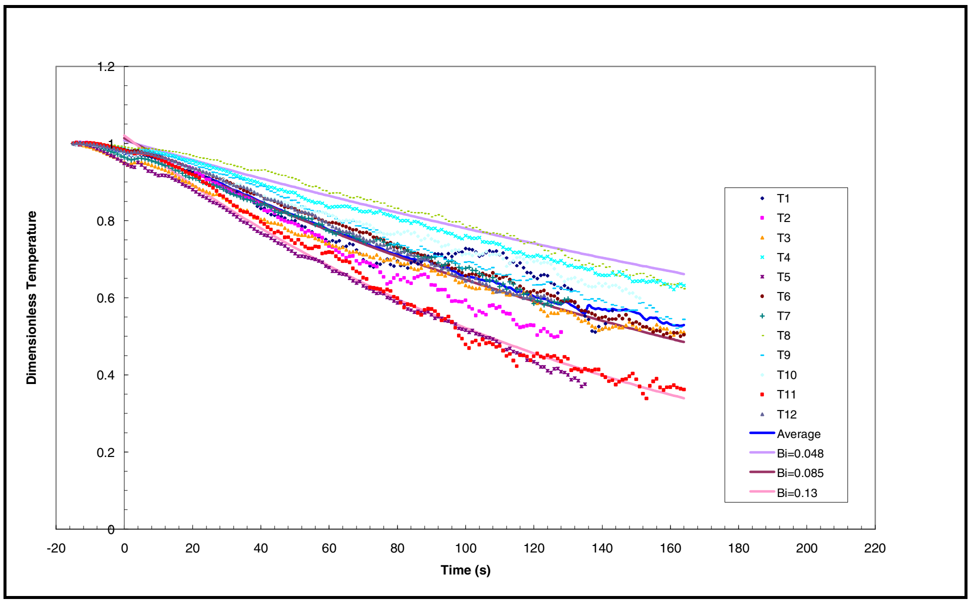

Figure 18: Continuous propane flame dimensionless temperature plot

Figure 19, removes the individual experimental lines and replaces them with an average experimental dimensionless temperature line. The average experimental line is a close match to the average Biot number line. After 140 s the average experimental line increases, indicating the Biot number is less than the 0.085 reported. The range of values for the Biot number representing the range of the experimental dimensionless temperature lines is also well defined in Figure 18. The range of Biot numbers that is represented in the experimental data indicates that a lumped capacitance method may be used to calculate the energy input from the burner.

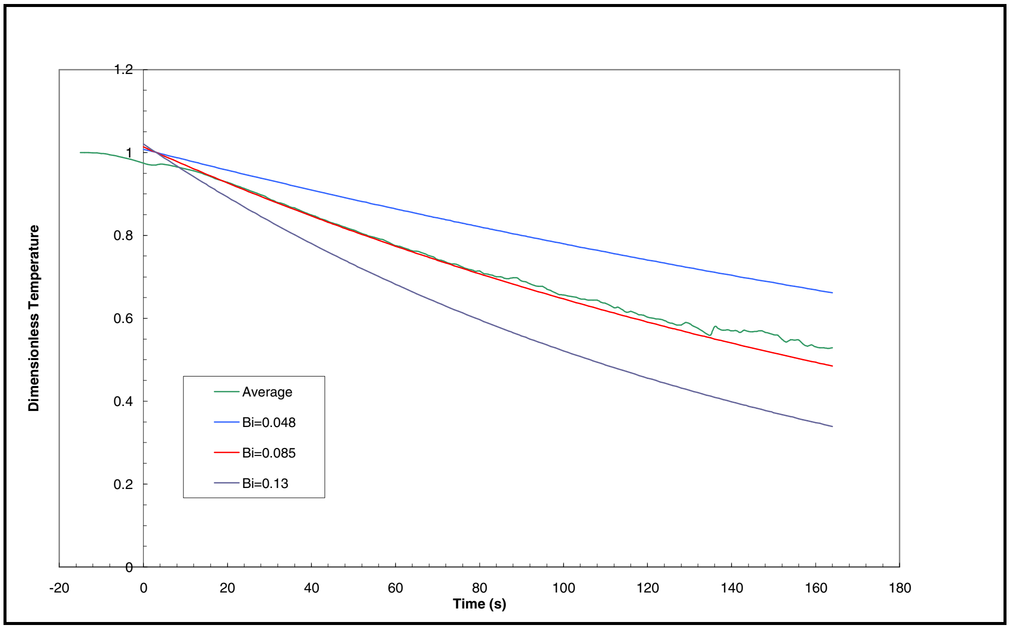

Figure 19: Continuous propane flame average dimensionless temperature plot

4.6.12 Energy Calculations Using the Biot Number

4.6.12.1 Introduction

The experimentally determined Biot numbers discussed above may also be used to determine a convective heat transfer coefficient. The Biot number determined heat transfer coefficient may be compared to the heat transfer coefficient calculated in section 4.6.4 and 4.6.5. The newly determined heat transfer coefficient may also be used to re-calculate the energy input from the propane burner to the tube. Both comparisons further expand on the validation and verification of the theory presented previously.

4.6.12.2 Experimental Heat Transfer Coefficient

Using the definition of the Biot number, the convective heat transfer coefficient may be calculated assuming the thermal conductivity of the tube is accurately known. The Biot number is known experimentally from the above plots. The definition of the Biot number is then rearranged to yield:

$$h = \frac{Bi \cdot k}{L} \quad \textbf{(55)}$$

Table 12 displays the range of heat transfer coefficients calculated based on the range of Biot numbers determined from experiments. A variance analysis of the thermal conductivity and its effect on the heat transfer coefficient is also shown in the table.

Table 12: Experimental heat transfer coefficient h (W/m^2 K)

	Thermal Conductivity (W/m K)				
Bi #	0.1	0.7	1	1.3	10
0.048	1.5	10.2	14.5	18.9	145.5
0.085	2.6	18.0	25.8	33.5	257.6
0.13	3.9	27.6	39.4	51.2	393.9

The average heat transfer coefficient value is 25.8 W/m^2K, when the thermal conductivity is 1.0 W/mK and the Biot number is 0.085. The previously calculated value for the heat transfer coefficient is 21.7 W/m^2K (Section 4.6.5), when the thermal conductivity is 1.0 W/mK. The similarity between the heat transfer coefficients indicates that the calculation methods are accurate.

4.6.12.3 Experimentally Determined Energy Input to Tube

The heat transfer coefficient that is determined from the continuous propane flame experiments is used to calculate the energy input to the tube. The range of heat transfer coefficients that are experimentally determined from the Biot number while keeping the thermal conductivity at one is entered into Equation 11 to solve for energy. The range of energy input to the tube from the propane burner at ignition is between 763 and 1468 kJ/m^2 with the average being 1153 kJ/m^2. The energy input calculated from the benchmark values is 1026 kJ/m^2 and is within fifteen percent of the average value calculated above from the Biot number.

The energy input from the burner is presented in Figure 20, using the experimentally determine average heat transfer coefficient from the Biot number and the individual test conditions. Figure 20 also further supports the idea that tube damage does not affect the ignition conditions of the tubes. The data points of the abrasion, forklift and un-damaged tubes are equally distributed on the plot indicating no strong tie between damage and ignition.

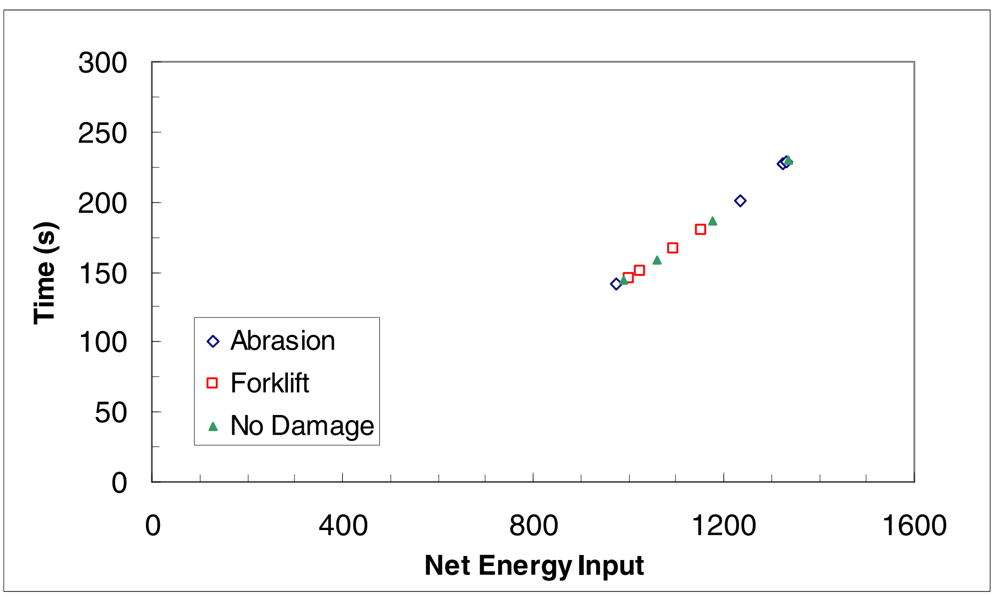

Figure 20: Continuous tests: Experimentally calculated energy input

4.7 Multiple Cycling Exposure Propane Flame Experiments

4.7.1 Introduction

The second of the propane flame experiments is a multiple cycling propane flame exposure experiment. The multiple cycling propane flame exposure involves the burner being turned on and off during the test. The time duration of each on and off cycle is independent of each other and predetermined before the test. The time durations are varied to create a test matrix of burner on and off times. The multiple cycling exposure propane flame experiments are used to test the tube sections by exposing them to a flame for a predetermined period of time at regular intervals. The maximum number of exposures the tube is subjected to is six because the rocket pod's six tubes equal the maximum number of rocket plume exposures. In the field, each rocket plume engulfs the other empty tubes. Time to piloted ignition and visual observation of flamelets on the inner tube wall is recorded.

4.7.2 Test Objective

The purpose of this test series is to provide the data necessary for the determination of the ignition parameters (duration) under different exposure and delay times between rocket launches. The experimentally determined Biot number is found from the data. Results are also compared by plotting the time to ignition versus the burner off time. The burner on and off times are analyzed to compare Biot numbers to the other experiments to confirm the test conditions.

4.7.3 Experimental Protocol

The multiple cycling exposure tests measure the time length duration for flamelets to propagate on the inner tube wall. The protocol is developed by maintaining a constant exposure time and varying the amount of time between exposures. The variation in time between exposures simulates a variable amount of time between rocket firings with the MLRS system. A constant time between exposures is also selected and the exposure time is varied. The tests are used to mimic the scenario where a rocket is fired from one tube and at some time later the other five rockets are fired at equal intervals. The multiple cycling exposure tests attempt to simulate the original rocket plume thermal insult to the tube and the subsequent five rocket plumes on the original empty rocket tube.

4.7.4 Hardware Requirements

The hardware is previously outlined in Table 6. The GFE is altered to create an experimental test matrix that addresses issues of concern to the sponsor, Table 13.

Table 13: Hardware requirements for the multiple cycle propane flame exposure tests, specific breakout of GFE.

Damage	Tube Type	Damage Type	Number of Tubes
No	Un-fired	N/A	20
No	Previously Fired	N/A	2
Yes	Un-fired	Simulated Forklift Puncture	5
Yes	Un-fired	Interior Abrasion	1

4.7.5 Experimental Procedure

The experimental procedure follows the same set-up and basic test procedure outlined above in section 4.5. Prior to the beginning of the test, the tube reference number is recorded along with date, time, ambient temperature, and humidity.

The multiple cycling propane flame exposure experiments test each tube for a maximum of six exposures. The tube is exposed to the propane flame for a set amount of time. At the conclusion of the set time period the burner is turned off and the propane flow system is closed. At the conclusion of the off time period, the burner is turned on and the tube is again exposed to the propane flame. The cycle is repeated until six exposures are accomplished. The time at which visual inspection on the interior surface of the tube develops flamelets is recorded. For safety reasons, some experiments are terminated prior to completion of the six cycles and the burner is shut-off and the time recorded. Further observations are recorded along with still photographs. A test matrix is provided in Table 14.

Table 14: Multiple cycling exposure test matrix, with tube conditions

Exposure Time (s)	Burner Off Time (s): 20 Tube Type/ Condition	20 # of Tests	40 Tube Type/ Condition	40 # of Tests	60 Tube Type/ Condition	60 # of Tests
40	Not Tested		Un-fired/No Damage	3	Not Tested	
			Un-fired/ Simulated Forklift	1		
			Previously Fired/No Damage	1		
60	Un-fired/No Damage	3	Un-fired/No Damage	4	Un-fired/No Damage	3
	Un-fired/ Simulated Forklift	1	Un-fired/ Simulated Forklift	1	Un-fired/ Simulated Forklift	1
	Not Tested		Un-fired/Abrasion	1	Not Tested	
			Fired/No Damage	1		
80	Not Tested		Un-fired/No Damage	3	Not Tested	
			Un-fired/ Simulated Forklift	1		
130	Not Tested		Un-fired/No Damage	3	Not Tested	
155	Not Tested		Un-fired/No Damage	1	Not Tested	

The limited number of GFEs restricts the number of tests and test scenarios that are conducted. The test matrix is intended to be representative of possible conditions with test repetitions provided to show repeatable results.

4.7.6 Temperature Profile of the Multiple Cycle Propane Burner Tests

The temperature profile of a single representative test of cyclic propane burner tests is plotted in Figure 21.

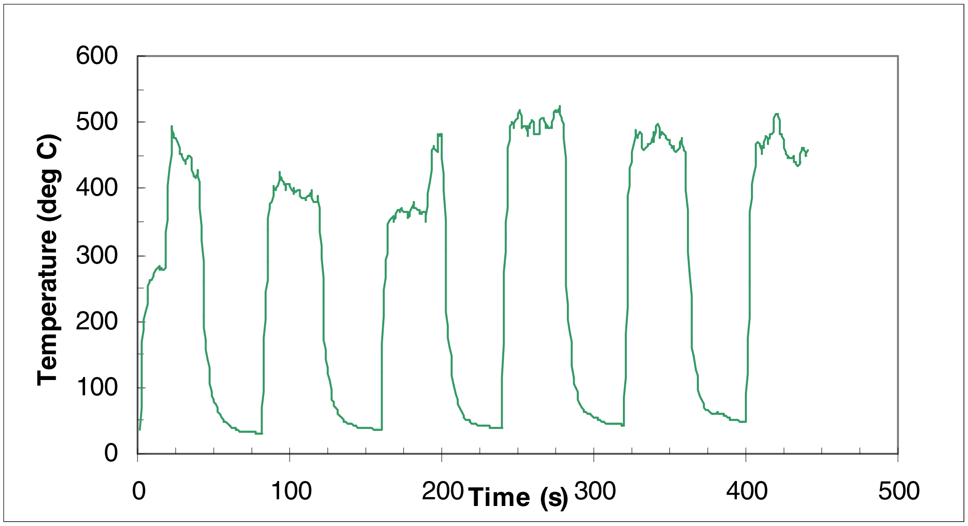

Figure 21: Multiple Cycle: Propane burner front temperature profile

The representative test in Figure 21 corresponds to Test 13 of the cyclic tests. Approximately the first 15 s of the test represent the time that the propane burner is on but, has not reached its peak temperature. The first time period is described as a burner pre-heat time. The line in Figure 21 abruptly ends as the burner is turned off.

The multiple cycle propane flame exposure test has a profile similar to the continuous test for the first approximately 30 s. After the first 30 s the cyclic test takes on a saw tooth profile due to the cycling on and off of the propane burner.

The front downstream plume temperature for the multiple cycle propane flame exposure test is presented in Figure 22. For the multiple cycles test, only the time that the burner is on is considered when the average temperature is calculated. By considering only the burner on time it allows for the results to be compared between the continuous and multiple cycles tests.

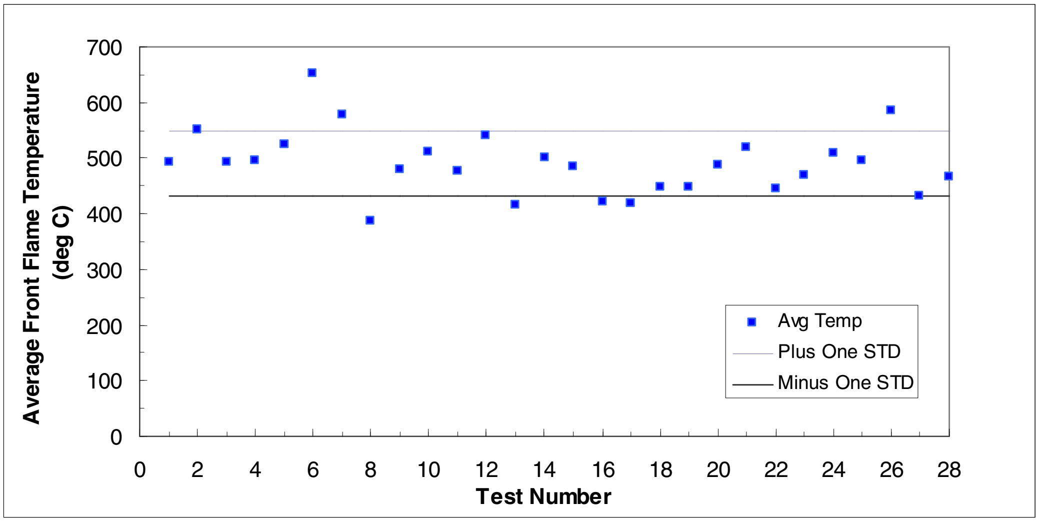

Figure 22: Multiple cycle propane flame exposure test flame temperatures

The two lines in Figure 22 represent plus and minus one standard deviation and are separated by 115 °C.

4.7.7 Multiple Cycles Time to Ignition

The time to flamelets is evaluated as the total time the propane burner remains on. The average time to flamelets for the multiple exposure tests is 190 s, only 10 s longer than the continuous exposure tests.

Table 15: Time to ignition for multiple cycle propane flame exposure test

Test Number	Damage	Condition	Burner Condition On s	Burner Condition Off S	Time to Flamelets s
4	No	Un-Fired	40	40	157
24	No	Un-Fired	40	40	187
19	No	Un-Fired	40	40	199
16	No	Fired	40	40	229
13	Forklift	Un-Fired	40	40	NI
17	Forklift	Un-Fired	60	20	174
22	No	Un-Fired	60	20	209
7	No	Un-Fired	60	20	232
20	No	Un-Fired	60	20	318
5	No	Un-Fired	60	40	100
14	Abrasion	Un-Fired	60	40	116
15	No	Fired	60	40	164
11	Forklift	Un-Fired	60	40	227
10	No	Un-Fired	60	40	233
9	No	Un-Fired	60	40	236
8	No	Un-Fired	60	40	NI
21	No	Un-Fired	60	60	168
18	Forklift	Un-Fired	60	60	178
6	No	Un-Fired	60	60	NI
27	No	Un-Fired	60	60	NI
3	No	Un-Fired	80	40	122
25	No	Un-Fired	80	40	151
12	Forklift	Un-Fired	80	40	160
23	No	Un-Fired	80	40	213
2	No	Un-Fired	130	40	95
26	No	Un-Fired	130	40	205
28	No	Un-Fired	130	40	252
1	No	Un-Fired	155	40	225

Four tests in the multiple cycle propane flame exposure test did not meet the criterion for ignition during the prescribed test conditions; they are indicated with NI in the above table.

The time to ignition versus various burner off times is plotted to depict the results presented in Table 15. The ignition behavior associated with burner off times is assessed to investigate whether a minimum time between rocket firings is needed to prevent ignition. The different symbols represent the various burner on times used throughout the multiple cycle tests.

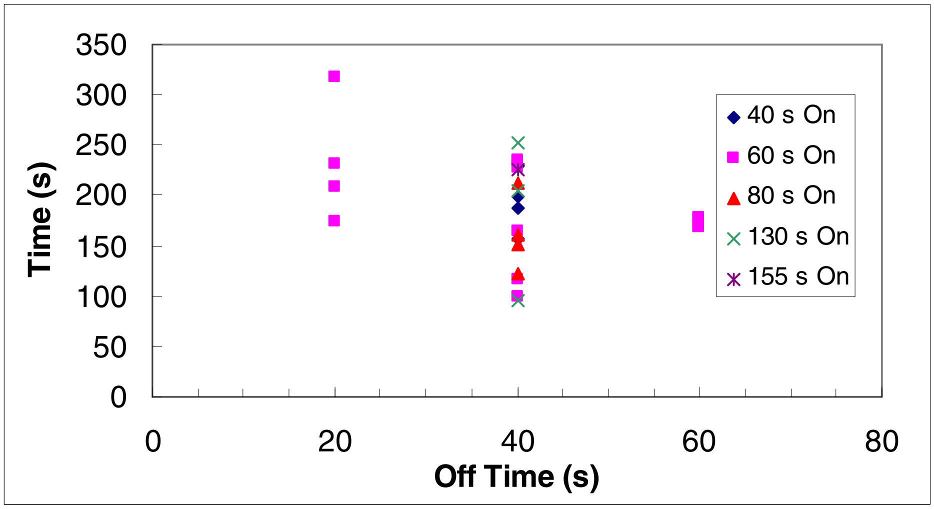

Figure 23: Multiple Cycle: Time to ignition versus burner off time

Figure 23 plots each multiple cycle test where ignition occurs. The average time to ignition is calculated for each burner off time, Figure 24. The bars represent the range of data points collected.

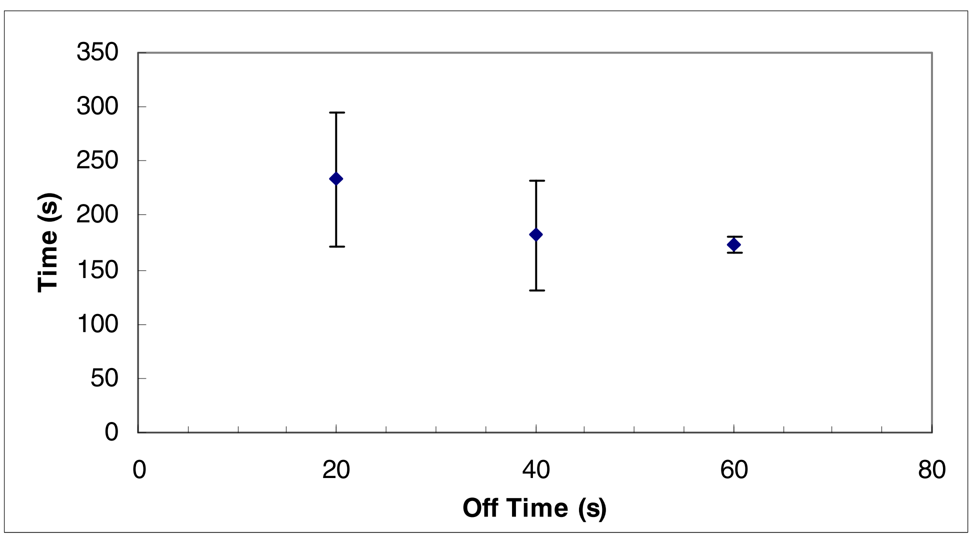

Figure 24: Multiple Cycle: Average time to ignition with range bars versus burner off time

The average time to ignition versus burner off time in Figure 24 form an approximate horizontal line at time 190 s. The close proximity of each burner off time group to the average ignition time indicate that over the range tested the burner off time does not affect the time to ignition.

4.7.8 Dimensionless Temperature Plots

The dimensionless temperature calculations described earlier for the continuous test is conducted for the multiple cycle propane burner experiments. The plots of the dimensionless temperature and the time are shown below for each experiment along with averages. The plots are able to show a range of Biot numbers for the continuous propane flame experiments. The plots show that the average Biot number is less than 0.1, supporting the use of the lumped capacitance method for energy calculation. Furthermore, the experimentally determined Biot number may be used to calculate the heat transfer coefficient. The experimentally determined heat transfer coefficient is compared to the coefficient calculated using the benchmark values for the propane burner. The heat transfer coefficient comparison provides further experimental validation.

The dimensionless temperature is obtained from the front flame temperature, the external tube temperature and ambient temperature thermocouple measurements. The equation for the dimensionless temperature is discussed in Chapter 1. The plots below incorporate the dimensionless temperature and Biot number lines. The Biot number lines are included in the below plots through curve fitting. The experimental dimensionless temperature lines were off-set by 15 s to correspond to the pre-heat time the burner experiences, as previously discussed in section 4.6.11. Figure 25 plots an average of each experimental sub-set along with the boundary Biot numbers. An experimental sub-set is the seven on and off time durations for the propane burner. The average Biot number is 0.083. The average Biot number of the multiple cycle test further confirms the ability to use a lump capacitance method for the burner energy calculation. Figure 26 also plots the average Biot number that a majority of the experiments trend with.

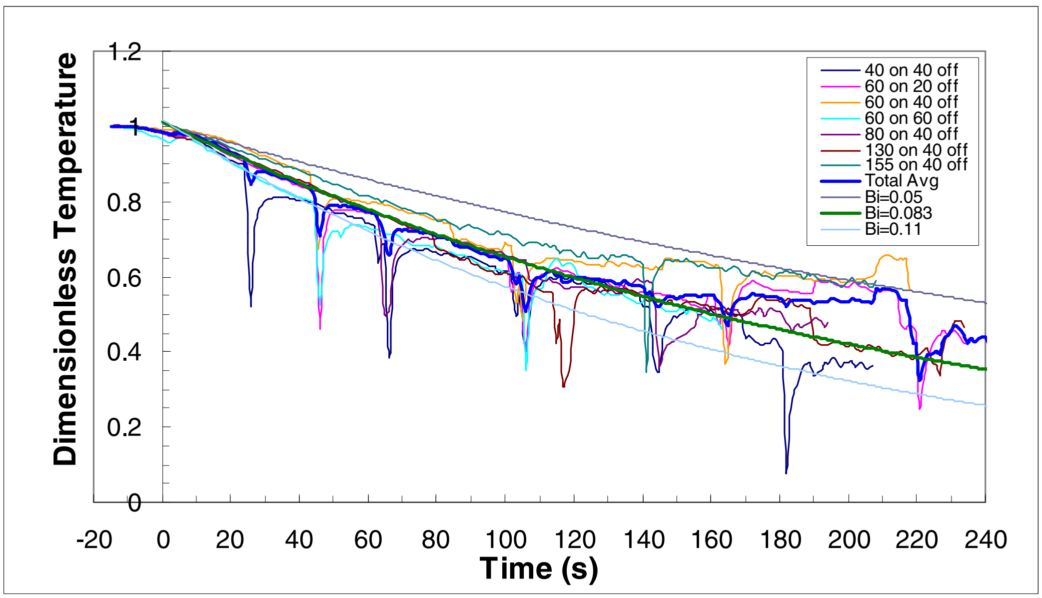

Figure 25: Multiple cycle test: Average dimensionless temperature of each test sub-series

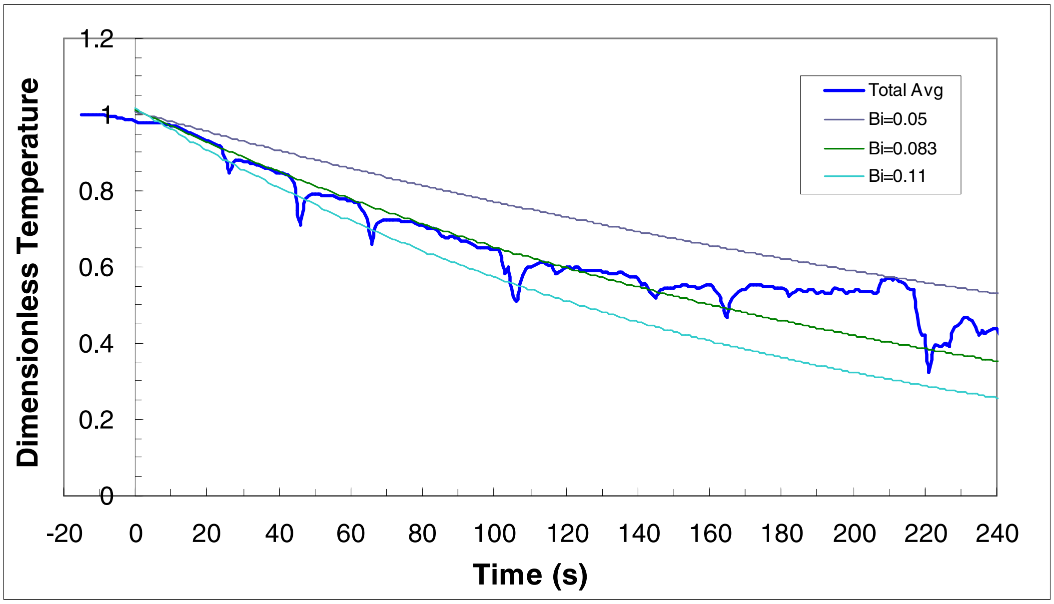

Figure 26: Multiple cycle test: Average dimensionless temperature of all tests

The dips in the otherwise smooth curves in the above plots correspond to the time that the propane burner is turned on and off. The main portion of burner off time is removed from the calculation indicating the sharp descents on the left portion of each dip. When the burner is turned on again a few seconds of warm up time are required before the flame is at full length. The gradual increases on the left side of the dips correspond to the warm up time.

4.7.9 Biot Number

The multiple cycle exposure test in Figure 26 indicate that the Biot number range is between 0.05 and 0.11 with an average value of 0.083. The range indicates that a lump capacitance method may be used when calculating the energy input. The increase in the average dimensionless temperature line after 160 s separates the average curve from the average Biot number curve. The increase in the dimensionless temperature line results in a Biot number closer to 0.05. A smaller Biot number indicates the lump capacitance method is more valid.

4.7.10 Experimental Heat Transfer

The multiple cycle test yields a range of Biot numbers. The definition of the Biot number and a range of conductivity values are used to determine an approximate heat transfer coefficient for the experiments, Table 16. The average heat transfer coefficient is 25.2 W/m^2K determined from the average multiple cycle test values.

Table 16: Multiple cycle heat transfer coefficient

	Heat Transfer Coefficient, h (W/m^2 K)				
	Thermal Conductivity, k (W/m K)				
Bi #	0.1	0.7	1	1.3	10
0.05	1.5	10.6	15.2	19.7	151.5
0.083	2.5	17.6	25.2	32.7	251.5
0.11	3.3	23.3	33.3	43.3	333.3

The average heat transfer value is consistent with the heat transfer coefficients determined from the continuous exposure experiments and benchmark value calculations. Furthermore the additional similarity in Biot numbers between propane test groups further indicate that experimental heating conditions are comparable throughout the testing protocol.

Chapter 5: Combined Energy Input Results

5.1 Introduction

Analysis of the rocket energy input and propane burner input allows for a comparison between the two exposures. The objective of the comparison is to determine an approximate number of rockets that must be fired in a short period of time to lead to tube ignition conditions.

The available rocket plume data is from only one rocket firing that did not result in a fire. Rocket plume data is not available for cases when tube ignition occurred.

The data gathered from the propane burner experiments allow for analysis of ignition conditions of the tube but with a propane flame not a rocket plume.

The results of the two energy analyses allow for comparison of a single rocket plume to tube ignition conditions. The calculated energy input for a single rocket plume and ignition energy input for the propane burner are shown below.

5.2 Energy Analysis

From previous analysis in Chapter 2 the average energy imparted to the tube by a single rocket plume is 756 kJ/m^2. The energy calculation using the benchmark experimental flame temperature and ignition time yields an average energy input from the burner to the tube of 1026 kJ/m^2. The average experimental energy calculation using the experimentally determined heat transfer coefficient from the Biot number trendline is 1153 kJ/m^2.

Dividing the propane burner energy for tube ignition by a single rocket plume energy input yields an approximate number of rockets that must be fired in rapid succession to obtain tube ignition conditions. Using the average values for the energy calculations approximately 1.4 rockets must be fired in rapid succession to lead to tube ignition conditions. The tube fire is a rare event that is supported by the result showing that more than one rocket must be fired in rapid succession before ignition conditions occur.

Chapter 6: Summary

The testing protocol described above is developed in the absence of testing with real rocket motors. The three experiments included in the protocol are conducted to determine the ignition conditions of fiber glass epoxy rocket tubes used by the U.S. Military. Each test is designed to test a large number of variables with limited resources in a repeatable manner.

The cone experiment is used to impart a well characterized incident heat flux in a controlled environment to small undamaged samples. The propane flame exposure tests are conducted to provide a repeatable test in a laboratory setting where experiments are done on tubes of various conditions.

The cone experiment demonstrates that an un-fired tube and previously fired tube ignite under approximately the same conditions. The cone tests have a controlled environment where the specimens are tested, limiting the number of variables affecting the test. The cone test indicates that the average time to ignition for the tube samples are independent of tube condition.

The propane burner experiments allow for different types of damage to be tested along with burner off times. The continuous burner experiments test the ignition conditions of different types of damage along with undamaged tube sections. The results of continuous burner experiments indicate that tube damage does not make a significant difference in the time to ignition. The average time to ignition for the continuous exposure tests are 180 s irregardless of tube damage. The multiple cycle test provides information on time to ignition when the burner is switched on and off several times. The burner off time is used to simulate the lag time between rocket launches. The limited range of the burner off times tested indicates that there is approximately no difference in the tube ignition time, average 190 s.

The propane burner experiments also provide information on the heat transfer coefficient by ways of determining an experimental Biot number. The experimental Biot number is calculated using a dimensionless temperature term plotted versus time. The average Biot number is approximately 0.085 indicating that a lump capacitance method may be used for the energy calculations. The approximate average experimental heat transfer coefficient is 25 W/m^2K.

Heat transfer correlations are also used to determine the energy input to a tube from a rocket plume and a propane burner. To use the correlations it is assumed that the rocket plume conditions and propane burner conditions fall within the recommended ranges. Specifically, complications due to the supersonic speed and high temperature of the rocket plume are ignored. It is also assumed that the conditions within the tube are fully developed for both the rocket plume and propane flame experimental set-up.

The heat transfer coefficient for the propane burner is approximately 26 W/m^2K, determined from the experimental Biot number trend lines. The Biot number trendline calculated energy input is 1153 kJ/m^2. Similar to the Biot number energy calculation, approximately 1030 kJ/m^2 of energy is put into the tube at the time of ignition following the benchmark value calculation.

The heat transfer coefficient for the rocket plume is approximately 1276 W/m^2K. One rocket plume imparts approximately 750 kJ/m^2 into the tube.

The propane burner energy input at ignition is compared to the amount of energy one rocket plume imparts to the tube. The comparison yields approximately 1.4 rockets must be fired in rapid succession to create tube ignition conditions.

To further test the reliability of the heat transfer calculations that are used in the comparative analysis between the rocket plume and propane burner key input variables are adjusted and the problem re-calculated to test their impact on the final solution. Through the adjustment analysis, it is found that the plume temperatures, rocket and propane, and the impact time of the rocket plume are driving factors in determining energy input to the tube. Thermal conductivity also plays a role in the experimentally determined heat transfer coefficient. The theory further supports that the temperature of the plumes and the time of impact are the controlling factors per the calculation section.

The MLRS rocket tube fires are rare events as reported by the U.S. Army. The experimental data indicates that tube type and condition do not affect the ignition conditions of the tube. Furthermore heat transfer analysis of the rocket plume data and experimental results indicate that over one rocket must be fired in rapid succession to lead to tube ignition conditions.

Chapter 7: Future Research

Future research goals may be to conduct the same experimental approach with more intense exposures, including using actual rockets to test different tube conditions. Full scale tests over longer lengths of tube with more intense exposures may also be conducted.

Sustained burning characteristics once the tube ignites may also be studied. During the experiments it was observed that the tubes had different burning characteristics and fire severities in the tubes that ignited. Some of the tubes self-extinguished quickly, while other tubes burned for many minutes with increasing intensity. Further investigation may focus on the severity of the fire that develops under different tube characteristics. Investigation into the tube manufacturing processes and tolerances allowed may also be the subject of additional study.

The burner off time may also be varied with the multiple cycle propane flame exposure test. A longer burner off time will expand the test criteria. The longer off times that may be tested will provide more data to determine what if any affect on time to ignition the burner off time has.

A similar sequence of tests using the propane burner may also be conducted with the tube orientation at angles other than 45°. The range of angles tested should fall within the abilities of the HIMARS.

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