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Min Eng. Author manuscript; available in PMC 2016 June 30.

Published in final edited form as:
Min Eng. 2016 June ; 68(6): 45–50. doi:10.19150/me.6628.

NEW IMPROVEMENTS TO MFIRE TO ENHANCE FIRE MODELING CAPABILITIES

L. Zhou [Mining Engineer]
NIOSH, Pittsburgh, PA

A.C. Smith [Research Chemist]
NIOSH Pittsburgh, PA

L. Yuan [Fire Protection Engineer]
NIOSH Pittsburgh, PA

Abstract

NIOSH's mine fire simulation program, MFIRE, is widely accepted as a standard for assessing and predicting the impact of a fire on the mine ventilation system and the spread of fire contaminants in coal and metal/nonmetal mines, which has been used by U.S. and international companies to simulate fires for planning and response purposes. MFIRE is a dynamic, transient-state, mine ventilation network simulation program that performs normal planning calculations. It can also be used to analyze ventilation networks under thermal and mechanical influence such as changes in ventilation parameters, external influences such as changes in temperature, and internal influences such as a fire. The program output can be used to analyze the effects of these influences on the ventilation system. Since its original development by Michigan Technological University for the Bureau of Mines in the 1970s, several updates have been released over the years. In 2012, NIOSH completed a major redesign and restructuring of the program with the release of MFIRE 3.0. MFIRE's outdated FORTRAN programming language was replaced with an object-oriented C++ language and packaged into a dynamic link library (DLL). However, the MFIRE 3.0 release made no attempt to change or improve the fire modeling algorithms inherited from its previous version, MFIRE 2.20. This paper reports on improvements that have been made to the fire modeling capabilities of MFIRE 3.0 since its release. These improvements include the addition of fire source models of the t-squared fire and heat release rate curve data file, the addition of a moving fire source for conveyor belt fire simulations, improvement of the fire location algorithm, and the identification and prediction of smoke rollback phenomena. All the improvements discussed in this paper will be termed as MFIRE 3.1 and released by NIOSH in the near future.

Keywords

mine fire; mine fire simulation; smoke rollback; conveyor belt fire

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Introduction

The MFIRE program, originally developed in the 1970s by the U.S. Bureau of Mines (now the Office of Mine Safety and Health Research (OMSHR) at the National Institute for Occupational Safety and Health (NIOSH)) and Michigan Technological University, has been a mainstay in modeling of the mutual influences between a fire and the mine ventilation system during an underground mine fire. Several update versions have been released over the years, including MFIRE 1.27, 1.29, 1.30, 2.0/2.01, 2.10, and 2.20. The MFIRE program logically comprises four parts: (1) a conventional network calculation, where it performs the basic network balancing without considering heat or mass transfer; (2) a temperature calculation to establish the reference temperature distribution before a non-steady state (transient-state) simulation; (3) a transient-state simulation that follows changes in ventilation step-by-step to produce a continuous description of the temperature distribution, smoke, and contaminant spread through the ventilation system during a fire event; and (4) a quasi-equilibrium simulation to predict the state of the ventilation system after a relatively long period of time (defaulted as 5 hours in MFIRE) as the fire reaches a quasi-steady state. In summary, MFIRE is a computer simulation program that performs normal ventilation network planning calculations and dynamic transient-state simulation of ventilation networks under a variety of conditions including the influence of natural ventilation, fans, fires, or any combination of these (Chang et al., 1990).

The MFIRE program is widely accepted as a standard for mine fire simulations. MFIRE, as an open source software, has been indirectly commercialized by many mine ventilation software companies with their graphical user interface (GUI). For example, Mine Ventilation Service, Inc. (MVS) adopted the MFIRE source code in conjunction with VnetPC, a mine ventilation simulation software published by MVS. MVS later utilized MFIRE in a commercial software product released as MineFire and the later MineFire Pro+ as part of its upgraded ventilation package VnetPC Pro+ (MVS, 2015; Schafrik, 2011). Ohio Automation, a mine planning, mine ventilation, mine fire, and mine water simulation software company, has developed and published the Integrated Computer Aided Mine Planning software (ICAMPS) MineFire, an AutoCAD application that offers powerful graphical user interfaces to the MFIRE program (Ohio Automation, 2015). The integration of VUMA-3D and MFIRE is undergoing development (Botma and Glehn, 2015). VUMA-3D is a windows based software packages for mine ventilation, cooling and environment control developed by Bluhm Burton Engineering (BBE) in South Africa (VUMA, 2015).

Besides its broad acceptance in the mining industry, MFIRE has also been used in tunnel fire modeling. Miclea (1991) reported very similar results of an application of both the Subway Environment Simulation (SES) and MFIRE from the same tunneling network. Cheng et al. (2001) used MFIRE to simulate a hypothetical fire outbreak in the Taipei Mass Rapid Transit System to investigate the direction and rate of airflow, temperature distribution, and emergency ventilation response. MFIRE was also verified with a laboratory-based fire simulation conducted in a small physical tunnel network prior to the application in a real fire by Cheng et al. (2001).

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Since MFIRE 2.20 was released in 1995, some significant modifications have been made to the program. These modifications mainly consisted of either changes to the programming language from the original DOS-based FORTRAN to object orientated programming languages (such as C++ and C#), or improvements to the fire models employed in MFIRE. MFIRE 2.20, written in FORTRAN 77 and running under a DOS operating system, is considered antiquated by current computer standards (Smith et al., 2012). Researchers at the University of Nevada-Reno converted the conventional network calculation part and temperature calculation part of MFIRE from FORTRAN language to C++ for the purpose of providing a ventilation simulation for a mine virtual reality project (Cheng, 2000; Liao, 2000). Zhou (2009) rewrote MFIRE from FORTRAN to Visual C++ to connect the core part of MFIRE with a mine ventilation software package named Mine Ventilation System Analysis software (MVSAS) developed by Xi'an University of Science and Technology in China. In this application, MVSAS serves as the GUI of MFIRE to allow users to input data and display simulation results graphically.

In 2012, NIOSH completed a major redesign and restructuring of MFIRE, released as MFIRE 3.0 (Figure 1). The redesign and the restricting of MFIRE replaced FORTRAN with an object-oriented C++ language and packaged MFIRE into a dynamic link library (DLL). The MFIRE DLL makes it easier for third-party developers to obtain ventilation network data from the common memory rather than the default MFIRE data output files. In addition, the program was split into a front-end with a simple GUI, and back-end containing the MFIRE “engine.” The MFIRE program was written as a discrete event simulation library so that it can be used to simulate the progress of mine fires over time, under the control of user inputs through the GUI. Additionally, MFIRE was also improved with eliminating the limit to the size of mine network that can be modeled, adding the ability to accept metric measurement units besides the original imperial units. (Smith et al., 2012).

In contrast to the broad attention on modernizing MFIRE with respect to the programming language, less has been done on the improvements of the fire modeling. Neither MineFire Pro+ nor ICAMPS MineFire has made any changes to the source code of MFIRE except for increasing the number of branches, junctions, and fans available to run in windows with MineFire Pro+ (Schafrik, 2011). The restructuring and recoding work in the modernization of MFIRE 3.0 focused on the upgrading of the programming language from FORTRAN to Visual C++ and Visual C#, and there were no changes nor improvements made in the fire modeling.

Since the release of MFIRE 2.20 by US Bureau of Mines in 1995, the first improvement to MFIRE's fire models was done by Zhou and Luo (2010, 2011). The improvements included the addition of a time-dependent fire source using a t-squared fire, the addition of a moving fire source typically used in the conveyor belt fire simulation. Zhou and Luo's improvements on the fire modeling were programmed into a new version of MFIRE termed as MFIRE 2.30 (Zhou and Luo, 2011). After the release of MFIRE 3.0 by NIOSH in 2012, Zhou and Smith (2012) made the improvement to MFIRE3.0 by adding a module to identify and predict smoke rollback phenomena. Unlike all the MFIRE versions prior to 2.20, MFIRE 2.30 and MFIRE 3.0 were both written with Visual Studio C++ language. However, MFIRE 2.30 doesn't utilize DLL technique to enable third party developers to get access to the input and

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output of MFIRE. Therefore, the code containing the new improvements to fire modeling in MFIRE 2.30 could not be used directly by NIOSH's MFIRE 3.0. A great amount of work was completed recently to migrate the fire source models, smoke rollback model, and moving fire model from MFIRE 2.30 to MFIRE 3.0. In addition, some other new improvements were also completed to bring MFIRE 3.0 to a new level functionally. In this paper, all the updates and improvements to MFIRE 3.0 in relation to fire modeling will be introduced and described. All the new improvements will be included in MFIRE 3.1 and released by NIOSH in future.

Addition of two time-dependent fire source models

When simulating mine fire behavior, it should be obvious that the accuracy of such a simulation is highly dependent on the successful specification of the fire source. MFIRE users can choose from among three types of fires (fixed heat input fire, oxygen rich fire, and fuel rich fire) to appropriately model a given fire situation. The fixed heat input fire refers to a fire which is defined by a specified heat influx and a specified fume production rate (Laage et al., 1995). The oxygen rich fire is defined by the concentration of oxygen contained in the ventilation stream downstream from the fire. MFIRE calculates a corresponding heat influx due to the fire by multiplying the amount of oxygen lost through combustion by the standard combustion ratio multiplier, for which Laage used 437 BTU per cubic foot (16,000 kJ per cubic meter) of oxygen consumed (Laage et al., 1995). The heat release rate from a fuel rich fire is defined by the ventilation rate through the fire zone and a user-defined heat release per cubic foot of oxygen delivered to the fire. MFIRE calculates a corresponding heat influx by multiplying the number of cubic feet per minute of oxygen lost through combustion, assuming the airflow contains 21% oxygen (Laage et al., 1995).

HRR from a “t-squared” fire

Oxygen rich and fuel rich fire modelling are somewhat unique to mine situations. Unfortunately both oxygen rich and fuel rich fire models require an estimation of the oxygen concentration in the fire affected area. The lack of data availability and the simplification of the MFIRE model limit the ability to model these type events. As the most easily defined fire source model in MFIRE, the fixed heat input fire has been found to be the most generally applicable fire type for routine fire modeling purposes (Laage et al., 1995). However, the drawback of the fixed heat input fire is obvious: the heat release rate (HRR) in the fixed heat input fire is constant throughout the whole fire period, while in real fires the fire intensity varies with time. A t-squared fire model with various heat release rates for each fire development stage was added to the MFIRE program to interpret the fire growth from ignition to fully developed, and through decay. T-squared fire, characterizing the HRR as the second power of the time measured from an ignition time, was introduced to MFIRE 2.30 (Zhou and Luo, 2010). The comparative results on the calculated temperatures from the t-squared fire and the fixed heat input fire in the simulation of a diesel fuel test in the Waldo Mine near Magdalena NM showed that the t-squared fire was in much better agreement with the experimental results than the fixed heat input fire (Zhou and Luo, 2010).

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As a result of the successful application of the t-squared fire in MFIRE 2.30, this model was incorporated into MFIRE 3.0, as well. Compared to the fixed heat input fire with the constant HRR throughout the entire fire period, the t-squared fire is capable of quantifying the HRR for different fire periods, growth periods, fully developed fire periods, and decay periods. Figure 2 displays the t-squared fire HRR curve profile initially used in MFIRE 2.30 and now included in MFIRE 3.0. To summarize the previous findings, the t-squared curve consist of three segments: an increasing HRR during the fire growth period (from t_0 to t_1), a simplified constant HRR for the fully developed fire period (from t_1 to t_2), and a declining HRR for the decay period (from t_2-t_3). The time period from 0 to t_0 is called the ignition delay period. This is the period from ignition to flaming. It is assumed that there is no heat release during this period. To input a t-squared fire in MFIRE 3.0, five variables are required to be specified—the time specifying each fire period t_0, t_1, t_2, t_3 and the maximum HRR $\dot{q}_{\max}$. More details about the t-squared fire and its validation study can be found in Zhou and Luo (2010).

HRR curve input from file

With the current fire models, such as a fixed HRR, oxygen rich fire, fuel rich fire, and t-squared fire, a fire with a measured HRR curve had to be simplified to the fixed input fire or t-squared fire due to the inability of the fire source model to accept the HRR curve. For example, Figure 3 displays a heat release rate curve obtained from a conveyor belt fire test conducted at NIOSH. With the current fire source models of MFIRE 3.0, the best way to input this fire is to simplify it to a closed t-squared fire. This simplification reduces the simulation accuracy, therefore, it is important for MFIRE to be able to read the exact HRR data as the input.

Although the real HRR curve from a mine fire is important in simulating the fire accurately, the HRR curves for different mine fires may not be available in practice. For the users of the MFIRE program, it is desirable to have typical HRR curves for commonly used combustible materials in underground mines such as coal, wood, and conveyor belt. The HRR curves for coal and wood crib fires were obtained by Egan (1987, 1986) through studying coal and wood crib fires in an intermediate-scale ventilated tunnel which simulates environmental conditions in underground mines. When applying these HRR curves to MFIRE simulations, the HRR curve needs to be input to the model, and the total amount of coal or wood involved in the fire needs to be estimated. Because those HRR curves were obtained from the intermediate-scale tests involving small amount of coal or wood, the curves need to be scaled to the total amount of coal or wood involved in a real mine fire. This is why the total amount of coal or wood needs to be estimated. For other mine fires like conveyor belt and equipment fires, as long as the HRR curves are obtained from full-scale tests, the total amount of combustible is not needed for the input. Only the real HRR curves are needed for the input, not any user defined functions. The HRR curve for the conveyor belt fire shown in Figure 2 was obtained by Yuan et al. (2014) in large-scale tests conducted in a ventilated tunnel. The belt tested was a styrene-butadiene rubber (SBR) belt that passed the 2G test, but not the Belt Evaluation Laboratory Test (BELT) as described in 30 CFR 14.20. The maximum HRR from the burning belt was over 7 MW. For more fire-resistant belts that pass the BELT test, the maximum HRR would be lower than 7 MW, and this can be considered as

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the worst-case scenario. Vehicle fires can also occur in underground mines. Hansen and Ingason (2013) measured HRR values of burning mining vehicles (wheel loader and drilling rig) in an underground mine. For different mining vehicles, the maximum HRR may be different, but the shape of the HRR curve can be similar. An effort will be made to create a typical HRR curves database for various mine fires in the future research.

It should be noted that the addition of t-squared or available heat release rate curves does not eliminate the available usage of the three original fire sources. The additions have given users more options to choose the best approach to enter a fire source in MFIRE 3.1.

Smoke rollback identification and prediction

Smoke rollback occurs in tunnels when the buoyancy force generated by a fire overcomes the inertial forces of ventilation to cause smoke migration upwind along the roof counter to the ventilation airflow. Smoke rollback can be a dangerous and potentially threat to miners and firefighters in an underground mine fire, preventing firefighters from getting close enough to fight a fire effectively in an underground mine entry. It can also bring flame from the fire back onto firefighters when they fight the fire at the upstream of the fire. Therefore, it is important to know if an evacuation path is free of smoke in an underground mine fire emergency. The MFIRE fire model is capable of tracking the smoke spread route in a ventilation network with consideration of the interaction between fire and ventilation. However, the MFIRE program is only able to simulate complete smoke reversal caused by flow reversal, with only one direction of flow, in an airway. The simulation of partial smoke rollback with the hot smoke layer flowing in the direction opposite to the ventilation stream is beyond the scope of MFIRE. However, the ability to predict smoke rollback can greatly improve the chances for safe miner evacuation and mine fire control and firefighting. In Zhou and Smith's (2012) research, a smoke rollback identification equation was incorporated into MFIRE 3.0, making it possible to recognize smoke rollback and calculate the smoke rollback distance. The main program of MFIRE calls the newly added smoke rollback function to calculate the critical velocity and compares the actual velocity to the critical velocity. If the actual velocity is lower than the critical velocity, the incoming airflow in the fire branch fails to prevent the smoke from rolling back. If the actual velocity is greater than the critical velocity, there is no smoke rollback. It should be also noted that the occurrence of smoke in an airway of a mine ventilation network can cause the resistance increase due to throttling effect in the airway and subsequently cause change to the actual air velocity.

A case study based on an experiment in the NIOSH Safety Research Coal Mine (SRCM) using the improved MFIRE model achieved good agreement between the predictions of the model and the experimental results. More details about this study can be found in Zhou and Smith's (2012). The smoke rollback identification and rollback length estimation have been included in MFIRE 3.1. However, MFIRE3.0 was restructured to a front-end with a simple Graphical User Interface, and back end containing the MFIRE engine. The improvements of MFIRE presented in this paper only occur at the back end engine. No effort has been, also not necessary, made to improve the interface. Therefore, smoke rollback cannot be visualized in MFIRE 3.1. We have been working very closely with some mine ventilation software vendors to integrate MFIRE to their commercial available software. With all the

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results provided by MFIRE, the vendors will be able to develop the smoke rollback visualization in their software.

Conveyor belt fire modeling

Conveyor belt fires present a serious safety hazard to underground mining and have always been a great concern in fire detection and prevention. A conveyor belt as a typical solid combustible can result in fire spread over considerable distance in an underground coal mine, unlike any liquid combustibles such as diesel fuels that generally limited to a localized region. An MSHA investigation report (Glusko, et al., 1991) stated that a conveyor belt fire spread a distance of about 274 m (900 ft) in about 9 hours. Research and experimental studies (Lazzara and Perzak, 1987; Yuan and Litton, 2007) have shown that the rate of the flame propagation along a conveyor belt is largely affected by the air velocity of the belt entry, and the peak flame spread rate is generally reached at the air velocity of 1.5 m/s. While the relationship of velocity to belt fire flame propagation has been long been recognized, all previous fire source models, including the newly added t-squared fire and HRR curve, are for stationary fires only and are incapable of simulating the flame spread along a conveyor belt. Obviously, a conveyor belt fire may be a moving fire spreading along the conveyor belt instead of a stationary fire localizing within a small region. To model the flame spread, a moving fire source model was developed and included in MFIRE3.1. The original MFIRE input file format was modified to allow the new variables relevant to the moving fire source, such as the maximum flame spread rate, the corresponding air velocity, and the potential traveling route, to be entered into the program.

To simulate flame spread of a conveyor belt fire, simplifications and assumptions are necessary in the one-dimensional MFIRE network model. First, the conveyor belt fire is considered as a point fire source without considering the length of the burning zone. Second, it is assumed that no heat is released from the burned conveyor belt area where the flame front has passed. Third, the model considers that the conveyor belting material is the only fuel involved in the moving fire. The model does not account for any combustion of coal on the conveyor belt, wood supports, or any other combustible material in the path of the moving flame front. Last, a conveyor belt fire only can move forward no matter what direction of air is flowing. As the airflow reverses, the flame will stop moving forward in MFIRE program.

The two critical aspects of developing a moving fire source model in MFIRE are the determination of flame spread rate and the tracking of fire location. There are two types of moving fire source models that were defined in MFIRE 2.30 (Zhou and Luo, 2011): the constant flame spread fire and non-constant flame spread fire. The constant flame rate refers to a flame spreading at a constant rate without being affected by airflow velocity during its spreading process. Users are required to determine this value based on the flammability property of a conveyor belt. The constant spread rate moving fire is a simplified moving fire source model.

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The non-constant spread rate moving fire takes into consideration the impact of airflow velocity on the spread rate. Equation (1) defining the relationship between the airflow velocity and the flame spread rate was developed by Zhou and Luo (2011).

$$\nu_f = \begin{cases} = & \frac{\nu_{fx}}{\nu_{ax}}\nu_a & (\nu_a \le \nu_{ax}) \\ = & \nu_{fx} - \frac{\nu_{fx}}{\nu_{ax}}\nu_a & (\nu_{ax} < \nu_a \le 2\nu_{ax}) \\ = & 0 & (\nu_a > 2\nu_{ax}) \end{cases} \quad (1)$$

where ν_f = flame spread rate

ν_{fx} = maximum flame spread rate

ν_a = airflow velocity in the fire branch

ν_{ax} = airflow velocity as the flame spread rate reaches the maximum

Given the airflow velocity of the fire branch (V_a) calculated by MFIRE dynamically, the maximum flame spread rate (V_{fx}) and the corresponding airflow velocity (V_{ax}) specified by users based on the flammability property of a conveyor belt, the flame spread rate can be obtained through Equation (1). Since the airflow in a fire branch changes dynamically due to the disturbances from a fire, the flame spread rate built upon this equation will change accordingly. The fire advances at the obtained spread rate for each simulation interval.

Compared to a stationary fire source in MFIRE, a moving fire source requires a continuous tracking of its location. The moving fire source responds to not only the advancement of each air segment but also the advancement of the fire source itself in a complex ventilation network. It is possible that the moving fire can move out of its original branch during the flame spread process. A potential travel route of a moving fire needs to be specified with branch IDs in sequence. The original MFIRE input file format was modified to allow the new variables relevant to the moving fire source, such as the maximum flame spread rate, the corresponding air velocity, and the potential traveling route, to be entered into the program.

Improvement on the fire source location

At the time the original MFIRE source code was developed, limited computer processing power compared to today lead to many simplifications. One such simplification was the location of the fire source. In the original MFIRE source code, the fire was assumed to always be located at the end junction of the fire branch. This assumption made it simple to trace each control volume in the transient state simulation. The starting junction of the fire source branch was taken as the starting point of the first control volume. In MFIRE 3.1, improvements are made to the program to locate the exact fire location. New variables are added to the fire source input card in the MFIRE input file to specify the relative location of a fire in the fire branch. The non-steady fire simulation starts from the exact fire location instead of the end of the fire branch. The improved fire source location model will lead to improved simulation accuracies compared to the simplified fire location model.

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Conclusions

In 2012, NIOSH released MFIRE 3.0 with a major redesign and restructuring to replace the outdated FORTRAN with the object-orient language Visual C++. However, the modernization of the MFIRE program did not involve any changes to the fire models applied in MFIRE. This paper reported on recent changes to MFIRE to improve its fire model since the release of MFIRE 3.0.

Fixed heat input fire, oxygen rich fire, and fuel rich fire are the three types of fire source models defined in previous versions of MFIRE. The inability of the fixed heat input fire model to account for fire growth and the difficulty in obtaining oxygen concentrations in a fire for the oxygen rich fire and fuel rich fire models have limited the application of MFIRE. A time-dependent fire model that can characterize the development of a fire against time, a t-squared fire, was added to the MFIRE 3.1 program. In addition, MFIRE 3.1 was improved to be able to include available heat release rate vs. time data. These improvements allow users to input more realistic fire intensity parameters.

A mathematical equation identifying the occurrence of smoke rollback in a fire entry was incorporated into MFIRE 3.1 to enable the program to issue a warning message once a smoke rollback occurs. Additionally, the length of the smoke rollback was also able to be predicted with the newly added smoke rollback identification model.

With all the stationary fire sources defined in the previous versions of MFIRE, it was not possible to simulate the flame spread along a conveyor belt. Two moving fire models, including the constant flame spread rate fire and non-constant flame spread rate fire, were incorporated into MFIRE 3.1. The non-constant flame spread rate fire was determined by considering the relationship between the flame spread rate and the airflow velocity.

An improvement has been made to more closely specify the location of a fire source in MFIRE 3.1. Previous versions assumed the fire at the ending junction of a fire branch.

Finally, this paper is an informational summary for the current and potential users of MFIRE regarding the upgrade of MFIRE from MFIRE 3.0 to MFIRE 3.1. Sufficient research has been done to test each improved feature and included into a couple of previous publications (Zhou, 2009; Zhou and Luo, 2010, 2011; Zhou and Smith, 2012).

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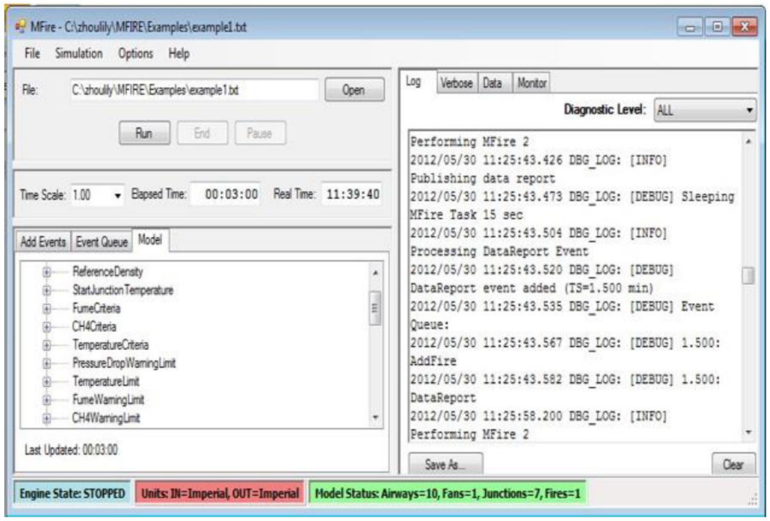

Figure 1.

Interface of MFIRE 3.0

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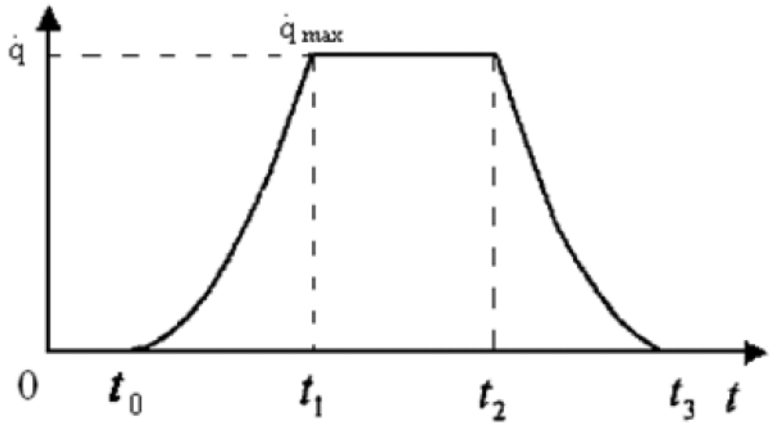

Figure 2.
Idealized t-squared fire curve with HRR vs. Time (source: Zhou and Luo, 2010)

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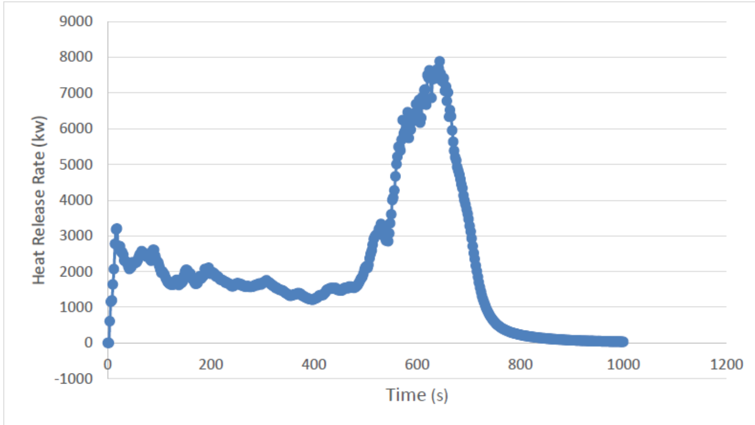

Figure 3.
An example of heat release rate curve vs. time