VIRTUAL FIRES via COMPUTERS

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ABSTRACT: This paper discusses simulation of a design fire in a typical building including mitigation with sprinklers and ventilation, but as affected by an approach boundary layer wind field. The computations used both CFAST (a zone fire model) and FDS (a field model) developed by NIST. The work combines understanding of building aerodynamics, exfiltration, infiltration, fire physics, and heating and ventilating.

1 INTRODUCTION:

Recent publication of world fire statistics reveals that costs of fires including prevention, protection and repression currently runs around 1% of GDP in most advanced countries. Deaths and losses in the United States tend to be the most extreme with annual losses of $13 bn/year.[1] The annual review performed by Munich Re of world disaster losses reveals that world-wide forest fire losses alone exceeded US$5.5bn and insured losses exceeded US$2.5bn during 2003. Such losses exceeded the sum of all losses from volcanic eruptions, hailstones, flash floods, tsunamis, landslides, avalanches, water drainage, frost, and local and winter storms combined![2,3] (Of course extreme events like the Baran earthquake, the European heat wave, floods, and severe and tropical storms like Katrina can individually exceed fire losses.) Human risk is demonstrated by the 2004 fire at a shopping mall in Asuncion, Paraguay during which 400 people were killed and hundreds were severely injured.

Building to preserve occupant safety is controlled by various national and international fire codes.[4, 5, 6, 7] Predicting smoke and flame behavior can be based on full-scale field experience, analytic integral approximations that capture the gross flow behavior, fine-scale numerical modeling and/or physical modeling at reduced scale...these methods are typically called full-scale, zone (algebraic or ode numerical), field (pde numerical), and physical modeling, respectively (a review of these alternatives is found in Meroney, 2007).[8, 9, 10] In this paper we will focus on the potential of a fast zone model (CFAST) versus the finer details provided by a field or CFD model (FDS).

1.1 *Merits of Virtual Modeling of Fire through Numerics*

Computational fluid dynamics (CFD) provides a design technique to examine the relative merits of various fire suppression strategies. Such programs can inherently consider irregular building and terrain geometry, heat transfer due to variable properties and radiation, time varying fire strength, fire chemistry, effect of fire suppression operation, and variations in weather phenomena. Realistically, however, many of our computational sub-modules for combustion, radiation, pyrolysis, etc. are still primitive, and even inclusion of all models within a computation becomes cumbersome to calculate, and excessive in use of computational resources and time. Models are also constrained by the simulation model chosen, since continued verification and validation are required at almost every level of CFD prediction. Thus, one should ask when is a fast approximate model appropriate, and when should one take the time to predict fire and flow details?

1.2 *Merits of Integral Models vs Field Models*

Integral Model: The software Consolidated Model of Fire Growth and Smoke Transport (CFAST) is a two-zone (layer) per room integral model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire. These can range from very small containment vessels, on the order of 1 m^3 to large spaces on the order of 1000 m^3.[11, 12]

The modeling equations used in CFAST take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently the first law of thermodynamics), the ideal gas law and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, smoke layer height and temperatures given the accumulation of mass and enthalpy in the two layers. The CFAST model thus consists of a set of ODEs to compute the environment in each compartment and a collection of algorithms to compute the mass and enthalpy source terms required by the ODEs. The program has added features to account for constant and time-dependent fire sources; suppression effects of water sprinklers, CO_2, or oxygen depletion; the effects of horizontal and vertical openings and mechanical flow vents; the presence of walls made of layered materials; thermal detectors, smoke alarms and water sprinklers; and the effects of external wind on flow through horizontal vents.[8] Fires in CFAST are pre-specified in terms of Heat Release Rate (HRR) based on empirical measurements; hence, the fire physics is not incorporated in the solution.

Field Model: The software Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires.[13, 14, 15]

The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES). FDS primarily uses a single step chemical reaction tracked via a two-parameter mixture fraction model to incorporate combustion, but, recently, adjustment algorithms permit the inclusion of suppression by oxygen depletion, CO_2 presence and water sprinklers.

Both CFAST and FDS can present results visually through the graphics program, SmokeView, that displays time varying slices, isosurface contours, and vector fields of temperature, concentrations, soot, pressure and velocities.[16]

Verification and Validation: The CFAST and FDS models have been subjected to extensive validation studies by NIST and others.[17] Table 1 summarizes how the two models performed when compared to ten experimental situations covering a range of fire scenarios. Typically predictions are accurate within 10 % to 25 % of the measurements, which were often within the range of uncertainty of the experiments.

For the most cases considered, the results of the field model, FDS, were not significantly better than those of the two-zone model, CFAST. FDS solves the basic transport equations instead of empirical and integral correlations, making it a more predictive model. However, the computational cost of solving the basic equations is substantial. The two-zone models produce answers in seconds to minutes, while FDS produces comparable answers in hours to days. FDS is better suited to predict fire environments within more complex geometric configurations because it predicts the local effects of a fire.

2.0 VIRTUAL FIRES IN A REPRESENTATIVE BUILDING

Comparison calculations were performed for a three-story gable-roofed building of rectangular plan-form. The building included a central stair case surrounded by a partial smoke curtain which connected the principal rooms on all three floors (giving the configuration an atrium-like characteristic). Additional offices, lobbies, and stairwells connected to the principal rooms on the 1st and 2nd floors. The configuration included flow through inlet and outlet registers, passive pressure driven vents, and preset mechanical exhaust vent flows on each floor and in the roof. A design fire of a burning upholstered chair located on the 1st level in a lounge fire was specified. Water sprinklers were installed above the chair to be activated by a heat detector. Additionally, he International Fire Code specifies that the influence of an extreme wind about the building occurring at a 1% likelihood be considered.[7] A wind condition set to 11.8 m/s (25 mph) at a 10 m height was incorporated into the analyses.

CFAST considers each room a separate compartment connected by horizontal and vertical vents (doors, windows, and ceiling openings). Room location is not relevant, just which rooms connect. Vent location is also not important other than their height above floor level. However, the program allows one to arrange compartments and vents horizontally and vertically to reflect their actual orientation in Smokeview (see Figure 1). FDS aligns all surfaces within a rectangular grid; hence, curved and inclined surfaces appear as "saw-toothed" shapes. Nonetheless, all vents, registers, fans, fires, stairs, and sprinkler systems can be placed in their actual positions and orientations (see Figure 2).

The upholstered chair design fire used in both CFAST and FDS simulations were identical. Figure 3 indicates the time dependent variation of Heat Release Rate (HRR) in kW versus time in seconds. Each calculation was permitted to simulate times up to 1200 seconds (20 min).

Wind effects are treated differently in the two models. In CFAST wind effects are determined from the building orientation and vent locations. Vents are subjected to positive or negative pressures dependent on a reference velocity, wind orientation and empirical pressure coefficients. This can result in enhanced ventilation through upwind vents, or reversal of flow from inlet to exhaust for downwind vents. In FDS the actual flowfield around the building is explicitly calculated, and associated secondary flows and pressure fields are determined from the flow dynamics (see Figure 4).

3.0 COMPARATIVE RESULTS

The zonal model of CFAST routinely produces time-dependent layer-averaged temperatures (ULT - upper layer temperature and LLT - lower layer temperature) and smoke layer heights (SLH) for each compartment. The field model FDS can calculate the spatial variation of temperatures, velocities, concentrations and soot throughout each room and on the external faces of the structure. A detector was placed in a central location on each floor of the FDS simulation which also permits local specification of ULT, LLT and SLH. However, since the detector has a unique location, the values are not layer-averaged over the entire floor; hence, it is expected FDS- predicted SLH minimums will be smaller than CFAST SLH minimums, and FDS- predicted ULT & LLT maximums will be larger than CFAST values.

Several of the CFAST and FDS simulations are compared in Figures 5 to 8. Each floor level and the conditions within the stair wells are displayed in separate bar charts. The left axis displays ULT and LLT temperatures (^{o} C), whereas the right axis displays SLH (meters). A simple design goal for occupancy safety would be to mitigate the fire such that the SLH remains above 2 m and the maximum exposure temperatures remain below 30 ^{o} C (a 10 ^{o} C increase in temperature over ambient conditions is often associated with visibility decreased below 10 m or 30 ft.) Thus, the black dotted arrow line points to a 2 m SLH, and the red dotted arrow line points to a 30 ^{o} C temperature. If these conditions are not maintained, then one designs for a "tenable" evacuation situation which does not expose occupants to excessive heat for too long. Human exposure studies have shown that temperatures up to 50 ^{o} C are tenable for periods up to 600 sec (10 min) or up to 70 ^{o} C for short periods (100-300 sec).

Results shown in Figures 5 to 8 suggest there are a few situations where SLH falls below 2m and ULT rise above 30 ^{o} C. However, closer examination of the detailed data time traces indicate that thermal exposure times are always less than 300 sec even for ULT as high as 60 ^{o} C. Separate obscuration detectors included in the FDS simulation also showed that at no time did the percent obscuration rise above 30%. A 30% obscuration permits sign visibility out to 77 m (252 ft); hence, visibility is not an issue during this simulated fire.

4.0 SUMMARY

An integral fire prediction model like CFAST provides a fast and accurate screening model during fire and smoke mitigation design studies. Its flexibility and speed permit many alternative scenarios to be examined quickly. On the other hand, some fire scenarios are not accurately defined by a two-zone model, or it is anticipated that spatial inhomogeneities within a room may influence smoke development and propagation. In these cases a field model like FDS provides valuable additional details concerning fire and smoke development.

5.0 REFERENCES

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Parameter		Fire Model	
		CFAST	FDS
Hot gas layer temperature ("Upper Layer Temperature")	Room of origin	Green	Green
	Adjacent room	Yellow ±30%	Green
Hot gas layer height ("Layer interface height")		Green	Green
Ceiling jet temperature ("Target/Gas temperature')		Yellow -16 to +100%	Yellow ±20%
Plume temperature		Not calculated	Green
Flame Height		Green	Yellow [1]
Oxygen concentration		Yellow ±20%	Yellow ±20%
Smoke Concentration		Yellow-35 to +450%	Yellow -33to +400%
Room pressure		Green	Green
Target temperature		Yellow ±50%	Yellow ±30%
Radiant heat flux		Yellow-50 to +150%	Yellow ±50%
Total heat flux		Yellow -90 to +70%	Yellow ±30%
Wall temperature		Yellow ±60%	Yellow ±50%
Total heat flux to walls		Yellow -70 to +90%	Yellow ±30%

Criterion 1 - Are the physics of the model appropriate for the calculation being made?

Criterion 2 - Are there calculated relative differences outside the experimental uncertainty?

Green	: Both criteria are satisfied, model can be used with confidence
Yellow	: 1st criterion is satisfied, but differences are outside experimental uncertainty with no pattern of over- or under-prediction.
Red	: 1st criterion is not satisfied.

[1] FDS does not use an empirical correlation to predict the flame height. Rather, it solves a set of equations appropriate for reacting flows and predicts the flame height as the uppermost extent of the combustion zone. This is a challenging calculation and the Yellow emphasizes that caution should be exercised by users.

Table 1: Results of the Validation and Verification of CFAST and FDS for Nuclear Power Plant Fire Modeling Applications [12]

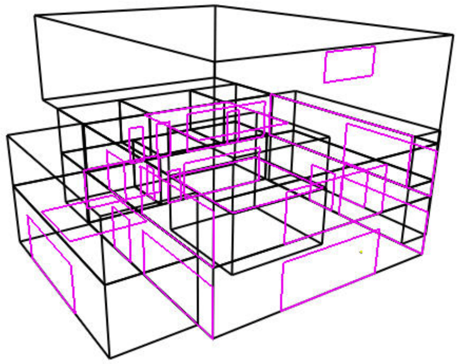

Figure 1: CFAST building configuration

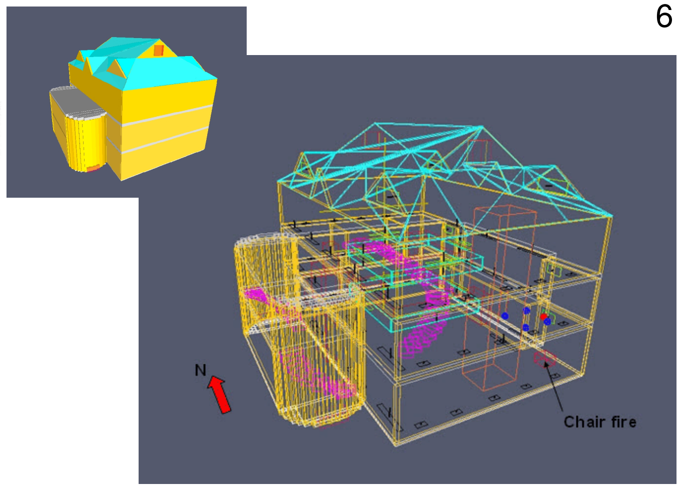

Figure 2: FDS building configuration

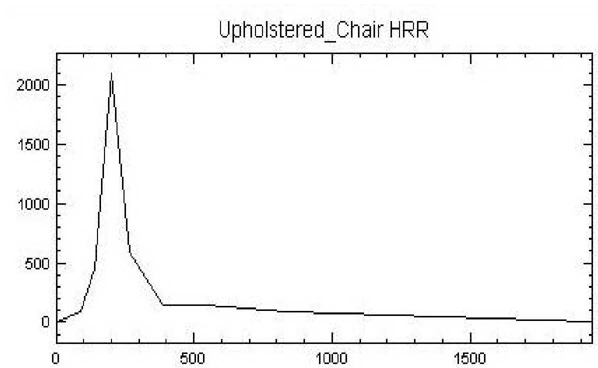

Figure 3: Heating Reaction Rate - upholstered chair (kW vs time, sec)

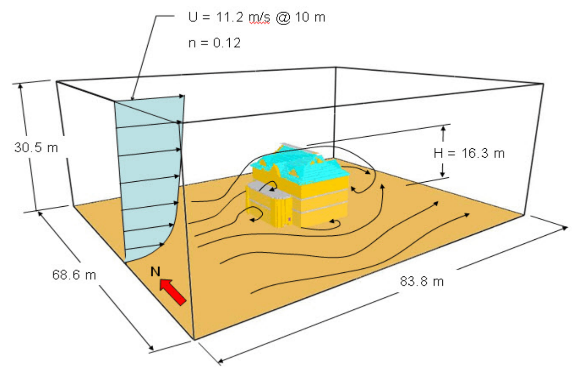

Figure 4: FDS Wind field schematic

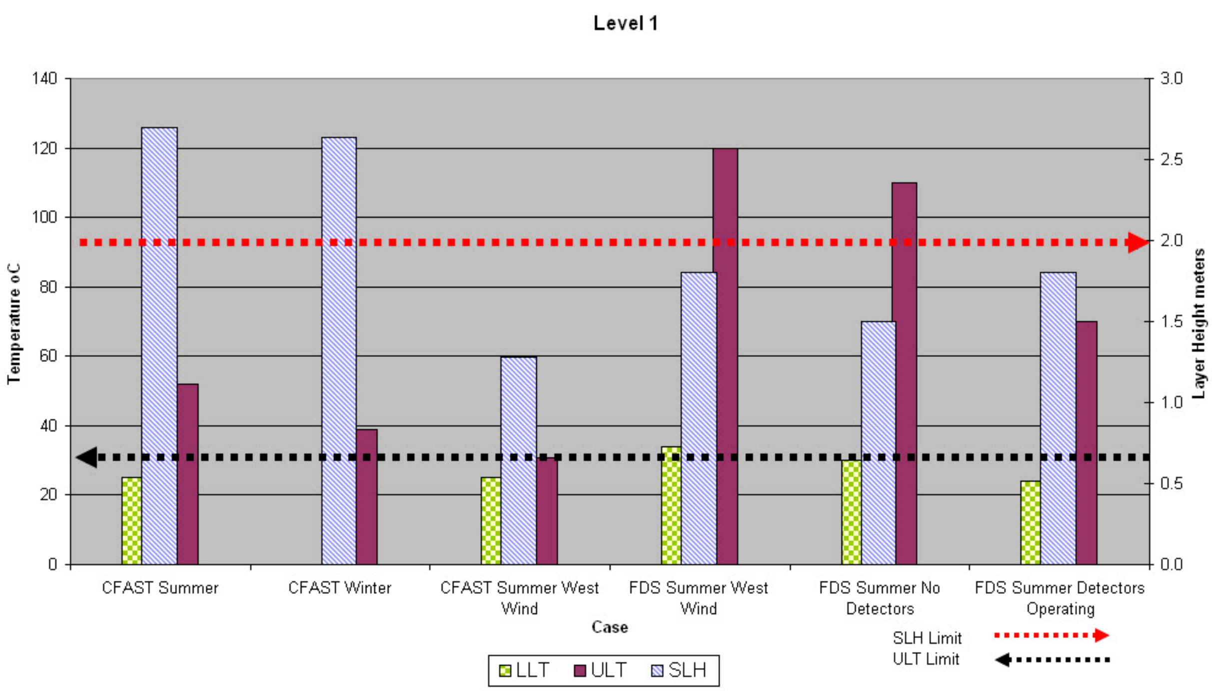

Figure 5: Lower layer temperatures (LLT), Upper layer temperatures (ULT), and Smoke layer height (SLH) on Level 1 (Main floor) for various CFAST and FDS case runs, Chair fire on Level 1, SE corner.

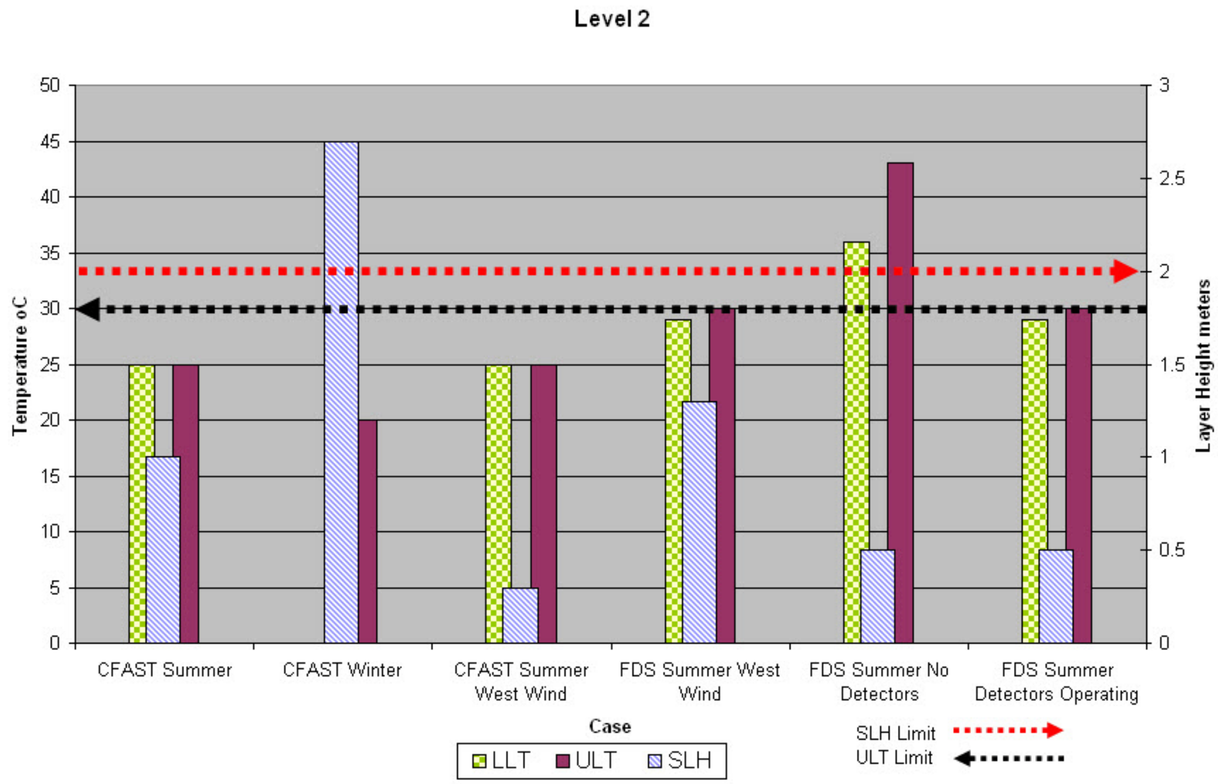

Figure 6: Lower layer temperatures (LLT), Upper layer temperatures (ULT), and Smoke layer height (SLH) on Level 2 (2nd floor) for various CFAST and FDS case runs, Chair fire on Level 1, SE corner.

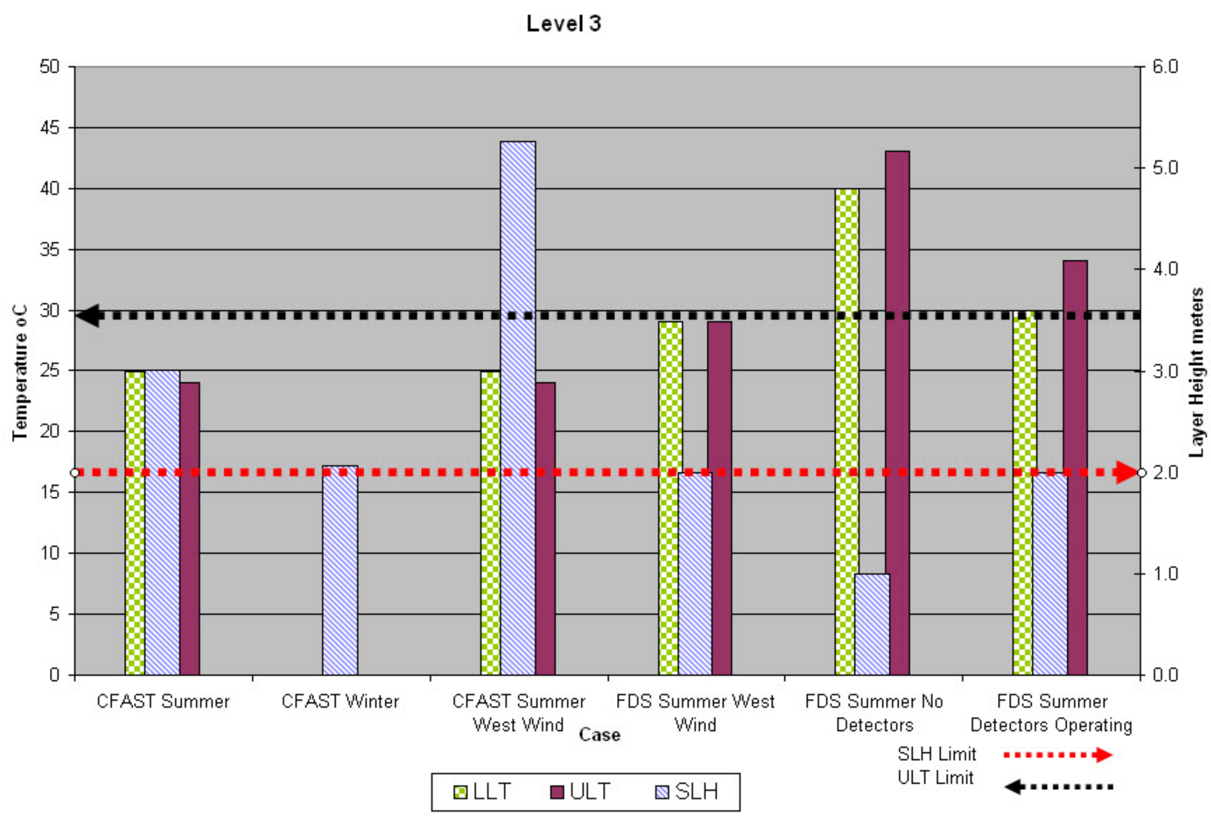

Figure 7: Lower layer temperatures (LLT), Upper layer temperatures (ULT), and Smoke layer height (SLH) on Level 3 (3rd floor) for various CFAST and FDS case runs, Chair fire on Level 1, SE corner.

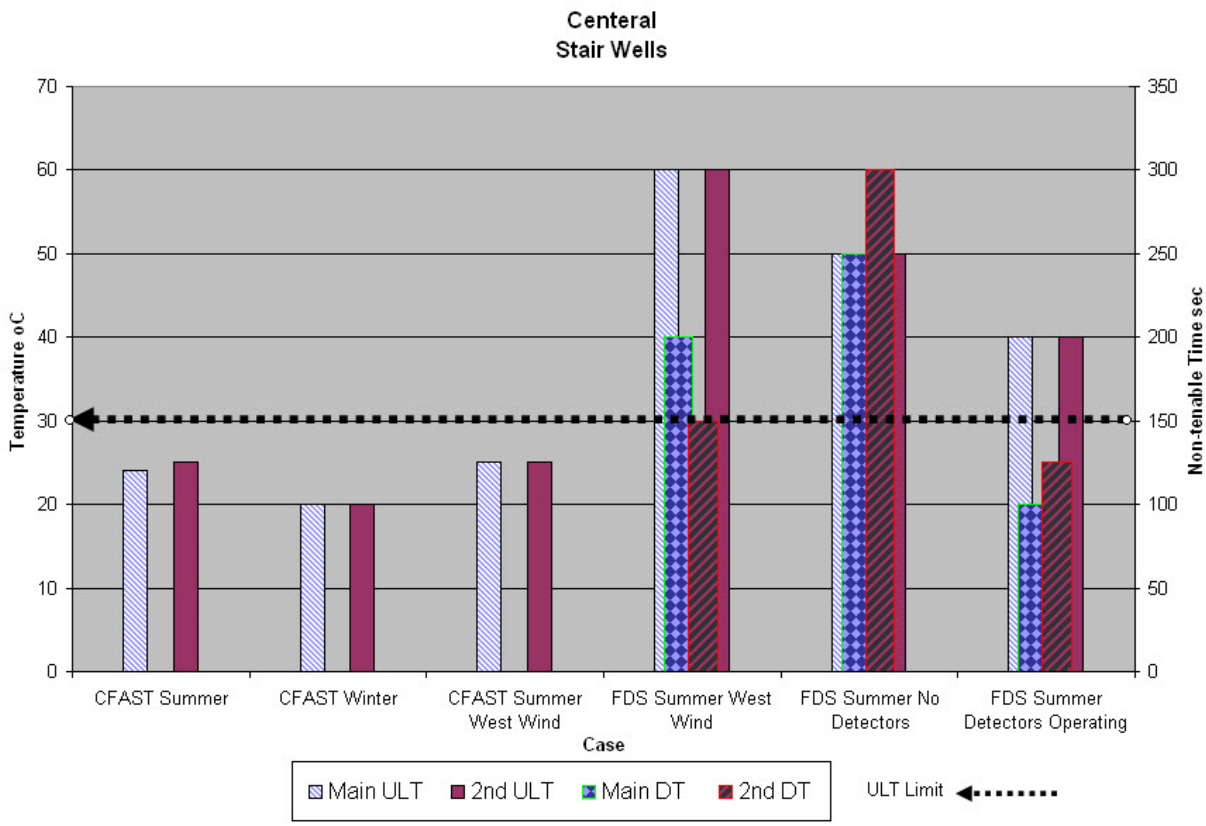

Figure 8: Upper layer temperatures (ULT), and Non-tenable time increment (DT) in stair wells for various CFAST and FDS case runs, Chair fire on Level 1, SE corner.