MODELING THE PERFORMANCE OF FIRE PROTECTION SYSTEMS IN MODERN DATA CENTERS

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BACKGROUND

The information age has led to the need to process and store vast amounts of data that are instantly accessible and crucial to the functioning of society. With the passing of the day when businesses could continue to function under manual backup procedures, the financial implications of the loss of access to data for even a few seconds is staggering. The growing use of cloud computing will result in this dependence only increasing.

The crucial nature of data storage has led to fault tolerant systems that automatically create and maintain multiple backup copies in data centers located on different continents such that no single event short of Armageddon could result in data loss. While this assures that data will not be lost, the loss of storage capacity by an event that takes even one data center off line could still be disastrous to operations where the need for access to pentabytes (10^{12}) of data is typical for many users.

DATA CENTERS AND TELECOMMUNICATIONS FACILITIES

Data centers have evolved into vast spaces filled with racks of servers with ever-increasing power densities. Space and energy demands are driven by the need to keep the systems cool and the power uninterrupted. Any arrangement that promises to reduce operating costs without compromising safety is explored for both cost control and sustainability.

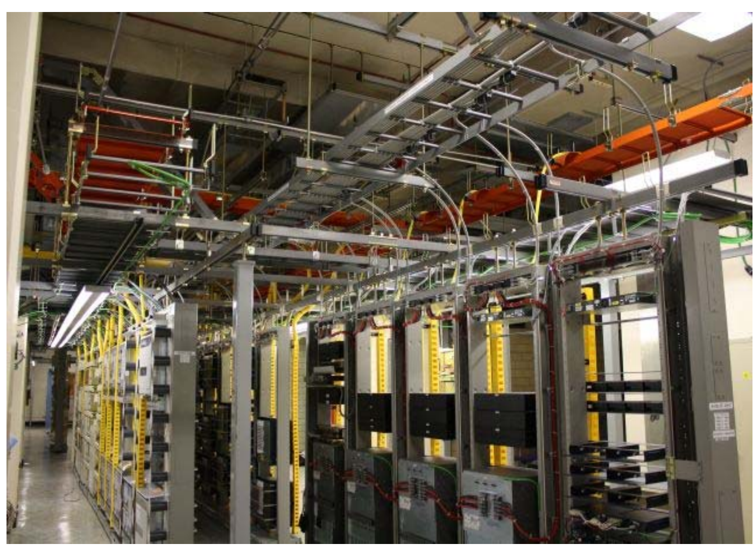

Figure 1 – Modern telecommunications central office

Telecommunications companies operate from facilities that are nearly identical to data centers but are descended from traditional Central Offices. In a wired telephone system, each telephone number involved a pair of copper wires that connected one or more telephones to the switching equipment at a Central Office. That equipment routed a call to the Central Office serving the number dialed and, thus, to the recipient.

Over time, the techniques of switching and transporting became more automated and involved many technologies including microwave and satellite links, and the switches became computers. Today the information carried will include a mix of voice, data, and video traveling as light over glass fiber with everything controlled by racks of servers nearly identical to the data centers operated solely for the storage and retrieval of data. Thus, for the remainder of this paper, the term data center will also refer to telecommunications facilities except where differences exist due to necessity or industry practice.

The chief differences between telecommunications and data processing/storage use of electronic equipment are rooted in the services provided and the users served. Telecommunications functions are switching and transporting data in real-time to and from a wide spectrum of users. Data in transit is lost if the systems fail for any reason. In recognition of this fact, the telecommunications industry evolved operating and power distribution practices that are different from those subsequently developed to support single-user data centers as they evolved. In traditional single-user data centers, procedures were available to conserve data so that, even in the event of failure, no data was lost. Currently, single-user data centers are disappearing as the functions they once served are being replaced by vast multi-user facilities. A damaging incident, such as a fire, in a multi-user data center could cause losses to many enterprises whereas a similar incident in a single-user data center would affect the only single enterprise.

Because of the crucial nature of data centers, the functionality has been designed to be fault tolerant. The system operates on a regional or even global basis so that any failure is instantaneously bypassed with no loss of information or functionality and totally transparent to the user. In the same way that a cell phone call from a moving vehicle is passed from one cell site to another, data stored at multiple sites can be retrieved without the user needing to know where it comes from. This is the essence of cloud computing where your data and software are stored in "the cloud" and can be retrieved at any time from any location. The system manages the data automatically, determining where it will be stored, and maintaining multiple copies at geographically diverse locations so that no single event can result in loss.

There are some differences in practice between data centers and telecommunications facilities. Telecommunications facilities have generally evolved from old Central Offices that were originally built to house racks of mechanical switching equipment. The switch racks were tall so ceilings are high and cables were distributed to/from the racks along trays in layers starting at ceiling level. The new computer racks are shorter, but the cabling still utilizes the ceiling mounted trays so most of the cables are above the racks (Figure 1). Cooling air distribution is usually from the ceiling into the room, then into the equipment racks. Power densities in the racks have tended to be lower in telecommunications facilities than in IT data centers, but that is changing as densities increase and in facilities that combine both types of services.

Data centers are usually built in new facilities. Some are designed with the racks on raised floors with cables entering/leaving from below. For some, the otherwise unobstructed ceilings carry the ventilation returns, detection and suppression system distribution and the subfloor serves as the supply for cooling air to enter the room and emerge at the top of the racks. An increasing portion of data centers are now built without raised floors and the cables are routed above the equipment. In both systems, cool air is dumped into the room and drawn into the rack, emerges from the rack into the room and is returned to the cooling system (CRAC).

As the electronic equipment used for all of the services, the physical arrangements have become more similar due to the increased heat density, effective cooling and energy conservation in HVAC systems.

AIR CONTAINMENT SYSTEMS

In recent years it has been recognized that if the temperature of the return air is increased, it will increase the efficiency of the cooling equipment and, in systems using economizers (cooling without running the compressor), further increasing system efficiency by lengthening the time that the economizer can be used[1]. This has led to the use of barriers (usually curtains) to segregate hot and cold air within the space[2].

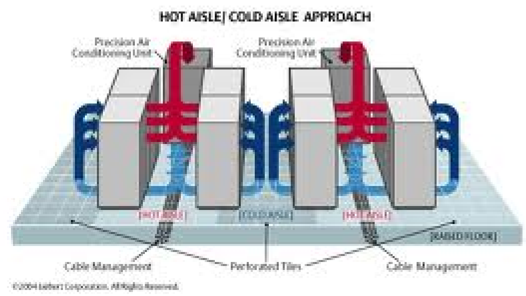

Figure 2 – Typical hot/cold aisle cooling system

Hot aisle/cold aisle systems arrange the equipment racks so that the fronts of two rows of racks face one aisle and the backs face the next (Figure 2). Curtains separate the environments of each aisle with cold air entering the aisle with the rack fronts and warm air returned from the adjacent aisle with the rack backs. Curtains are used so that the equipment can be accessed by personnel when necessary.

A variant is the so-called "hot collar" system where curtains or a duct form a collar above racks at the air discharge location to carry hot air directly to the return. Cold air is supplied to the room but does not mix with the hot (Figure 3).

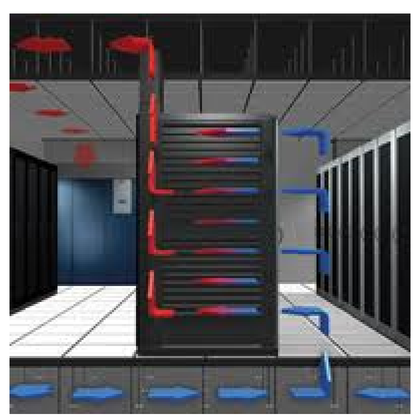

Figure 3 – Airflow in a hot collar system

FIRE PROTECTION IN DATA CENTERS

The problem faced when air containment systems are used is that fire protection for these spaces is normally accomplished with open area detection mounted on the ceiling of the space and clean agent suppression systems that discharge at the ceiling to flood the space. The containment curtains must be located with respect to the air supply and return locations and the locations of intake and exhaust for the racks, so they frequently interfere with the location of detectors and nozzles. Tests in a telecommunications facility[3] showed that air sampling systems were especially effective in these high airflow conditions, but locating air sampling intakes in each equipment rack is cost prohibitive. Guidance in the National Fire Alarm and Signaling Code (NFPA 72) on locating detectors in high airflow applications is minimal and it is not clear whether agent concentrations are always adequate at critical locations within the racks when discharge nozzles are located at the ceiling. Wide variability in equipment configurations and airflows make verification testing impractical.

The air containment curtains act as barriers to the free flow of air and may, therefore, have a profound effect on smoke detection system performance, but they do not form a compartment. The equipment being cooled contains fans which draw the cooling air through the equipment lineups, so the lineups do not define a compartment. Neither are the equipment aisles plenums. They are aisles necessary to perform maintenance and operations of the equipment and are arranged for access by authorized people.

FLUID DYNAMICS MODELS

It has been suggested that computational fluid dynamics (*cfd*) models can be used to predict the details of the airflow with sufficient accuracy to permit optimal siting of smoke detectors, either spot-type or the intake ports of aspirated detectors. Fluid dynamics models are commonly used in the analysis of a broad range of problems from designing aircraft wings to ventilation systems for buildings and tunnels, and many commercial codes are available, although commercial license fees can be high.

All fluid dynamics models work by solving the *Navier-Stokes Equations* for fluid flow. The Navier-Stokes Equations predict the velocity (flow) field of a fluid in space and time and are solved as a set of nonlinear partial differential equations. What sets the different *cfd* models apart is the technique(s) used to address turbulence. Many models use time-averaged equations and are referred to as Reynolds Averaged Navier-Stokes (RANS) models. Additionally, cfd fire models traditionally include κ-ε models for turbulent kinetic energy to avoid significant numerical challenges. The major problem with this approach is that the values of κ and ε must be estimated by the user based only on experience, so this introduces a significant source of uncertainty.

In recent years, cfd fire models have been developed using the technique of Large Eddy Simulation (LES) to address turbulent flows. LES models solve the flow from first principles without the need for user-selected parameters, resulting in lower uncertainty. The problem was that LES approaches are computationally expensive, so engineering models needed the availability of computers with significant processing power at low cost. Today, the computing power available to most engineering firms, especially computer clusters running parallel enabled codes, permit LES models to be applied to many problems. Today the typical “smart phone” like an Android or iPHONE has 36 times the processing power of a Cray 1 supercomputer that cost $700k in the late 1970s.

Some fluid dynamics models have been adapted to modeling fires. This requires that variations in temperature and density can result in buoyancy-driven flows in addition to mechanical sources. Heat transfer (conduction, convection, and radiation) is modeled, primarily as a means to transfer energy out of the gas. Species tracking is also needed to follow the distribution of chemical species and soot carried in the flow, allowing prediction of local concentrations. Despite many attempts over the years to incorporate prediction of chemical reaction rates, this remains beyond the state-of-the-art.

Combustion is an exothermic chemical reaction; the fire itself cannot be predicted from first principles and must be specified over time by the user. Since the development of oxygen consumption calorimetry, the description of the (free-burn) rate of heat release has been straightforward as long as radiant enhancement from the surroundings is not significant. Similarly, the specification of the release of species including soot by a yield fraction of the fuel mass lost produces predictions with reasonable uncertainty (similar to the uncertainty of measurements taken in full-scale experiments). Adjusting yield fractions as a function of local equivalence ratio addresses the fact that yields can vary significantly as a function of oxygen availability and combustion efficiency.

PREDICTING DETECTOR RESPONSE

Smoke detectors have become common in both residential and commercial applications. Commercial smoke detectors are usually based on light-scattering sensors but ionization is still sometimes used. Aspirated systems sometimes used in data centers also operate on light scattering.

The response of light-scattering sensors correlates best with the mass concentration of soot in the sensor and cfd models can track mass concentrations carried in the flow when the user specifies a soot yield at the source. The dynamics of the soot in transit does not affect the mass concentration except for losses by deposition on surfaces. Predicting the response of ionization sensors is more problematic. These correlate with particle number density and this changes drastically over time. Large numbers of small particles released at the source agglomerate, resulting in far fewer number of aggregates. One would need to specify a particle size distribution at the source and include a coagulation model to predict the dynamics, and several attempts to do this have been unsuccessful. Correlating the response of ionization sensors to mass density is generally unsatisfactory.

PREDICTING AGENT CONCENTRATIONS

The other fire protection design feature that is desirable to predict in data centers is the local agent concentration within the equipment to ensure that it meets or exceeds the minimum design concentration for extinguishment. This should be possible since it is the same calculation as the local mass concentration at the sensor(s), except that one would need to specify the mass discharge rate at the nozzles as the source term. Like soot, the agent mass is carried in the flow and is reduced by dilution. Deposition to surfaces should not be a factor with most agents.

SELECTING A CANDIDATE MODEL

Numerous *cfd* computer models have been developed for use in fluid flow and heat and mass transfer processes including convective heating and cooling over a range of physical scales. Some commercial codes (e.g., Fluent, Phoenics, and Flow-3D) have been utilized to provide detailed analysis of cooling air flows in rooms[4], including data centers. Because of the inherent difficulties of modeling turbulent flows with these κ-ε models some have begun to utilize LES models for the purpose. Models configured to be used for fire predictions already have the ability to track mass concentrations of species carried in the flow, so these would be preferable.

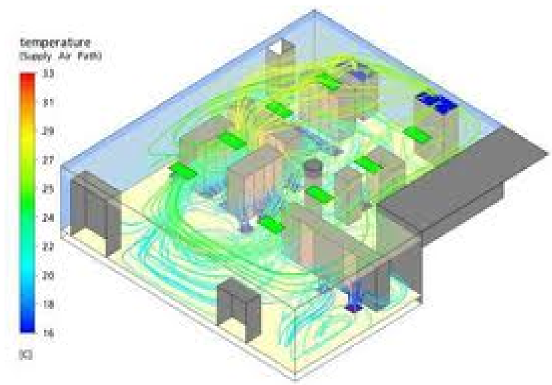

Figure 4 – CFD model of airflow in a data center

Another consideration is the cost of a license. Commercial *cfd* models are expensive to create and even more expensive to support given the limited customer base. While highly-discounted licenses are available for educational uses, commercial user licenses are pricey, in the range of $20,000 to $60,000 per year. Further, the source code is not available so modifications to address specific issues are not possible without developer participation.

These considerations speak strongly to the use of the Fire Dynamics Simulator (FDS) model from the National Institute of Standards and Technology (NIST). This LES model was developed for fire predictions so it can track species mass carried in the flow[5], is configured to run on computer clusters reducing the time required to execute cases involving a fine grid resolution, and has a capable visualization package, Smokeview (SMV). Best of all, it is free to all. Where improvements are needed to address a specific problem, collaboration can be arranged with the developers at NIST where the only costs are those incurred by the outside party and with the only condition being that the improvement be made available to all without cost.

At least two possible outcomes are envisioned. If a modeling tool is developed that is based on a readily available platform, it should be possible to use it effectively in the design process for specific data centers. On the other hand, if it is necessary to develop the tool based on a platform that is restrictive in its use, then it would be necessary to use the tool to develop guidance for facility designers.

IDENTIFYING DESIGN FIRE SCENARIOS

The analysis undertaken for a telecommunications facility or IT data center should reflect the range of fire scenarios expected over the life of the facility. Details of such design fire scenarios are normally identified from the historical fire record and would identify the source of ignition and principal fuels. Several, significant fires in telecommunications facilities are in the public record and can be used to establish appropriate cases for study[6]. Fire records for IT data centers are not generally available due to their shorter history and operations confidentiality. From the few news accounts of fires in data centers, it appears that many of the fire hazards that have historically been found in computer rooms are still present. These include transient fuels associated with maintenance or construction and improper storage of combustibles under raised floors and above suspended ceilings.

DESIGN FIRE SCENARIOS

In the absence of well documented fires in data centers, it is necessary to develop suitable design fire scenarios based on known fuel packages, facility characteristics and industry practices. Representative fuel packages include electronic equipment and cable arrays. Some fires in the record for telecommunications facilities involve battery racks, but the changing technology in the industry has resulted in significant changes to the types and characteristics of battery systems including UPS systems. Fires started in administrative and technical support areas are essentially office occupancy fires that have been well studied and reported in other contexts, and will not be addressed here.

Electrical Fires in Digital Electronic Equipment

Digital electronics historically operated at 5 vdc or less. In recent years as circuit densities have increased, the operating voltages have been significantly reduced in order to reduce heat and to reduce power demand on batteries. Today, multi-core microprocessors and associated components including memory operate at around 1 vdc. There is simply not enough energy available, even under fault conditions, to initiate fires. There have been fires started when equipment overheats and ignites cable insulation, although polymers utilized in wire and cables are relatively difficult to ignite and self-extinguish when the heat source is removed.

Figure 5 – Fires can destroy the capacity, but the data is usually safe at a mirror site

When fires start in the equipment, they typically start in power supplies including UPS systems that contain higher voltages and energies. Power supplies are the most efficient when operating near their maximum capacity, and are the most stable and efficient when powered from 240 vac sources[7]. Since the fault energy available in the high voltage portions of the system is significantly higher, these are the most likely sources of ignition in data center equipment racks.

Locating power supplies close to the equipment powered reduces the length of low voltage (and correspondingly high current) wires and the energy losses associated with resistive heating. This improves efficiency, but exposes equipment to fires that may begin in the power supplies. According to accepted practice, equipment is positioned in the racks locating heavier equipment at the bottom to increase stability. Since power supplies are the heaviest due to the weight of transformers and batteries, this places the components more likely to be the source of a fire at the rack bottom where it is more likely to spread upwards to other equipment.

Cable Tray Fires

Cable in trays is a primary source of fuel for fires in telecommunications facilities and data centers. While difficult to ignite and slow to spread flames, modern cable insulation can burn, releasing smoke and acidic gasses that can damage equipment even after the fire is extinguished.

Since the 1975 Browns Ferry Nuclear Plant fire, there has been significant interest in cable tray fires. In the decades immediately after this fire, the Electric Power Research Institute (EPRI) funded numerous studies including the measurement of fire properties (critical flux for ignition, HRR, flame spread) of a broad range of cable types used by the nuclear industry[8] and models for ignition and flame spread of cables in trays were developed. In the past decade, several verification and validation studies of models (zone, cfd, and lumped parameter) have been conducted and published by the US Nuclear Regulatory Commission[9] and by the European Union[10].

In telecommunications facilities and data centers, most of the cables carry low voltage signals so the fire hazards are as fuel ignited by other sources. Power cables that might be fire sources are physically separated from data cables. NRC model exercises have evaluated the ability of models to predict the ignition of a target cable by an external source, which is the primary scenario of interest here.

Several models including CFAST and FDS have been validated and verified which includes quantification of predictive uncertainty, and they are certified for regulatory use by NRC, thus they are suitable for data centers. Fire property data for most cable types is also available as input parameters for models. Design fire scenarios involving cables in trays will be straightforward to implement.

Electronic Equipment

Manufacturers of the robust type of electronic equipment that is used in commercial IT and telecommunications applications submit their products to evaluation and testing against accepted industry standards. Equipment assemblies are then listed or approved for use in commercial IT and telecommunications systems. The two most prevalent standards are

- UL 60950 by Underwriters Laboratories, and,
- Network Equipment Building Standard (NEBS) GR-63 by Telcordia.

The UL standard is the prevalent standard applied to IT equipment. The NEBS standard is applied to telecommunications network equipment.

Major ITE facilities include automatic fire suppression systems. Many telecommunications facilities include automatic suppression systems in non-equipment areas, but not in the switching equipment areas. Regardless, the objective in the event of any fire in an ITE area is to detect and extinguish the fire before the automatic suppression system operates. This requires early detection, and rigorous alarm response and action to terminate the fire. Available fire detection systems are capable of detecting electrical and component overload events before flames are present.

Established burning of solid combustibles occurs in the presence of flame height of approximately 25 cm. It is desirable to detect component overloads and established burning at the earliest practical time to initiate actions that will terminate the incident before fire suppression operation becomes necessary. Therefore, the range of design fires for electronic equipment should include one that is at the commencement of established burning. While it would be desirable to include a smoldering fire representing electrical overload of electronic components, available fire models may not be able to include a smoldering fire in the analysis.

In a private study[11] performed and peer reviewed among three well known fire protection engineering consulting firms for a major operator of telecommunications and data center facilities, two applicable design fires were identified

- NEBS GR63 fire and
- UL 60950 fire.

Both are characterized with T^2 (time squared) growth rates and maximum heat release rates based on the results of full-scale testing against the identified test standards and acceptance criteria.

NEBS GR63 Compliant Telecommunications Equipment

Figure 6 shows the results of a fire test involving an equipment frame of 2002 vintage telecommunications equipment. Note that fire spread is limited to the upward direction, following a classic “V” pattern of fire growth. In this photo, which shows the ‘back plane’ of the equipment, fire spread to the circuit boards on the front side (plugged into

Figure 6 – Results of NEBS Fire Test on 2002 vintage equipment

the other side) of the back plane was minimal. The fire originated in the rack level at the bottom of the photo, damaged the plastic trim piece seen at the top (trim was bent upwards so that the doors could be opened for the photo), but did not spread beyond the cabinet.

A review of data from NEBS tests indicated that in approximately ninety percent of full-scale equipment tests, the peak heat release rate falls between 15 and 20 kW. This design fire is characterized as follows:

- A growth phase that follows the $\dot{Q}(t)=\alpha t^2$ fire growth model described in Schifiliti *et. al.* [1995], with a fire growth constant (α) of 0.001 kW/sec^2, which tracks the fire growth of the full-scale tests.
- A constant steady-state phase will begin when the fire has grown to a heat release rate of 100 kW, and will remain at a steady 100 kW until the fuel is exhausted. This 100 kW steady-state fire bounds the test results of NEBS compliant equipment and matches the average heat release rate criterion in the NEBS standard.

Qualitative and quantitative acceptance criteria for the NEB GR63 full scale equipment testing includes:

- The fire shall not spread beyond the confines of the equipment assembly being tested. The fire shall be judged to have spread beyond the equipment under test if any of the following occur:
  - Ignition of any material in equipment frames placed adjacent to the test frame or in overhead cabling.
  - Visible burning of any exterior surface material for 30 seconds or more.
  - Visible flames extending beyond the horizontal or vertical confines of the equipment under test for 30 seconds or more.
  - Flaming drippings that continue to burn upon reaching the ground.
  - Heat flux, as measured by radiometers, that exceeds 15 kW/m^2 for 30 seconds or more.
  - Temperature, as measured by any of the specified thermocouples, exceeding 540°C (1,004°F) for 30 seconds or more.
- The peak rate of heat release shall not exceed 150 kW at any time during the test, and,
- The average rate of heat release shall not exceed 100 kW over any 30-minute period during the test.

Given the information taken from the private report and long-term success seen as the absence of fires in NEBS GR63 compliant equipment and the absence of telecommunications equipment fires spreading, the NEBS GR63 design fire is an appropriate candidate.

UL 60950 Listed IT Equipment

The generally accepted standard of safety applicable to electronic equipment is UL 60950, *Standard for Safety of Information Technology Equipment.* This standard employs a series of small-scale fire resistance tests intended to limit the ignitability of the small plastic items or components in the assembly. There are no full-scale fire tests used in the standard. The standard places a heavy reliance on limiting the energy that may be available for initiating a fire event through circuit analysis and related engineering controls.

Research that includes heat release rate data from full-scale tests of burning electronic equipment in cabinets was conducted by Mangs[12] and Keski-Rahkonen[13] [Mangs, 1994; Mangs, 1996]. These tests conducted under a fire products collector used a 0.5 - 1.5 kW propane line burner ignition source at the bottom inside of a fully loaded electronic equipment cabinet. In these tests, the heat release rate typically grew slowly and reached a peak of less than 400 kW in between 15 and 40 minutes. Figure 7 shows the heat release rates for six of these tests.

Considering the results of the six tests and the protocol of the UL 60950 test standard, a design fire representing IT equipment listed in accordance with UL 60950 can be characterized as follows:

- An initial fire growth phase that follows the $\dot{Q}(t)=\alpha t^2$ fire growth model described in Schifiliti et. al. [1995], with a fire growth constant (α) of 0.001 kW/sec2, (which tracks the fire growth of the full-scale tests presented in the figure).
- A constant steady-state phase will begin when the fire has grown to a heat release rate of 200 kW, and will remain at a steady 200 kW until the fuel is exhausted

Given the information taken from the private report and long-term success seen as the absence of major data center equipment fires, the UL 60950 design fire is an appropriate candidate.

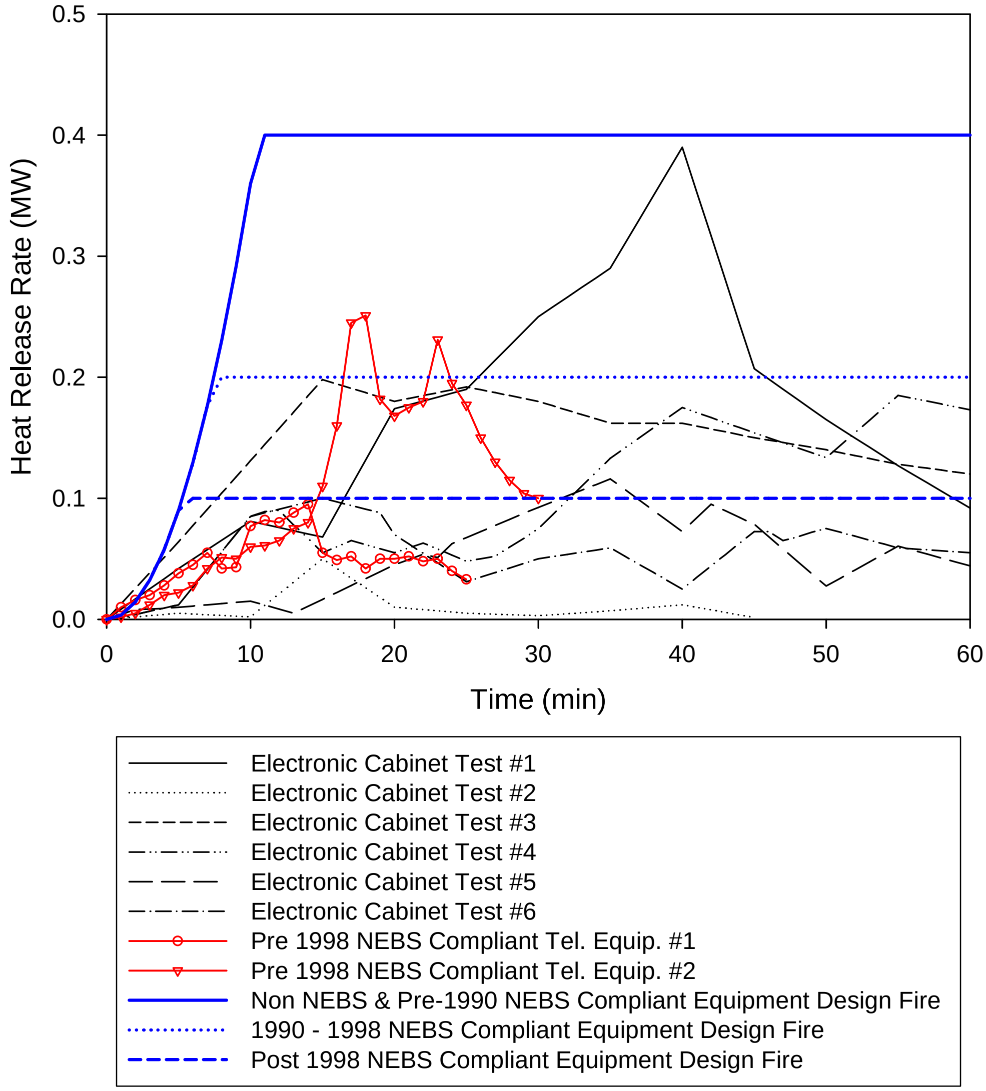

Figure 7 – Electronic Equipment Fire Tests & Design Fires

Smaller Design Fire for IT Equipment

Figure 7 illustrates that selected ITE fires may exceed the maximum heat release rate suggested for the UL 60950 fire. Yet, the objective is to detect fires and overloads small enough to be terminated without the use of suppression systems. Therefore, for modeling to meet the objective, small design fires are more appropriate than the worst credible fire would be. Considering that the experience of full-scale NEBS testing of telecommunications equipment indicates that in approximately ninety percent of full scale equipment tests the peak heat release rate falls between 15 and 20 kW, a smaller design fire is justified to meet the objective.

Tests of printed circuit boards determined that a fire limited to typical ITE boards can be represented by a maximum heat release rate of 3 to 10 kW[14]. If an electrical overload, component failure or incipient fire can be detected before it spreads to another printed circuit board – before established burning – then the objective can be better met.

Therefore, the design fires for electronic equipment should include a third T^2 fire with a maximum heat release rate of 25kW.

Proposed ITE Design Fires

Therefore, ITE design fires maybe conservatively represented as T^2 fires with maximum heat release rates of:

- 200 kW,
- 100 kW and
- 25 kW.

To this, ideally, a smoldering fire could be added if it could be used with an appropriate model.

CONCLUSIONS

Based on the discussions contained in this paper, it should be possible to utilize a *cfd* fire model to predict both the local mass concentration of smoke from a specified design fire and to predict the local concentration of gaseous extinguishing agents released at a specified rate from nozzles in the space. The resulting predictions should be useful in assessing the potential of smoke detectors to respond to these design fires and for the agent to reach the minimum extinguishing concentration within the equipment.

Once accomplished, experiments should be conducted to assess the uncertainty of both predictions to quantify the predictive accuracy and to validate the technique. Given the potential economic impact of the loss of telecommunications or data storage capacity, particularly as more use is made of cloud storage, and the investment in such facilities, funding needed to accomplish these tasks should be achievable.

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