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Analysis of Sprinkler use in a Library Stack Room Using Fire Dynamics Simulator

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Analysis of Sprinkler use in a Library Stack Room Using Fire Dynamics Simulator

A Major Qualifying Project Report:
submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
By

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Jennifer Moseley
and
Ryan Thomann

Abstract

The NIST Fire Dynamics Simulator (FDS) was used to analyze the effects of implementing an automatic sprinkler system in a library. An initial simulation was run using a point source ignition of 10kW, which indicated that FDS was not accurate in modeling fire spread. This resulted in the use of gas burners with constant heat release rates. Results indicated that the sprinklers retarded temperature rise, which increased the available egress time and the period of structural integrity for the supporting columns.

Acknowledgements

We would like to thank RDK Engineers for their ideas of the library stack room analysis, and also Professor Nicholas Dembsey for his help with fire modeling and Fire Dynamics Simulator. We would also like to thank Professor Tryggvason for taking the time to advise our project.

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Executive Summary

Introduction

Exposure to smoke, fire, and flames has claimed 3.4% of all accidental deaths in the United States according to the National Vital Statistics Report of 2002. This amounts to 3,377 fire-related deaths. The large university library studied in this project is a public building holding the primary source of research materials for a campus of over 25,000 students (based on the university website).

The current problem is that the library is housed in a high-rise building with the fire protection system consisting of four standard smoke detectors per floor. No sprinkler systems have been installed. The columns of the bookcase stacks support the concrete slab and the immediate above floor. This can create a problem in a fire situation because the critical failure temperature for steel is 538°C which can be reached within ten minutes of the start of a fire.

The situation presents problems concerning tenability conditions and structural integrity. Without a fire protection system in place that will control or stall fire growth, the potential for a life threatening situation is undeniable.

Project Goal

The goal of this project was *to use FDS to analyze fire scenarios and the effects of sprinkler systems in a large university library*. Objectives were created to ensure completion of the goal and to demonstrate the need for a fire protection system in the building:

- Create a model of the library.

- Design plausible fire scenarios.
- Design a sprinkler system appropriate for the space.
- Analyze the results given through the use of FDS and hand calculations.
- Compose the results into a set of recommendations for a fire protection system for a typical mezzanine stack floor.

Background

The decision to use FDS was made based on the availability of the software and ease of use. FDS can be downloaded for free from the National Institute of Standards and Technology's website. The program incorporates a form of the Navier-Stokes equations, which are specifically geared towards low-speed, thermally-driven flow, in order to successfully model the movement of smoke and heat from fires. It is most widely used to model smoke movement and fire scenarios in complicated buildings with many obstructions and complex geometry. Once the proper input parameters have been received by FDS, and the program has successfully run through the simulation without error, the output information from FDS is then displayed by a visualization program called Smokeview, which is also readily available on the NIST website.

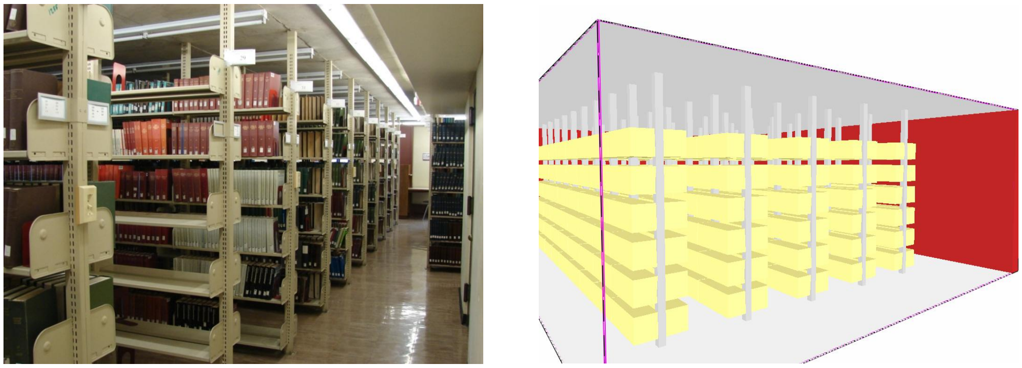

Figure 1: Library stacks were modeled using FDS.

Approach

To analyze the effectiveness of FDS, a model of a typical mezzanine stack floor was created. Due to the symmetry of the stacks and the building, only one corner of the library was modeled with FDS. The book stacks were modeled with the thermal properties of yellow pine to eliminate the time lag to ignition presented by densely shelved books. Temperature sensors were then placed on the tops of the steel columns, which were 2½” x 2½” (cross sectional area), in order to determine the time at which their critical failure temperature was reached.

A preliminary test was run to determine the accuracy of the model. The fire spread unexpectedly fast, which revealed the inability of the program to accurately model fire growth. This is largely due to the fact that FDS assumes the presence of flames when the ignition temperature of a material has been reached. This assumption does not account for pyrolysis, which would take a considerable amount of time to occur in a real fire situation. To combat this, gas burners with constant heat release rates (HRR) were used in place of a growing fire. Using gas burners assumes that the design fire modeled in FDS has already reached its peak HRR, and that a steady state HRR is produced throughout the simulation. Plausible fire scenarios were then created using gas burners with heat release rates ranging from 200kW (wastebasket fire) to 1000kW (arson fire with accelerant), which were consistent with the fuel loading of a typical mezzanine stack floor.

A sprinkler system was added to the model to determine its effectiveness against a growing fire. The sprinklers were positioned with a 10' by 12' spacing and rated for a ordinary hazard group II occupancy.

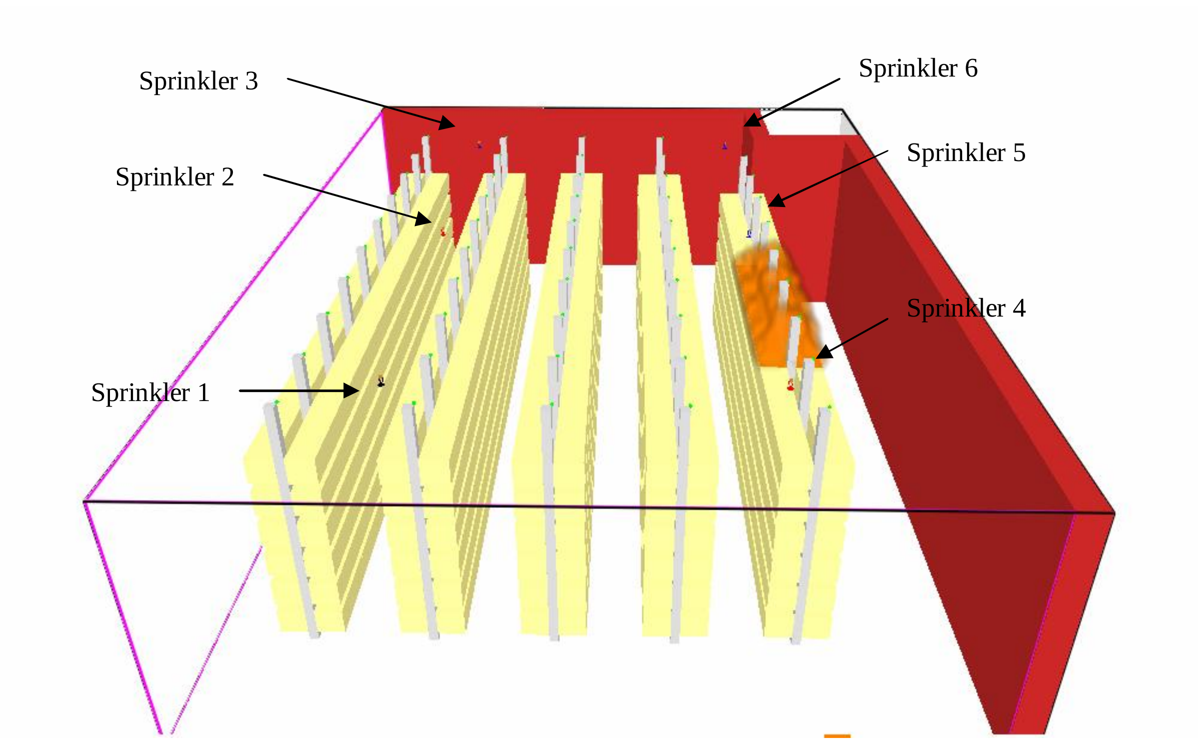

Figure 2: A sprinkler system was designed using NFPA 13 and implemented into the model.

Results and Recommendations

Using the FDS simulation, data was collected from temperature sensors located on the steel columns. Simulations were run with and without sprinklers for the range of heat release rates specified. In some cases, the fire reached a level where temperatures on the columns exceeded the critical failure temperature and local flashover was experienced. In the simulations including sprinklers, the activation of the sprinklers delayed the occurrence of localized flashover. This increases the available safe egress time and maintains tenable conditions longer than the situations without sprinklers. The graphical representation shown below for a 750kW fire shows that the time to localized flashover was almost doubled with the added protection of a sprinkler system.

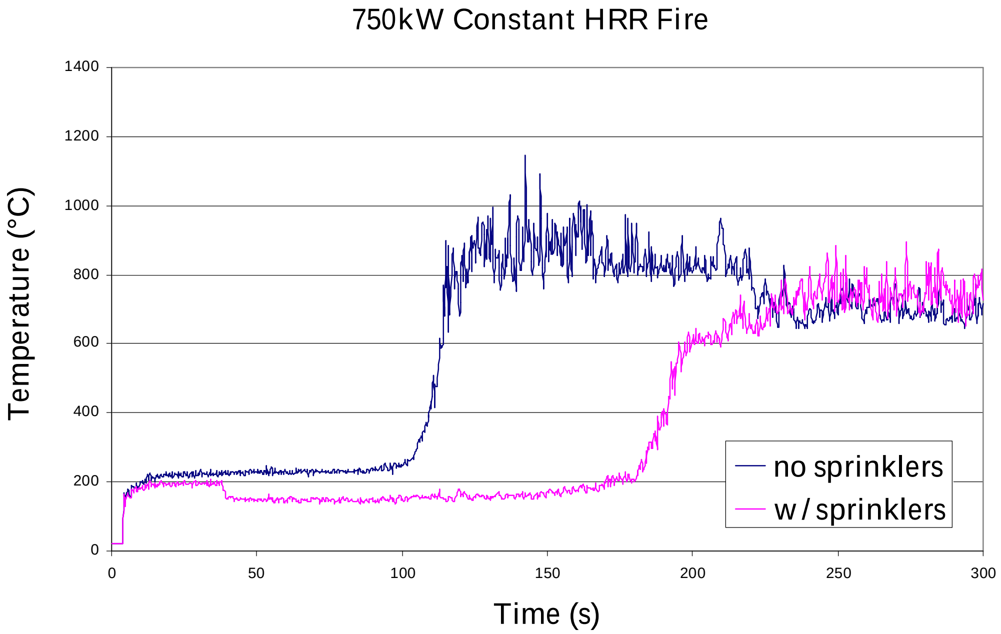

Figure 3: Temperature history for a 750 constant heat release rate fire.

The addition of sprinkler systems in fires ranging 500kW to 1000kW proved to be effective. This means that similar sprinkler systems provide a significant advantage for egress time and tenability conditions for fires in this range. In the cases of lower HRR fires, localized flashover does not occur so a sprinkler system has less effect on egress time.

Fire Dynamics Simulator was successfully used to analyze fire scenarios and the effects of a sprinkler system in a model of the large university library. FDS was effective in creating the model, simulating design fires, and implementing a sprinkler system; however, deficiencies were discovered in modeling fire growth. With the assumptions necessary to produce the most accurate model possible, FDS still proved to be a useful and accurate tool for modeling smoke production and sprinkler activation times. Using

the results from the simulations the following conclusion was drawn. For a typical mezzanine stack floor of any library the installation of the sprinkler system extended the time available for egress and tenable conditions significantly. With this conclusion, installing a similar sprinkler system on mezzanine stack floors of the large university library is highly recommended, although further analysis is necessary to compensate for the deficiencies found in FDS.

Introduction

Exposure to smoke, fire, and flames has claimed 3.4% of all accidental deaths in the United States according to the National Vital Statistics Report of 2002. This amounts to 3,377 fire-related deaths. The large university library studied in this project is a public building holding the primary source of research materials for a campus of over 25,000 students (based on the university website). The library is housed in a building that is classified as high-rise and the only fire protection system in place on a typical mezzanine stack floor consists of four standard smoke detectors. There are no sprinkler systems installed throughout the entire building. The scenario described presents a potentially tragic situation when paired with a fire of any magnitude. In addition to the already life-threatening potential, stacks on the mezzanine levels support the concrete slab ceiling and floor directly above. If the steel columns are exposed to a fire for any significant time, the structural integrity of the steel could fail. This could cause not only a threat to human life, but also to the building itself.

To model the aforementioned situation, a fire simulation program called Fire Dynamics Simulator (FDS) was used to create a model of a typical mezzanine stack floor. Fire situations were tested and analyzed using this computer program, which solved the necessary governing equations. With the data collected, a set of recommendations was presented in the conclusion of this report to help alleviate the risk of fire spread and damage.

Project Goal and Objectives

The problem presented was a large university library that was vulnerable to fire due to the lack of sufficient fire protection systems. There were no sprinkler systems and minimal smoke detection devices. Due to a stipulation in the National Fire Protection Association's (NFPA) 13, all high rise buildings must be protected by an automatic sprinkler system *except* for the case of high rise libraries. This caused the building owners to neglect the installation of any further fire protection systems than those specified in the prescriptive codes. Now, the situation is being analyzed further to determine the advantages of implementing additional fire protection systems.

The goal of this project was *to use Fire Dynamics Simulator to analyze fire scenarios and sprinkler systems in a large university library*. The decision to use FDS was made based on the availability of the software and ease of use. FDS is a free program provided by the National Institute of Standards and Technology (NIST) and is easily downloadable from the their web page. It is most widely used to model smoke movement and fire scenarios in complicated buildings with many obstructions. This pertains to the scope of the project because the library is comprised of many right angles and book stacks that replicate throughout the space. FDS does have limitations as to what level of complexity and accuracy it can deliver; therefore, hand calculations were performed to compare the output data with expected results. The discrepancies between the results given by FDS and the expected results were analyzed throughout the project. The project goal of using FDS to analyze the large university library was partitioned into objectives.

- *Create a model of the library.*

Fire Dynamics Simulator is a complex program, which requires a substantial amount of time to run a single simulation. To reduce complexity of the model and remain within the academic time limitations only a corner of the floor was modeled. However, the results can be extrapolated to encompass the entire library floor due to the symmetry presented. A typical mezzanine stack floor was modeled due to the fact that the risk to the structural integrity of the building was deemed greatest on these floors. On the mezzanine stack floors the steel columns of the bookcases are the only support to the cement slab floor above. There are seven of these floors throughout the building. The model includes the steel shelves as well as the books, and the thermal properties of yellow pine were used in lieu of the books to avoid the time lag to ignition presented as a result of the high density of the tightly packed books.

- *Design plausible fire scenarios.*

After assessing the fire risk on the typical mezzanine floor, possible causes of fire were limited to a wastebasket fire or arson. The heat release rates were compared and fires ranging from 200kW to 1000kW were modeled. The limitation of FDS to model fire growth forced the use of gas burners, which produced a constant heat release rate. This solution eliminated the possibility of faulty data due to the inability of FDS to accurately model fire growth.

- *Design a sprinkler system appropriate for the given space.*

The most efficient way to combat a fire situation in the large university library was determined to be through the use of a water-based automatic sprinkler system. NFPA 13 contains the standards for the installation of these automatic sprinkler systems including the spacing requirements and was used to design a system based on an ordinary hazard II classification.

- *Analyze the results given through the use of Fire Dynamics Simulator.*

The results produced through the use of FDS include sprinkler activation times, smoke detection activation times, and temperatures at specified points throughout the model. Also given in the output data are special files that can be viewed using Smokeview as a pictorial representation of the model's results.

- *Provide recommendations on a fire protection system for the large university library.*

The results from this project were translated with the intention of presenting the information to be understood by multiple parties. The subsequent recommendations were created based on the results from both Fire Dynamics Simulator and comparable hand calculations. The accuracy of FDS as determined throughout the project and was considered in the recommendations.

With all objectives completed, the project goal to use Fire Dynamics Simulator to analyze fire scenarios and sprinkler systems in the large university library was achieved. The results gathered through the process of the project provided increased knowledge and recommendations as to what steps must be taken to ensure fire safety within the library.

Background

FDS and Smokeview

With the field of fire protection engineering becoming more advanced, the ability to analyze different fire scenarios from a performance-based option has presented itself. Now it is possible to go beyond the limitations of the prescriptive codes and hand calculations, and see the results of implementing certain fire protection systems in a particular design fire. The state of the art program, which allows us to analyze the performance of such fire protection systems, is the Fire Dynamics Simulator. Fire Dynamics Simulator is a computational fluid dynamics model of fire-driven fluid flow, which was created by NIST. The program incorporates a form of the Navier-Stokes equations, which are specifically geared towards low-speed, thermally-driven flow, in order to successfully model the movement of smoke and heat from fires. Once the proper input parameters have been received by FDS, and the program has successfully run without error, the output information from FDS is then displayed by a visualization program called Smokeview. Smokeview provides a visual representation to analyze the effects implementing active and passive fire protection systems have fires.

FDS Applications

NIST BFRL Positive Pressure Ventilation Modeling (2005)

Positive pressure ventilation (PPV) is a tactic used on fire grounds worldwide to both improve tenability for fire suppression activities and after fire extinguishment for firefighters. Typically a fan is started outside the doorway of a building, which creates a positive pressure in the building. The pressure created in the room then forces heat, smoke, and other combustion products out of the building through a vent created by either opening a window, or the roof. The process of PPV can be seen in the figure below.

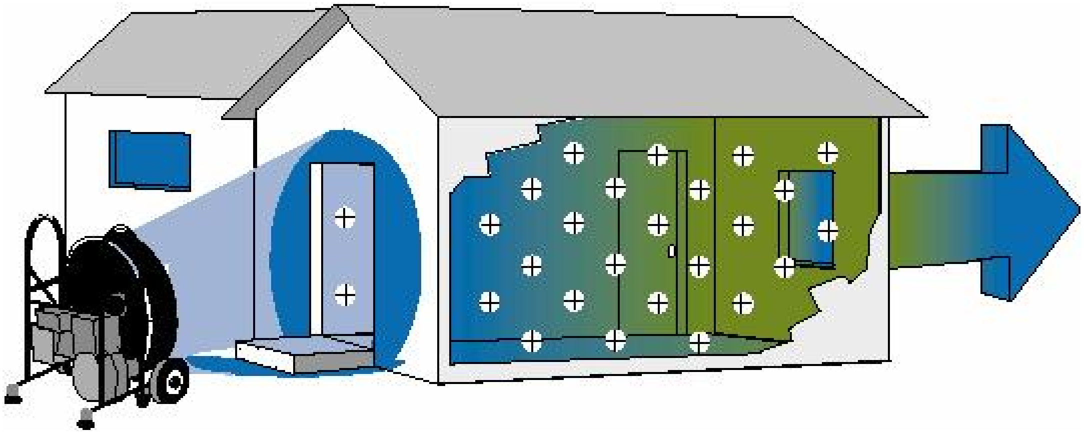

Figure 4: Positive pressure ventilation (Kerber, pg.15).

Despite the positive aspects of applying PPV, questions have been raised as to the negative effects that PPV may be introducing, such as intensifying fire growth by adding additional oxygen. As such, the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) compared data from three full-scale experiments with that of FDS to see exactly what the effects of using PPV in a typical room fire would be. Data on gas velocities, burning rates, heat release rates etc. compiled from the experiments conducted at NIST showed very similar results to those achieved using FDS. As shown in the figures below, the Smokeview visualizations taken at various times during the fire proved to be almost identical to pictures taken during the actual burn tests at the same instances.

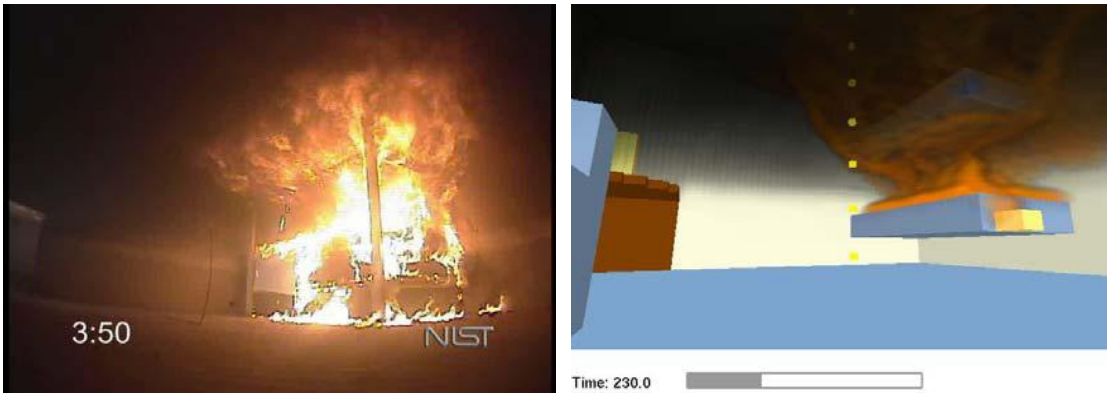

Figure 5: Just before full room involvement (Kerber pg.87).

Figure 6: Fire and smoke movement using PPV (Kerber pg.101).

NIST House to House Fire Spread Tests

With more densely populated areas arising, and building materials changing to meet economic needs, there is a concern as to how these factors may be contributing to the ease of house to house fire spread. The National Institute of Standards and Technology used FDS to compare its models to actual burn tests conducted on house to house fire spread. In the experiments performed at NIST two sixteen foot tall walls were separated by a distance of six feet to represent the exterior walls of two houses (see

Figure 7). The six foot separation distance was used because this was the minimum distance permitted by the building codes.

The walls in the experiment consisted of 2”x 4” construction with a plywood backing, followed by a layer of weather warp and vinyl siding. Between the studs was fiberglass insulation and on the interior side of the studs was a layer of gypsum board. In addition, both walls had windows in them. The fire was started in one “house,” which was furnished with a sofa, chair, tables, carpet, and wall paneling. In the first simulation the fire was started on the sofa and the window broke out 223 seconds into the test. (Maranghides and Blair, pg. 4). After five minutes the flames that were being released from the structure where the fire began had melted through the vinyl siding and ignited the plywood on the target wall (Maranghides and Blair, pg.4). In a second experiment, a layer of gypsum board was also placed between the plywood and the weather warp barrier. In this case the plywood on the target wall was prevented from ignition after an extensive period of flame impingement due to the fire resistance of the gypsum board. The FDS model that was used for this experiment was very accurate in modeling the time at which flames would impinge and ignite the plywood on the target wall. As shown in Figure 7, the FDS model showed an almost identical flame projection as that observed during the full scale burn test.

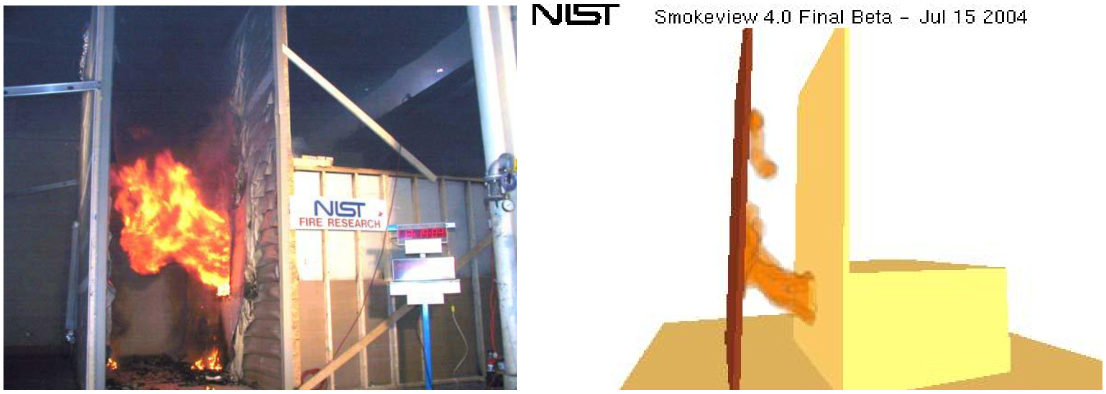

Figure 7: House to house fire spread model

In addition, the heat release rates, gas temperatures, and gas velocities produced by the FDS model were very similar to those obtained during the full scale burn test. The data compiled from both the burn tests and FDS will help fire code officials, firefighters, and fire protection engineers better understand the potential for house-to-house flame spread within tightly spaced communities. This test is also another step toward proving the verification and validation of Fire Dynamics Simulator.

NIST Modeling of Roof Collapse

In response to the rise of firefighter deaths in the U.S. due to lightweight construction's inability to withstand fire conditions long enough for suppression activities to be carried out, NIST is using FDS to model structural collapse of roofs during house fires.

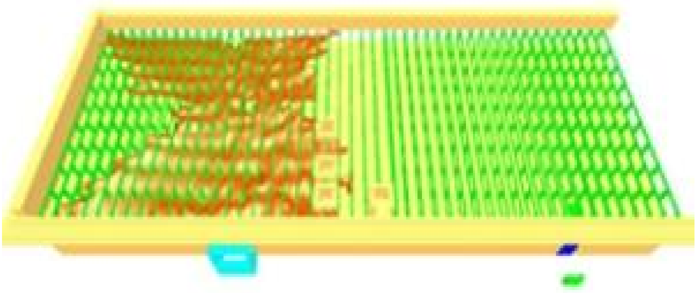

Figure 8: FDS model for roof structure collapse (Vettori, and Walton, Pg 22).

A series of different fire scenarios were modeled to see what amount of time the firefighters have from the time they are informed of the fire to the time the roof will collapse. One particular test that was conducted at NIST used FDS to model a roof collapse of a restaurant which claimed the lives of two firefighters in 2000. The model was used to show the time of inception of the fire, the thermal insults present, and the fire spread from its origin to the upper attic space where it burned away the lightweight trusses. It showed that when the firefighters reached the fire, the structure had already lost its integrity and was on the verge of collapse.

The future of FDS is demonstrated in applications similar to the roof collapse case. Fire Dynamics Simulator will help aid forensic specialists in determining what might have occurred during a particular fire and why.

Approach

Introduction

The method of determining the effects of sprinklers in the library was to first create a model of a typical mezzanine stack floor. Approximate dimensions of the bookcases and steel structural columns were used to simulate a portion of the library floor of interest. A fire was inserted in the simulation with a constant heat release rate and was positioned towards the corner of the floor under the first row of books. A 10 kW fire was used for the first simulation, which compared to the size of a small trash barrel fire. The assumption used for the simulation was that a small trash can fire had begun which could have been ignited from a burning cigarette or similar source. The 10kW fire grew unexpectedly fast and in less than one minute, the entire model experienced localized flashover. This indicated that FDS was not accurate in modeling fire growth. After further research, a deficiency in FDS was discovered. Instead of modeling pyrolysis, when FDS calculated the surface temperature of an object at its ignition temperature, it assumes flames were present. To control this deficiency and continue using FDS to complete the project, the second case of arson was considered. An assumption was made that the design fire had already reached a peak heat release rate which was modeled using constant heat release rate gas burners. The gas burners were set to constant heat release rates within the range of 200kW to 1000kW to best represent the present fuel load in the library.

The book stacks were located towards the center of the library. Student desks were stationed around the outer walls of the building for ease of study from sunlight. The possible trash barrel scenario stemmed from the assumption that a full trash barrel was left unnoticed and a student discarded a cigarette or other ignition source into the barrel, thus starting a fire. The fire would most likely consume the desk and move through the stacks. The second scenario of arson assumed the perpetrator spilt gasoline or another fuel source on a stack and ignited the pool. For the sake of maintaining as much control over the simulation as possible and limiting the variables, the gasoline situation was used. Constant heat release rates were maintained to focus the data collected from the simulation on the results of the sprinklers and smoke production.

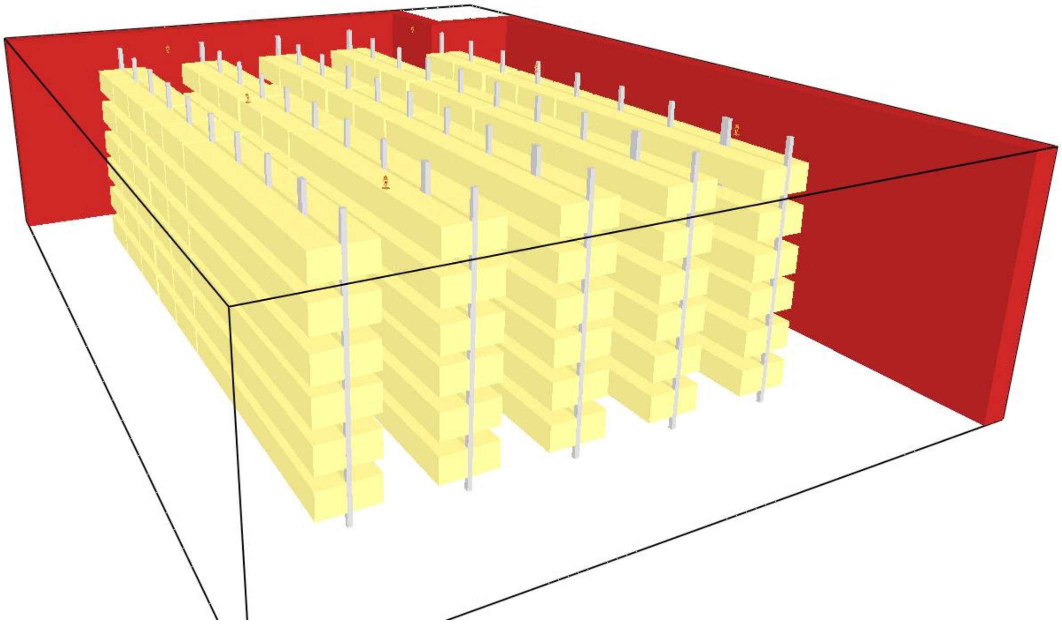

Figure 9: Simulation model of the corner portion of the library

The previously mentioned assumptions were valid for this stage of the design because the key factors to be gained from the model were smoke movement in the space, activation of smoke detectors, activation of sprinklers, and temperature profiles throughout the area.

Grid Refinement

FDS uses a three dimensional rectangular grid system to create the environment defined in the source code, which is comprised of walls, obstructions, boundaries, etc. The size of the grid system is defined in the source code and can be adjusted to accommodate the size of the area in study. Depending on the size of the fire scenario, the grid spacing can be varied to obtain the desired level of precision. If the scenario is a very small fire in a small compartment, the grid spacing will be very small, whereas if a very large fire is of interest in a large area, the grid spacing will be significantly larger.

A preliminary test was conducted using FDS to determine the appropriate grid scale based on fire scenario and simulation efficiency. A room proportional to the area of interest in this study was used as a model for the grid refinement test. The dimensions of the room were 5.2m long by 5.4m wide by 2.4m high. The model consisted of a single room split in half by a wall with a one meter wide door in the center. A fire was simulated on one side of the wall directly in front of the doorway, and a temperature sensor was placed on the opposite side of the doorway. As expected, the temperature of the sensor increased with the duration of the flame as heat built up at the ceiling. The temperature sensor was placed a distance away from the flame source so that fluctuations in flame height would have less of an effect on the sensor, and a smoother curve could be obtained.

This simulation was run with three different grid resolutions to determine which would be the most efficient and accurate. The first simulation was run with approximately 4 inch (0.1m) separation between grid points in all three coordinate directions. The grid in all dimensions remained at a 1:1:1 proportion because it produces much more accurate result parameters. Grid point separation was then doubled and the simulation was run again with approximately 8 inches (0.2m) between grid points, and again with approximately 12 inches (0.3m), or one foot between grid points. The results of this test are shown in the figure below.

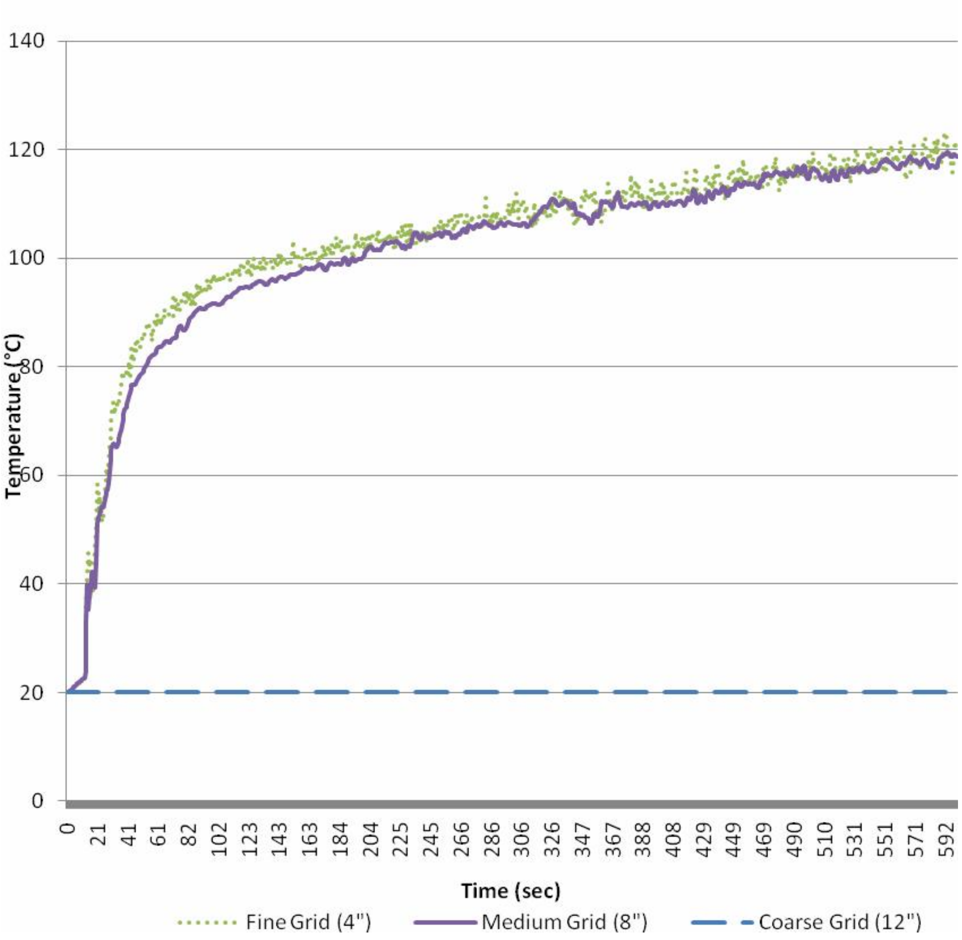

Figure 10: Grid refinement

The simulation with the 12-inch grid as shown on the graph did not measure any temperature change in the room and remained at ambient temperature of 20 degrees

Celsius. This was because with such a large grid system the program was not able to recognize the flame source as a solid object and so was not able to model a fire.

Temperatures recorded with the 4 inch grid were quite accurate but caused a large amount of fluctuation over small time intervals which produced a graph containing a great deal of “noise”. The large amount of grid points becomes unnecessary when there are small meaningless fluctuations in the data. A fine grid simulation such as this also required a lot of time and computer power.

The ideal grid refinement comes with a smooth curve of data measurement as shown by the 8 inch grid in the figure. There was very little fluctuation in the graph as compared to the fine grid system, which resulted in a smooth constant curve and also accurate data. The smooth curve gave the most useful results because it gave an accurate representation of the measurement being taken without producing excessive variation in values, which lead to ‘noise’ in the graph. Taking into account the dimensions of the room the grid division of 8-inches related to 52 grid points in the x-direction, 54 grid points in the y-direction, and 24 grid points in the z-direction. This grid refinement was used as a scale for the library study to determine the number of grid points to use in the larger scenario. The ratio of grid division to the dimension of the room was translated to the model of the library.

Sprinkler Layout

The sprinkler system design used in the simulation was a standard wet pipe water-based suppression system designed to a ordinary hazard group II occupancy. In the 2002 edition of NFPA 13, which is the current standard for the installation of automatic sprinkler systems, section A.5.2 lists libraries under light hazard occupancy; however, the proceeding section A.5.3.2 lists a more specific description of a library stack room under ordinary group II occupancy. The difference between the two is that the light hazard library is based on a reading area having tables, chairs, and some racks. Ordinary hazard group II library areas are based on large stack rooms with high stacks of books and other combustible commodities. To produce more conservative results, the ordinary hazard group II classification was used when designing the system.

The maximum sprinkler spacing for sprinklers in a ordinary hazard occupancy is 130 square feet. The sprinklers used in the model were spaced 12ft by 10ft to give a spacing of 120 sq. ft. per sprinkler which is typically seen as a conservative spacing. Sprinkler heads used in the simulation were ordinary temperature rated standard response pendent sprinklers with an activation temperature of 74 degrees Celsius.

Results

Introduction

Simulations of a fire on a typical mezzanine stack floor were run to determine the effectiveness of sprinklers on the results of the fire. Each simulation scenario was run with and without sprinklers, keeping every other condition the same so variable in the study was a fire situation with a different heat release rate. The focus of the study was the impact sprinklers would have on the safety and well-being of any occupants in the area or floor. Smoke detector obscuration was measured to determine how long it would take for the detectors to alarm and indicate to the occupants that there is a fire present. The activation time of the sprinklers was measured to determine if and when the sprinklers would discharge water to control and suppress the fire. Also, temperature histories were measured along supporting columns to determine the time for the structural steel to reach critical failure temperature and time for localized flashover to occur.

Smoke Detector Activation (with sprinklers)

The 10kW design fire simulation was located under the book case in the corner of the room, which was almost directly under sprinkler number 6. The graph below indicates that for the simulation that was run with sprinklers, a 100% obscuration within the detector was not reached until 329 seconds into the fire. This is roughly 5.5 minutes, which is a considerably long activation time for a detector located in a room with these dimensions. The most significant contribution to this lag to activation time was assumed to be the two walls of the room were open to the atmosphere which allowed a sufficient amount of air flow into the room. This was needed to prevent the fire from depleting the room of its oxygen supply, which would ultimately choke the fire out. Due to the smoke mixing with the airflow into the room, which resulted from opening these two walls, it took much longer for the smoke detector chamber to reach its 100% obscuration level. Too add to the slow detection time, sprinklers closest to the fire activate which can have cooling effects on the smoke which could have contributed to the lag time before detector activation was achieved. This cooling hinders the smoke's buoyancy driven forces, ultimately inhibiting the smoke's ability to reach the detector.

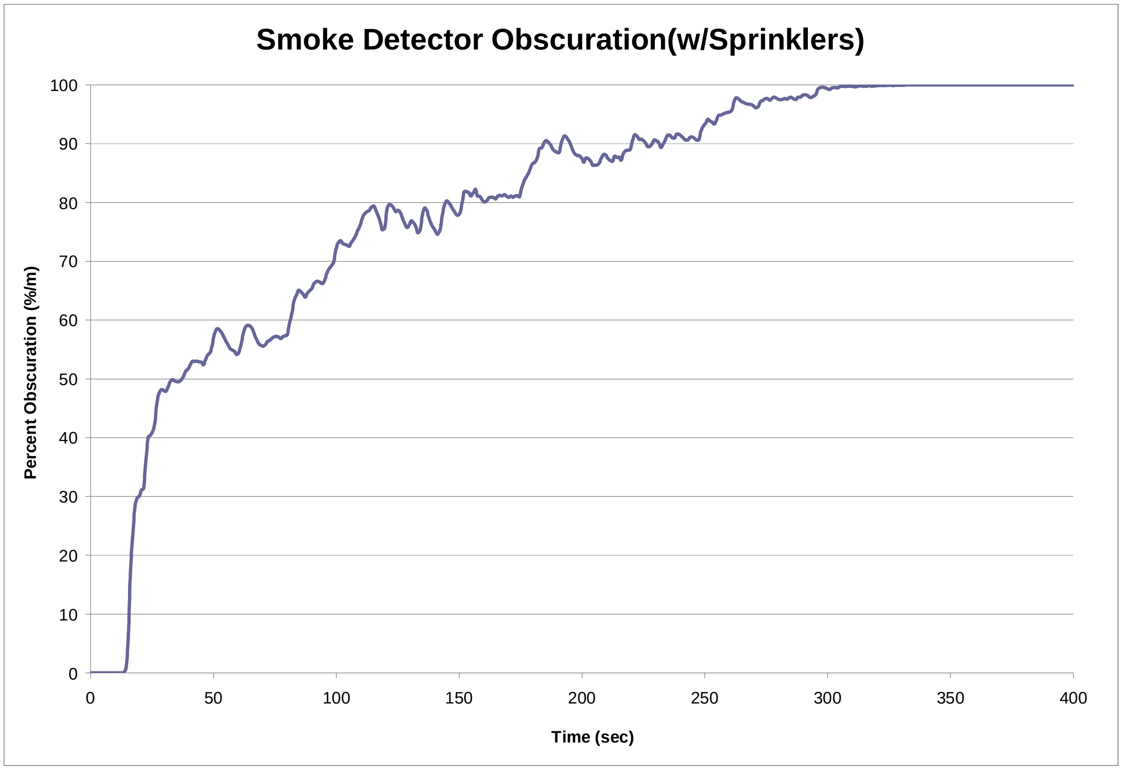

Figure 11: Smoke detector activation time with sprinklers.

Smoke Detector Activation (without sprinklers)

The same design fire was run for a second simulation to determine the activation time of the smoke detector, but this time without sprinklers. As indicated in the figure, 100% obscuration within the detector was achieved at 203 seconds. This is about 3.5 minutes, which is more reasonable activation time than that of the smoke detector in the sprinklered room, but still impractical for a room of this size. Again, two walls of the room were “open” to allow a sufficient amount of air entrainment needed to fuel the fire. It was evident after analyzing the data from both tests that the free air flow through the two open walls was the main contributor to the lag to activation time of the smoke detector.

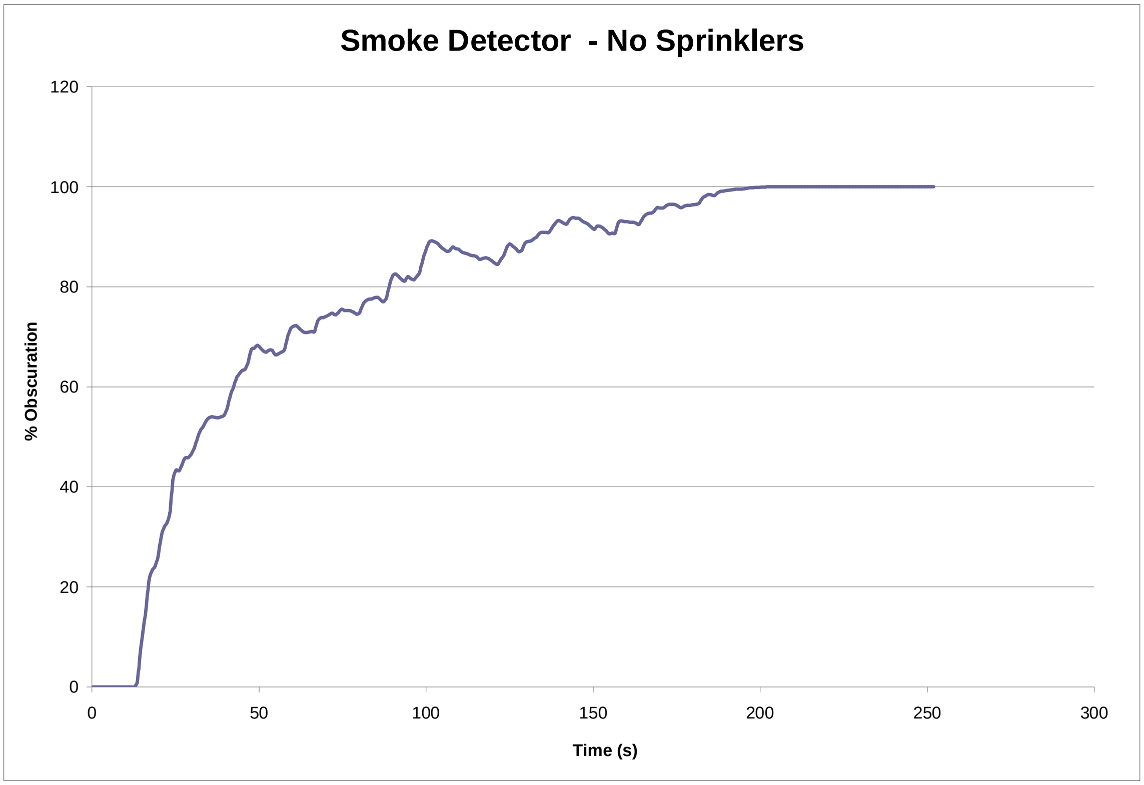

Figure 12: Smoke detector activation time without sprinklers.

Comparison with Cylindrical Volume Approach

A calculation was made to determine the activation time of the smoke detector based on the Cylindrical Volume Approach using mass optical density, as formulated in Annex B of NFPA 72. In this calculation, a t^2 fire growth was assumed and the material properties for a similar pine species were used to model the stacks. Also, a time lag of ten seconds was incorporated, which accounts for the time needed for smoke to reach the detector. The same size room was used for this calculation, but the activation time was determined for a compartment, hence there were no open walls. An activation time of 27 seconds was determined using this method. This is a more reasonable activation time for a smoke detector given the design fire that was used in a room of this size, although significant assumptions are incorporated into the formulas. (*See Appendix for calculation*)

Sprinkler Activation Time

The thermal response element for the sprinklers used in the simulation was rated to actuate at 74 degrees Celsius. Therefore, once the sprinkler head was exposed to this temperature long enough to overcome the thermal lag associated with the element, the sprinklers would be expected to activate. The graph in Figure 13 is a visual representation of the sprinkler activation times. As indicated in the graph the first sprinkler to activate is sprinkler 6, which reaches its activation temperature at 331 seconds into the fire. This is what would be expected due to the fact that sprinkler 6 was located directly above where the fire originated. The activation of sprinkler 6 is followed by the activation of sprinklers 3, 5, 2, 4, and 1, which activate at times 376s, 389s, 401s, 412s, and 434s respectively. The sprinkler activation times were a direct result of there orientation with respect to the origin of the design fire, and as expected the most remote sprinkler, sprinkler 1, had the slowest activation time.

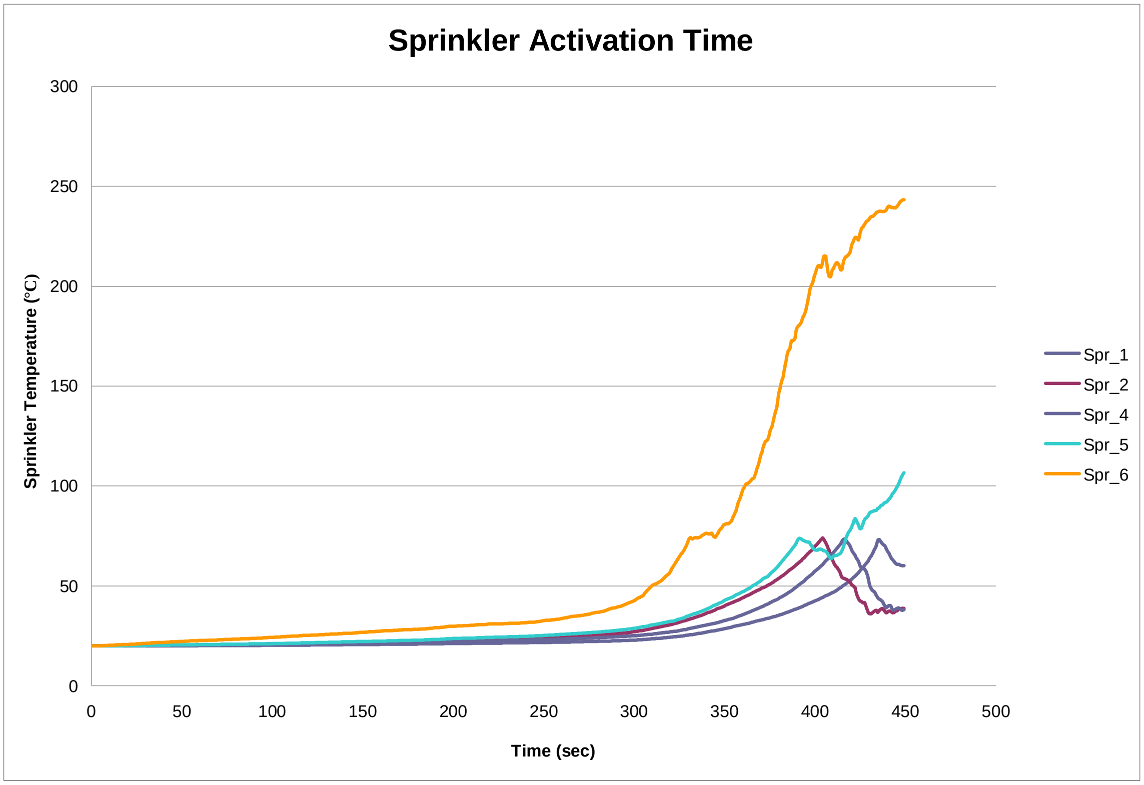

Figure 13: Sprinkler link temperature growth.

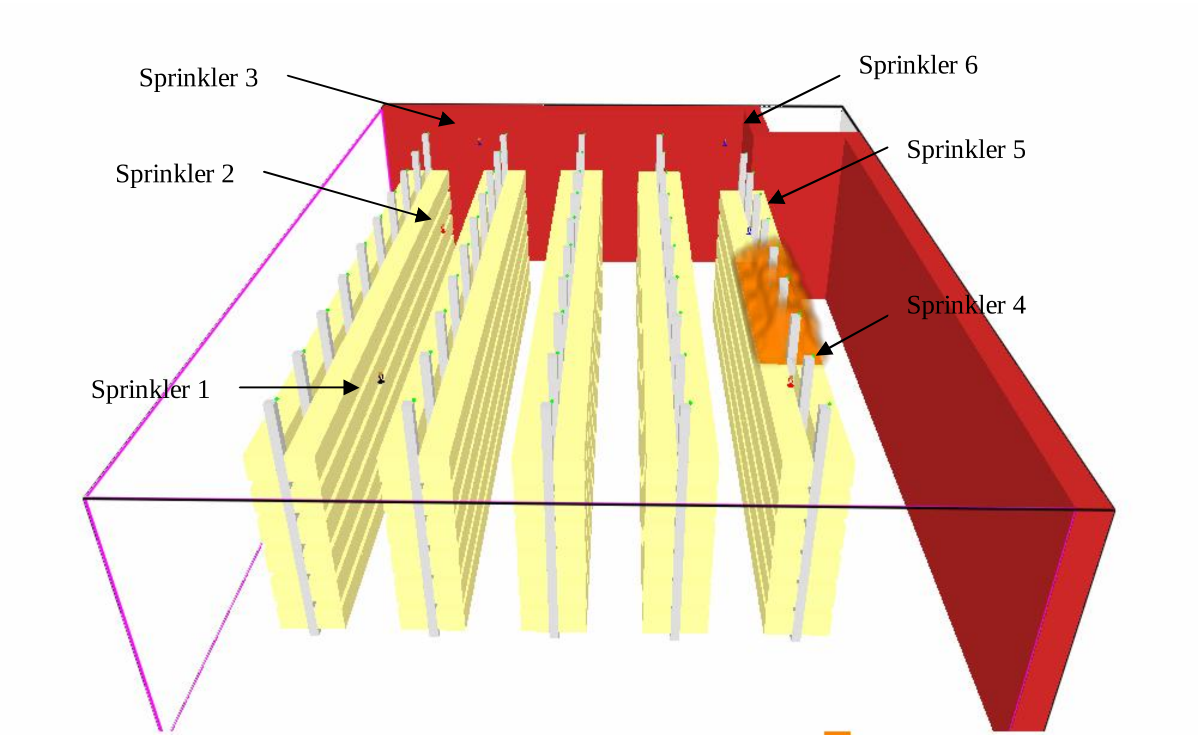

Figure 14: Sprinkler number indication.

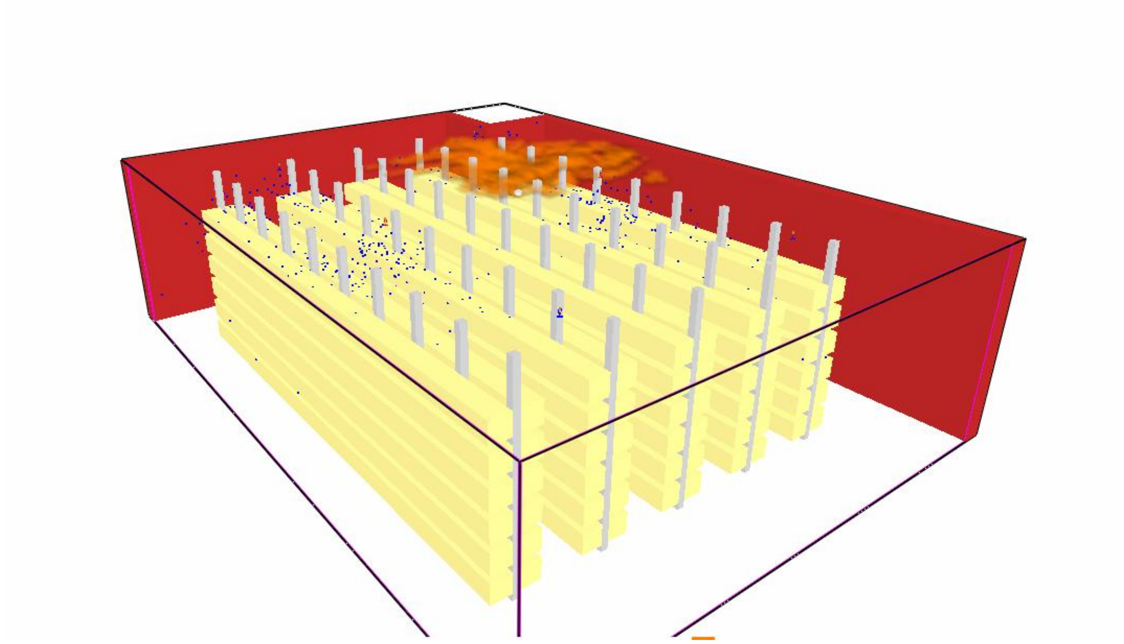

Figure 15: Sprinkler activation in FDS.

Supporting Column Analysis

Temperature sensors were placed in the model at the very top of each supporting column. Temperatures taken from the columns close to the flame source displayed a sharp increase to a high temperature and then a level average temperature with a great deal of variation due from fluctuation in flame height. Further away from the flame source, the columns had a smooth increase in temperature and remained at a peak temperature with less variation or "noise" in the graph because the fluctuation in flame height has little effect at that distance from the fire. Because it would produce the most useful (accurate) data, the column indicated by the arrow in the figure below was used as a point to measure temperature.

The simulation as shown below was run first without sprinklers and then run again with sprinklers to observe the effect that the sprinklers would have on the temperature of the supporting columns.

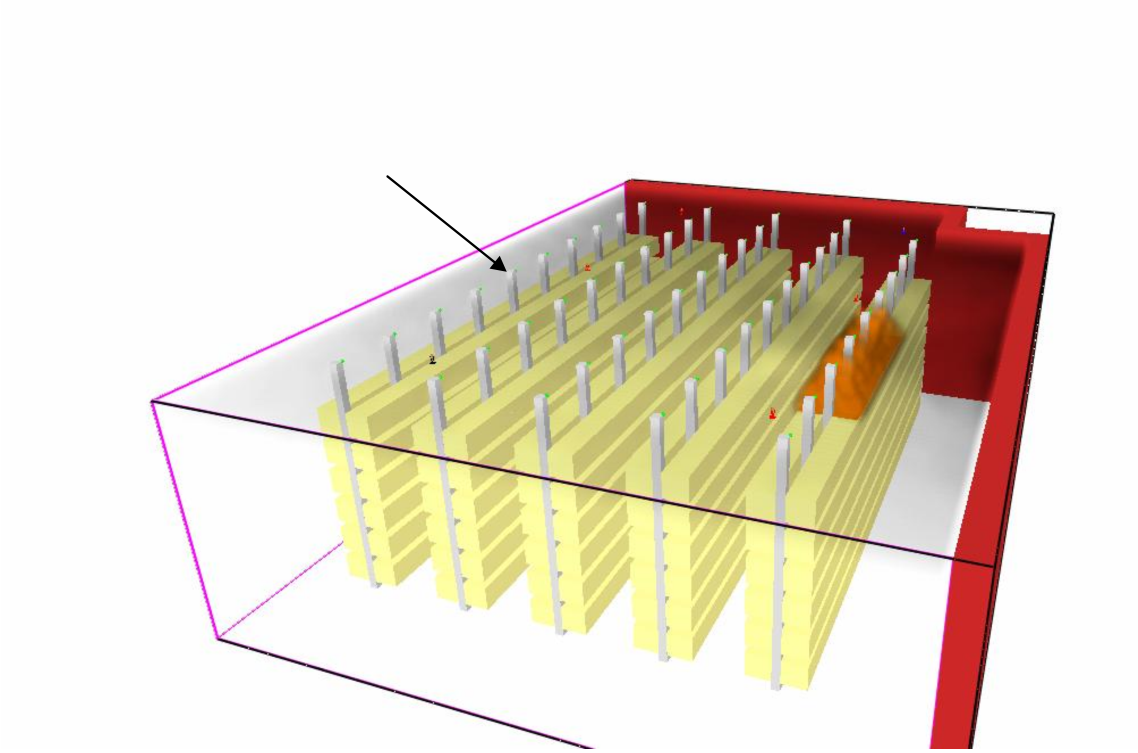

Figure 16: Library model with arrow indicating column at which temperature was measured.

The simulation was run with various heat release rates of the fire and the effect of the sprinklers was recorded at each.

A 500kW constant heat release rate fire produced the following temperature profiles.

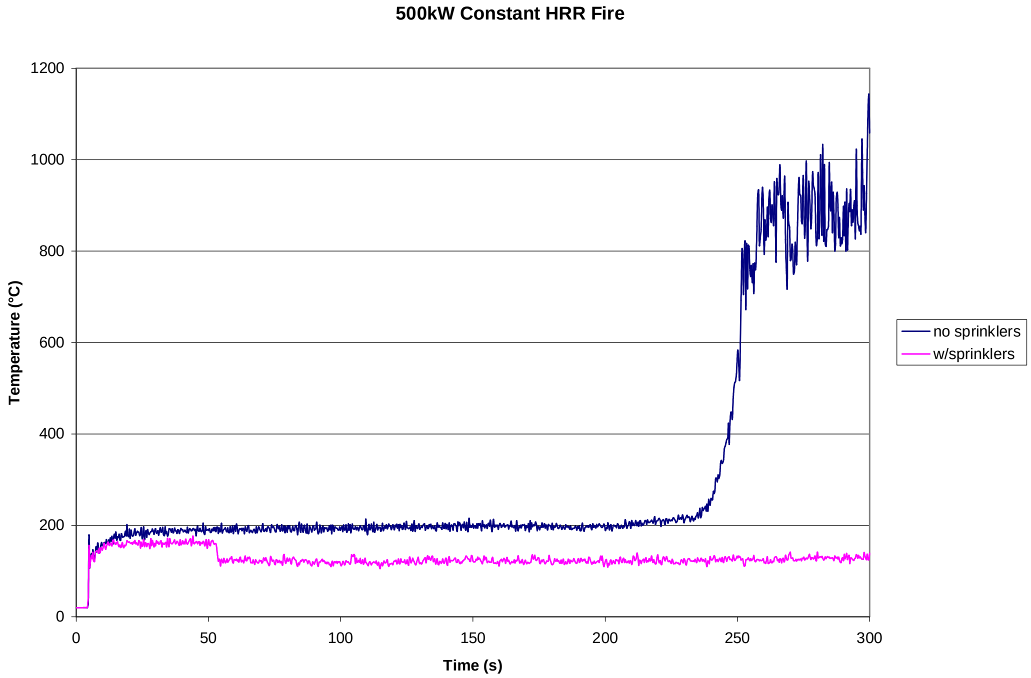

Figure 17: Effect of sprinklers on 500kW constant heat release fire.

The temperature at the column increased quickly to a temperature of about 200°C without sprinklers and about 160°C without sprinklers. The difference was due to sprinkler activation which suppressed the flame and decreased the temperature. At approximately 50 seconds, the temperature dropped in the sprinklered model because additional sprinklers activated which suppressed the fire and temperature. With no sprinklers installed, the temperature of the supporting columns rose to a very high temperature at around 250 seconds. This can be explained by localized flashover when everything contained in a room or area reaches a critical temperature and ignites.

From the above graph the conclusion is that sprinklers would have a great impact on reducing the temperatures found on the steel members in a 500kW fire case. The steel supporting column would reach its critical temperature of 538°C at approximately 250 seconds. With this column reaching the critical temperature, it is obvious that all columns closer in radial distance to the flame will also reach this temperature at some earlier time.

As mentioned previously, the model was used only for informational purposes under the assumption that the fire had already started and had reached a peak heat release rate of 500kW.

The same simulation was run with a 200kW constant heat release rate fire. The results are shown in the figure below. With a smaller heat release rate there is a difference in peak temperature of about 15 or 20 degrees Celsius. In the simulation with sprinklers, the temperature increased to about 110 degrees, same as the simulation without sprinklers, but then dropped when the first sprinklers activated at about 40 seconds. The temperature then remained constant until 240 seconds when additional sprinklers activated and suppressed the fire to decrease the temperature output.

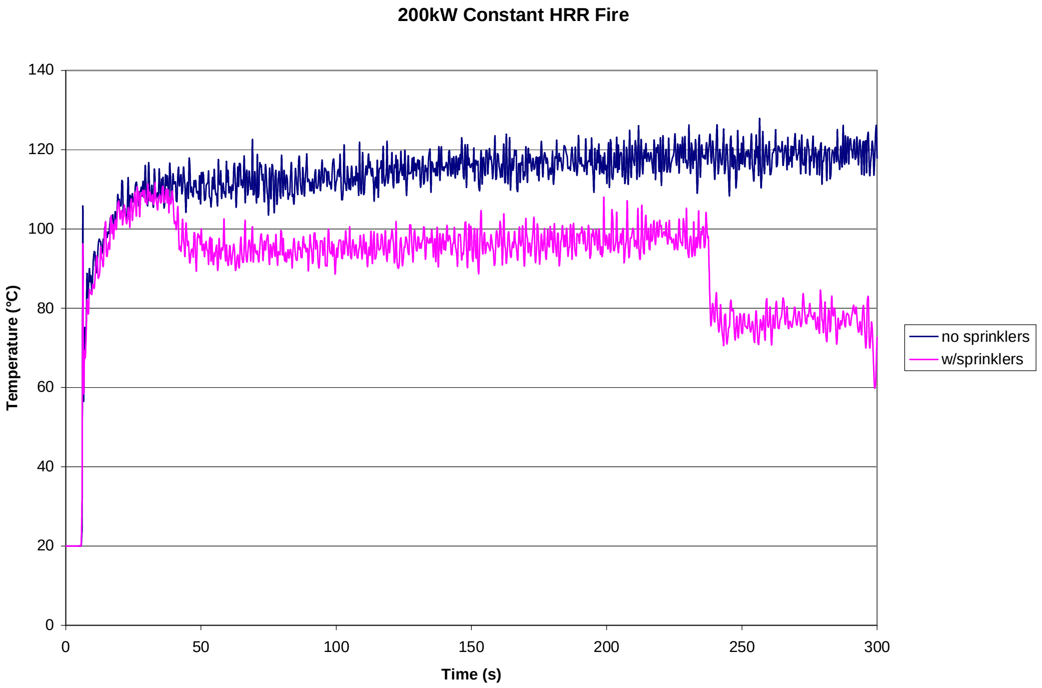

Figure 18: Effect of sprinklers on a 200kW constant HRR fire.

In this simulation no localized flashover occurred. The data showed that the critical temperature for the steel supporting columns was not reached as the maximum temperature measured was 130 degrees Celsius. Identical simulations were run at 100kW intervals of heat release rates from 200kW to 500kW and the only fire that output enough heat for flashover was the 500kW fire. From this information, a conclusion was made that for fires less than 500kW, the installation of sprinklers will not have a great impact on the temperature increase in the area over the first five minutes.

After observing the effects of fires up to 500kW and the point of flashover, the next step was to test fires over 500kW. The graph below displays the temperature rise during a simulation of a 750kW constant heat release rate fire.

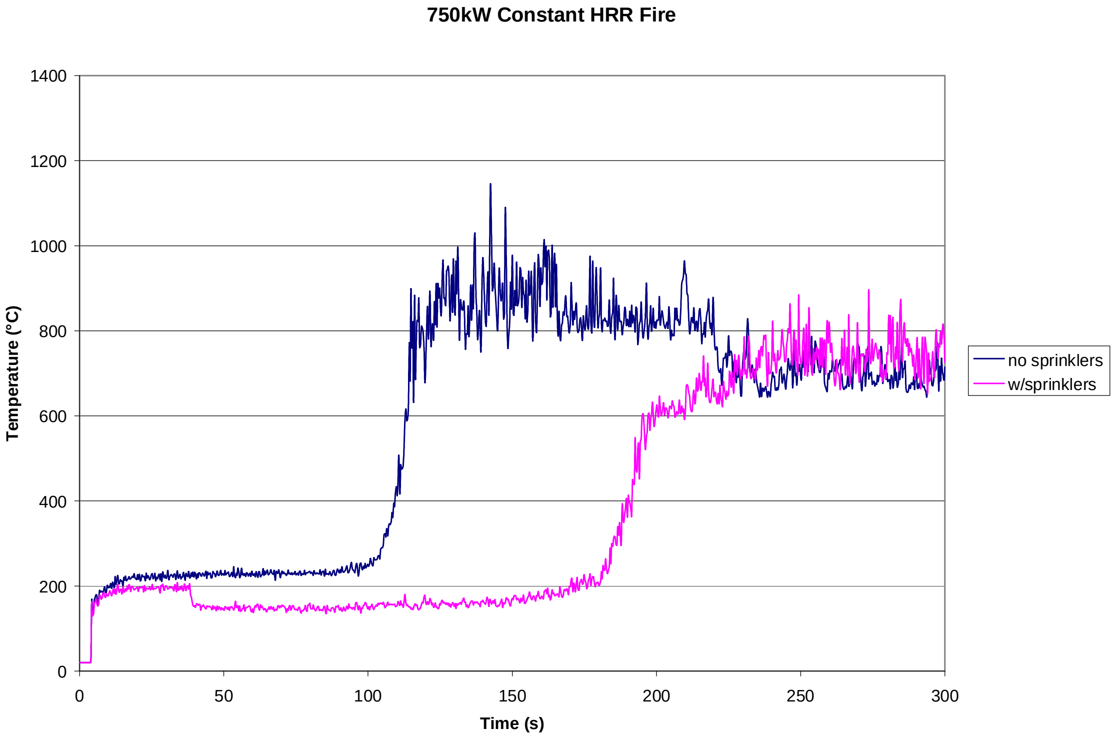

Figure 19: Effect of sprinklers on a 750kW constant HRR fire.

In this case, localized flashover occurred much sooner than with the 500kW fire. The temperatures at the column for simulation without sprinklers increased to maximum of 220°C until it reached the point of flashover at 110 seconds. After 110 seconds, the temperature rose to a maximum temperature of 1100°C during localized flashover. After the point of flashover, the temperature started to decrease because the fuel was being burned off and the flame size was decreasing as a result.

With sprinklers involved in the simulation, the time to flashover was increased to 200 seconds (on average). This is an increase of about 90 seconds which relates to an extra minute and a half of occupant egress time before flashover occurs. For a fire size of 750kW, the recommendation is that sprinklers would provide effective protection both for the safety of occupants and preservation of the building.

The heat release rate was increased to 1000kW for the final simulation. For this very large 1000kW fire, localized flashover occurs fairly quickly for both simulations. The temperature in the room is decreased after sprinkler activation shown in graph at 30 seconds. For the simulation with the sprinklers, flashover occurs at 100 seconds as opposed to 60 seconds without sprinklers.

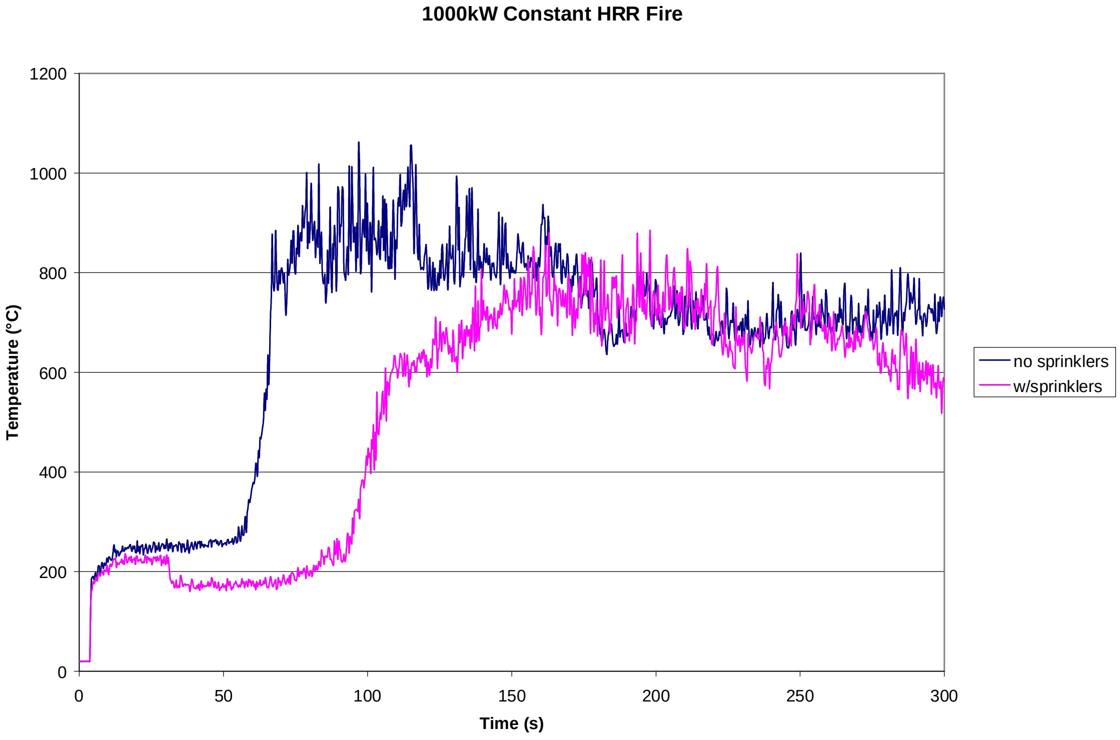

Figure 20: Effect of sprinklers on a 1000kW constant HRR fire.

From the results shown in the graphs, the effectiveness of the installation of sprinklers in the library stack room can be observed. For small fires with heat release rates less than 500 kW, the installation of a sprinkler system would not prove effective. At these smaller fires, flashover does not occur because the temperature in the area does not accumulate enough to reach the temperatures required of localized flashover. In a real-life fire scenario the sprinklers in the area would in fact help contain the fire to protect any materials stored in the area and may completely suppress the fire under the correct conditions. For the subject of this study which is concerned mainly with occupant safety, the sprinklers would not make a significant difference for fires with small peak heat release rates.

In scenarios where the fire heat release rate is 500kW and above, the installation of sprinklers would be effective and important in terms of occupant safety. The activation of the sprinklers in these cases kept the temperature in the room lower so that it took longer for the heat to accumulate. This delayed the occurrence of localized flashover, which would most likely be fatal to any occupants in the area. Sprinklers would give these occupants extra time to evacuate the building, or at least the immediate area when the first signs of fire are noticed. In some cases, the sprinklers prevent the occurrence of localized flashover altogether (for the first 300 seconds), which not only provides a great deal of protection to occupants, but also to the structure of the building.

Conclusion

Although some limitations of FDS were discovered through this project, there are still inaccuracies that occur based on assumptions built into the governing equations of the program. When using FDS as a primary source of information, these assumptions skew the results gathered from the program tending to err more conservatively than the expected results. To ensure that the data produced through the program is accurate, further research is necessary. FDS could be used to run a simulation prior to a physical burn test but a real, full-scale test should be conducted to gather actual data to compare the simulation.

Further research must also be conducted to determine the specific peak heat release rate of a stack fire. This should be done through a full-scale burn test where measurements are taken of temperature of the fire and the smoke density. This information can be used as input parameters for the FDS source code. As for accuracy within the model, a full model representing the entire floor of the library should be simulated to ensure that results gathered from a corner translate into a larger scale.

Even with the simplifying assumptions used in this project, FDS can be a useful tool. A sprinkler system was analyzed using the model and the results gathered were found to be accurate based on hand calculations. For the preliminary analysis of the sprinkler system, the application of FDS was successful. Based on the results of the simulations, the installation of a sprinkler system was recommended for fires over 500kW. To determine the potential heat release rate of the stacks, a burn test would be necessary. With the burn test, a more accurate model can be created using the input parameters mentioned previously, and a more accurate simulation could represent the need for a sprinkler system. For fires with heat release rates below 500kW, a different fire protection system such as increased smoke detectors or a ventilation system could be more effective than a sprinkler system. The FDS model could be used to model these fire protection systems, with changes to the code and further analysis of the intricacies of the building. Due to time restraints, this was outside the scope of this project.

With the fire protection field evolving as rapidly as it has over the past few years, it can be expected that Fire Dynamics Simulator will be used widely and for many applications both within and beyond the realm of fire protection. Updates are constantly being made to programs used in fire protection based on an increased knowledge of the field and a growing attention to computer modeling technology. As more companies continue to use FDS for different applications, the limitations of the program are discovered and alterations are made. Fire Dynamics Simulator is already useful in modeling smoke and hot gas movement. With continued use of the program, the full limitations and applications of the program will be discovered and in the near future, a new version of the program can be expected to be able to model all aspects of fire.

References

Blair, John. "Lab Experiments Simulate House-to-House Fire Spread." www.nist.gov. 30 July 2004. 20 Jan. 2008 <http://www.nist.gov/public_affairs/techbeat/tb2004_0730.htm#fire>.

Blair, John. "NIST Lab Experiments Simulate House-to-House Fire Spread." Nov. 2004. 15 Mar. 2008 <http://www2.bfrl.nist.gov/userpages/wmell/PUBLIC/WUI/House_to_House_Fire_NIST_Fact_Sheet.pdf>.

"Fire Dynamics Simulator and Smokeview." Offical Website Hosted At NIST. 12 Nov. 2007 <http://www.fire.nist.gov/fds/>.

Kerber, Stephen. "Evaluation of the Ability of FDS to Simulate Postitve Pressure Ventilation in the Labratory and Practical Scenarios." Official NIST Website. Apr. 2006. 15 Jan. 2008 <http://fire.nist.gov/bfrlpubs/fire06/PDF/f06065.pdf>.

Klote, John H., Milke, James A. Principles of Smoke Management. Atlanta: American Society of Heating, refrigerating and Air-conditioning Engineers, Inc., 2002.

Vettori, Robert L., Daniel Madrzykowski, and William D. Walton. "Simulation of the Dynamics of a Fire in a One Story Resturant." www.fire.nist.gov. Oct. 2002. 20 Mar. 2008 <http://www.fire.nist.gov/bfrlpubs/fire03/PDF/f03019.pdf>.

Westminster International OxyReduct®, "The Better Solution". 23 Apr. 2008 <http://www.wg-plc.com/international/fire/oxyreduct.html>.

Appendix A

Smoke Detector Activation (Cylindrical Volume Approach)

Given:

- Spacing used (S) = 30' (9.14m)
- Ceiling height (H) = 3m
- Time delay (t_e) = 10 sec

$r = S/\sqrt{(2)} = 9.14m/\sqrt{(2)} = 6.5m$

*because only a corner of the library was modeled => r = 3m

- From table B.2.3.2.6.2(a) of NFPA72, item #2 was used.
- Assume t^2 fire growth.

$t_g = 90$ sec
$\alpha\, t_g^2 = 1055$ kW
$\alpha = 1055\text{kW}/(90\text{sec})^2 = 0.1302\ \text{kW/s}^2$

For properties of yellow pine => Table 3-4.14 in the SFPE Handbook 3rd Edition:

$\Delta H_{ch} = 12.4$ kJ/g
$\Delta H_{con} = 8.7$ kJ/g

$X_{conv} = 8.7/12.4 = 0.701$

$\Rightarrow \alpha = 0.70(0.1302) = 0.09135\ \text{kW/s}^2$

$D_A = 0.14\ \text{m}^{-1}$

$h = 0.25(3m) = 0.75$ m

$D_m = 0.28\ \text{m}^2/\text{g}$ (SFPE Handbook Table 2-13.5, Douglas Fir)

Using equation B.51 from NFPA72:

$$t_{act} = ((3\ D_A\, \pi\, r^2\ h\ \Delta H_{ch})/(\alpha\ D_m))^{1/3} + t_e$$

$$t_{act} = ((3(0.14)(\pi)(3m)^2(0.75m)(12.4))/(0.9135(0.28)))^{1/3} + 10\ \text{sec}$$

$\mathbf{t_{act} = 26.28}$ **seconds**

Appendix B

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&TIME TWFIN=300.0 /

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    PART_ID='SMOKE'
    COLOR='ORANGE' /

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    SPECIFIC_HEAT = 0.84
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    DENSITY       = 7850. /

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    SPECIFIC_HEAT = 0.88
    DENSITY       = 2000. /

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        CONDUCTIVITY                    = 0.147
        DENSITY                         = 640.
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        NU_FUEL                         = 1.
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        HEAT_OF_COMBUSTION        = 19400. /


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    COLOR         = 'FIREBRICK'
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    COLOR         = 'WHITE'
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```

Appendix C

By Jennifer Moseley

Tenability

Tenability criteria are necessary to maintain in spaces where people are expected to be before and during an evacuation. While this seems an easy task to incorporate into a fire protection design, tenability requires that many different aspects be taken into consideration. Tenable conditions can be based on smoke layer height in a space, the density and type of smoke, the radiant heat from the fire in the space, and the level of toxic materials in the space. All aspects of the fire must remain within a reasonable level for a specified egress time based on the building's occupancy. When designing the fire protection system, the most important tenability criteria that should be maintained are that the smoke layer does not drop below 6 feet above the floor (above the heads of people who are exiting the floor).

The scope of this project did not extend to smoke management. There are limited ventilation systems present in the library. Ventilation systems are the main resource for maintaining smoke layer height. The air system would provide not only movement of smoke away from a fire, but also hot gases that could fuel the fire. Currently, there are enclosed structures in the corners of the library that most likely house the electric wiring. If these enclosures run between floors, they would be an ideal place to insert ductwork. If installing a new system is not an option, a smoke detector that continuously analyzes the air in the duct could be used to trigger the system. In the case of a fire, the ventilation system could increase air intake and help move smoke. A smoke management system could be modeled through FDS. For best results, a full scale burn test of a book stack would be necessary to gather information on the peak heat release rate of the books and also information on the smoke composition and production.

Stair Pressurization

Stair pressurization could be an aspect of fire protection needed in the large university library. Based on buoyancy forces, the hot gases and smoke that is produced by a fire can move into the stairwell and then move through the rest of the building. Temperature differences between the air inside the stairwell and outside the building create pressure differences inside the stairwell. Low pressures are located near the top of the stairwell and higher pressures are located at the bottom of the stairwell. The change between the lower pressure and the higher pressure is the neutral plane. At the neutral plane, the pressure is the same as the average pressure found throughout the rest of the temperature-controlled building. If a fire is located below the neutral plane, the smoke will rise in the stairwell and move onto floors above the neutral plane. If a fire is located above the neutral plane, the smoke could remain in the stairwell and lower fast, effecting tenable conditions in the stairwell. Smoke in the stairwell will tend to lose heat and thus buoyancy, and stratify. Stratification will cause smoke to move onto many floors.

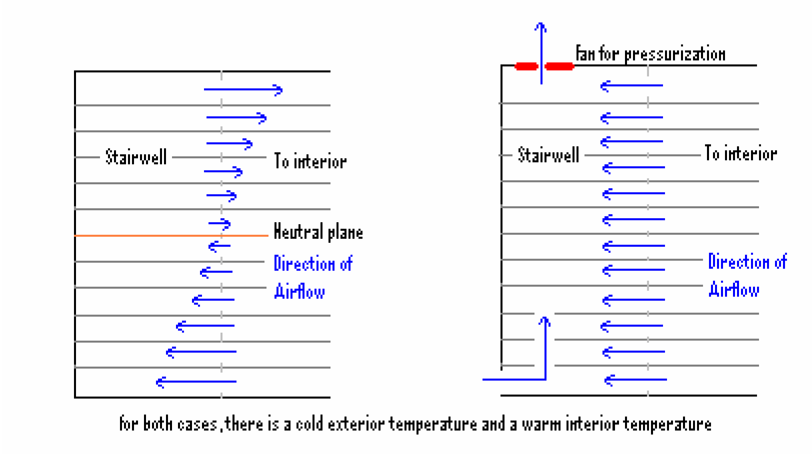


Figure C1: Air flow in stairwell with and without pressurization.

Stair pressurization can be maintained through a fan at the height of the stairwell. When activated, the fan can exhaust smoke and air through the roof, thus creating a negative pressure in the stairwell that will pull smoke from the affected floors. An inlet vent that could be considered a fire door (that opens to the exterior of the building) that could open mechanically upon alarm would provide intake air without changing the building structure. FDS could model smoke movement, but another program, CONTAM might be more efficient at modeling leakages between floors and also the effects of stair pressurization. CONTAM is another program provided by NIST. It does not give a visual representation as does the pair of FDS and Smokeview, but it is a simple program that does not take a long time to compute results.

Alternate Fire Protection Systems

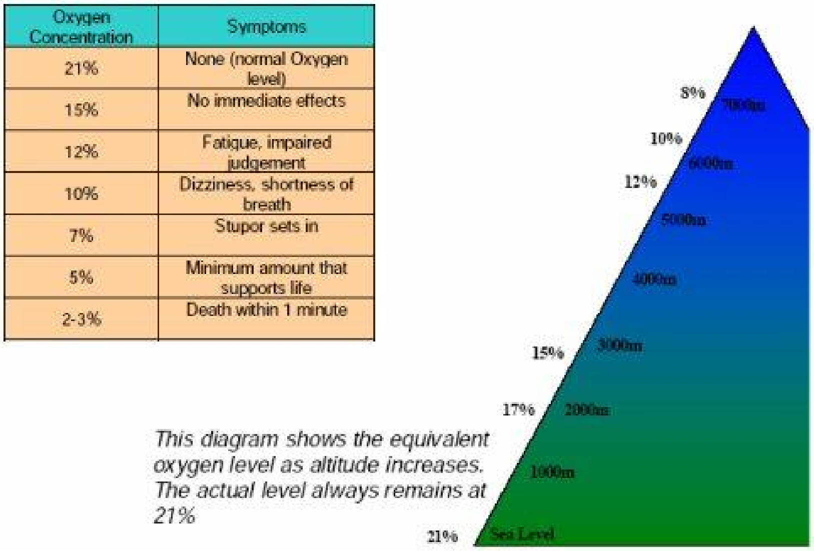
The fire protection system analyzed in this project was a water sprinkler system. It utilized standard sprinkler heads that actuated at a common activation temperature. The system was chosen based on availability of the materials and the relatively low cost associated with installing the system. If cost was not an issue, other methods of fire protection could have been considered. Due to the value of the materials in the library and the potential for great loss suffered in the event of false sprinkler activation, alternate methods could prove more cost efficient on specific floors. Two methods of fire protection that could be considered are a water mist sprinkler system, and an oxygen reduction system.

Water mist sprinkler systems utilize high pressure water which sprays a fine mist upon activation. The water droplets are small enough that they most likely evaporate quickly. This steam then expands in the area of the fire, thus dispelling oxygen from the fire source. In a contained room, this is enough to extinguish the fire. In a larger space, the supply of oxygen would probably continuously renew, rendering the water mist system ineffective. An advantage of water mist systems is the ability for the system to suppress a fire with an average of 1/3 the amount of water used in a traditional sprinkler system. Disadvantages include the initial cost of a system as well as a limited application. The cost could be overcome by analyzing the risk of ruining valuable archives. Books with this value could be enclosed in a smaller room where a mist system would be most effective.

A second alternative to a traditional water sprinkler system is an oxygen reduction system. Air has an oxygen percentage of about 20%. Fires require oxygen for sustainability, so to reduce the oxygen percentage in the ambient air will remove the possibility of a fire. Oxygen reduction systems have been traditionally used in engine rooms on ammunitions ships. Once a fire was detected, doors were sealed and a chemical was released into the area to remove oxygen and replace it with carbon dioxide.

Although this system was effective, it has since been deemed outdated and unsafe. The system does not allow for occupants in the room to survive. Depriving the fire of oxygen using carbon dioxide also deprives occupants of oxygen. A second factor that determined these systems were to be phased out of use was that the chemicals used in the system were not environmentally safe. Since this system was deemed unusable, a new system has been designed and is currently in use throughout the world.

The oxygen reduction system that would be most effective in the library situation imports nitrogen into the air controlled room. The nitrogen displaces enough oxygen to maintain a percentage suitable for tenable conditions, but not suitable for fire ignition. This oxygen percentage is around 15%.



Oxygen Concentration	Symptoms
21%	None (normal Oxygen level)
15%	No immediate effects
12%	Fatigue, impaired judgement
10%	Dizziness, shortness of breath
7%	Stupor sets in
5%	Minimum amount that supports life
2-3%	Death within 1 minute

This diagram shows the equivalent oxygen level as altitude increases. The actual level always remains at 21%

Figure C2: The effects of a reduced oxygen atmosphere.

Recent studies have not found any adverse effects on people working under reduced oxygen conditions. People exposed to this system have described the lack of oxygen similar to a feeling of being at a higher altitude. Similar oxygen reduction systems have been applied to computer storage rooms and labs. The large university library could apply this fire protection system in an archive room as was suggested for the water mist system mentioned previously. The application of the oxygen reduction system is not cost efficient for the entire building, and is only applicable in sealed areas with controlled ventilation.

For any alternate fire protection system to be installed, an analysis is needed to determine the effectiveness of the program. The value of the objects needing fire protection should be analyzed due to the potential costs associated with installing and maintaining these proposed alternate fire protection systems.