NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 2

Kellie Ann Beall, Editor

June 1997
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FLAME SUPPRESSION BY HALON ALTERNATIVES

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ABSTRACT

A series of experimental measurements were conducted in a baffle stabilized turbulent jet spray flame and a baffle stabilized pool fire in an effort to provide an improved understanding of the influence of various parameters on the processes controlling flame stability. The importance of a number of parameters including the agent injection duration, air velocity, air temperature, and system pressure were tested. A comparison of flame stability in pool fires and spray flames showed that for similar air flows and baffle sizes, baffle stabilized pool fires were more difficult to extinguish than baffle stabilized spray fires. For small air flows, the agent required to extinguish the pool fires was similar to the peak flammability limits related to premixed flames.

1. Introduction

Ratification of the Montreal Protocol in 1987, has led to limits in the consumption and production of ozone depleting substances. In the Protocol, two common fire extinguishing agents, Halon 1301 (CF_3Br) and Halon 1211 (CF_2ClBr), were identified along with a number of other halogenated compounds, as detrimental to stratospheric ozone. Halons have been commonly used as fire-fighting agents since the 1940s mainly because of their ability to extinguish fires at low concentrations with essentially no residue. As these agents are replaced by possibly less effective alternatives, continued effective fire protection becomes a challenge.

At NIST, a series of studies have been conducted in an effort to identify suitable alternatives agents (Pitts *et al.*, 1990; Grosshandler *et al.*, 1994; Gann, 1995). This multi-year investigation has focussed on a wide range of relevant issues including agent thermodynamic properties, fluid dynamics of agent discharge, stability under storage, metal and elastomer seal compatibility, human exposure and environmental impact, and suppression of fires and quasi-detonations. The NIST effort has been directed mainly towards aircraft fire protection, which has many commonalities with other types of applications in the transportation and communication industries.

A key aspect of fire safety on an aircraft involves protection of the engine nacelle, which encases the jet engine compressor, combustors, and turbine. A nacelle fire is typically a turbulent diffusion flame stabilized behind an obstruction in a moderate speed air flow. The fuel source for a fire in the nacelle can be leaking pipes carrying jet fuel or hydraulic fluid that can feed the fire either as a spray or a pool. Extinguishment occurs when a critical amount of agent is transported to the combustion zone.

In the NIST flame suppression measurements, the effectiveness of candidate replacement agents were tested in a number of combustion configurations including a cup burner, an opposed flow diffusion flame, and two baffle stabilized flame configurations, a spray flame and a pool fire (Grosshandler *et al.*, 1994; Gann, 1995). In addition to agent ranking studies, measurements were conducted in the spray burner to test the impact of operating parameters on agent requirements. These measurements underscored the importance of agent entrainment into the recirculation/combustion zone. The remainder of this paper is a description of some of the suppression measurements conducted on obstacle stabilized flames.

2. Experimental Method and Apparatus

Figure 1 shows a cross-sectional view of the spray burner which has been described previously (Gann, 1995). The apparatus incorporated an air delivery system, a fuel delivery system, an agent injection system, and a combustion zone. Air co-flowed around a fuel tube within a 7.3 cm stainless steel tube. The fuel was injected along the centerline through a pressure-jet nozzle that formed a 45° solid-cone spray. The flame was stabilized by a steel disk (3.5 cm diameter) attached to the body of the nozzle. An attachment to the burner facilitated tests on the influence of super-ambient pressures on flame stability.

The mass of agent delivered to the air stream was determined by measuring the initial temperature and the transient pressure in the vessel and using the Redlich-Kwong equation of state. The vessel pressure data were collected at a rate of 1000 Hz. Uniform dispersion of agent across the air stream was verified by hot film probe measurements. The amount

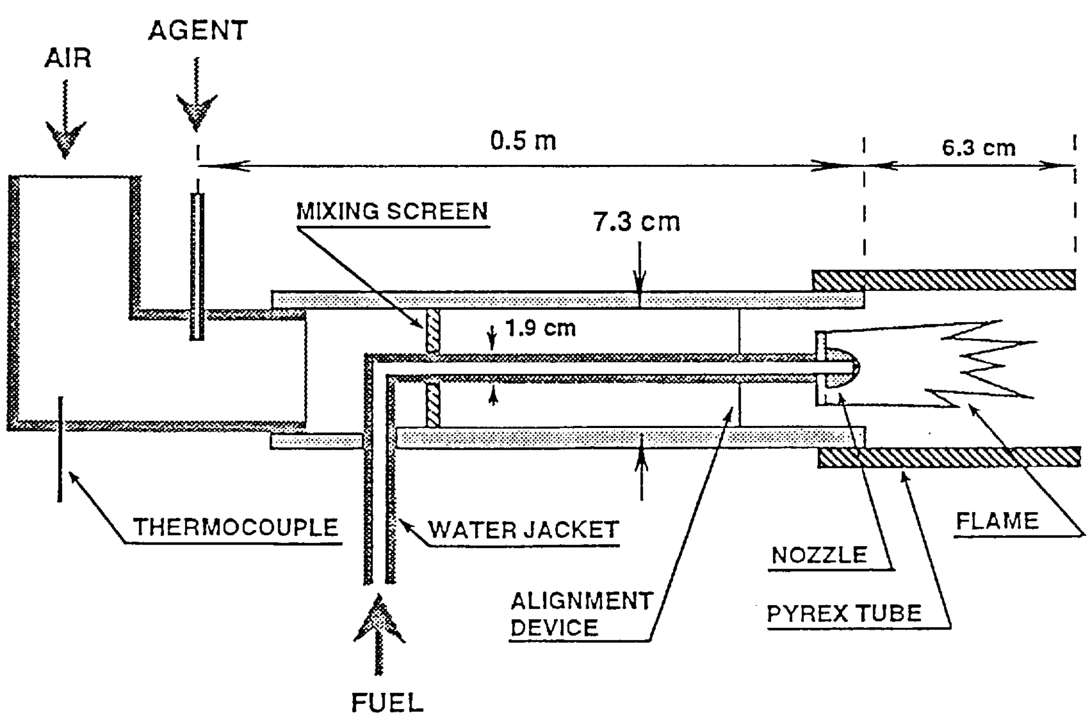

Figure 1. Schematic diagram of the baffle stabilized spray burner used for suppression testing.

of injected agent was controlled by varying the initial vessel pressure, the time the solenoid valve was open and the valve opening diameter. The agent injection system under idealized conditions was designed to deliver a square-wave pulse of agent to the burner for a controlled amount of time.

The independent parameters which were controlled in the spray burner facility were the air flow, the agent delivery interval or injection duration, the air temperature, the system pressure, the fuel flow, and the agent temperature. The primary dependent experimental parameters were the agent mass, and the rate and duration of agent injection required for suppression. Extinction measurements were performed with CF_3I, C_2HF_5 (HFC-125), and C_3HF_7 (HFC-227), which were selected as candidate halon replacements for engine nacelle applications due to a number of positive attributes (Grosshandler *et al.*, 1994). Measurements were also performed using CF_3Br (halon 1301) to establish a performance reference.

3. Experimental Results

3.1 Effect of Agent Injection Interval. Figure 2 shows the critical mass fraction (ß) of CF_3Br and the three alternative agents at extinction as a function of agent delivery interval for a constant air velocity equal to 7.5 m/s. For conditions below the data points in Fig. 2, the flames were not extinguished, whereas for conditions above the data points, the flames were extinguished. As the delivery interval increased, the critical ß decreased, and approached an asymptote for long delivery intervals. CF_3Br required the least mass fraction to extinguish the flames, followed by CF_3I, and the other two agents, C_2HF_5 and C_3HF_7. The shape of the curves for all of the agents in Fig. 2 were nearly identical, but displaced along the y-axis.

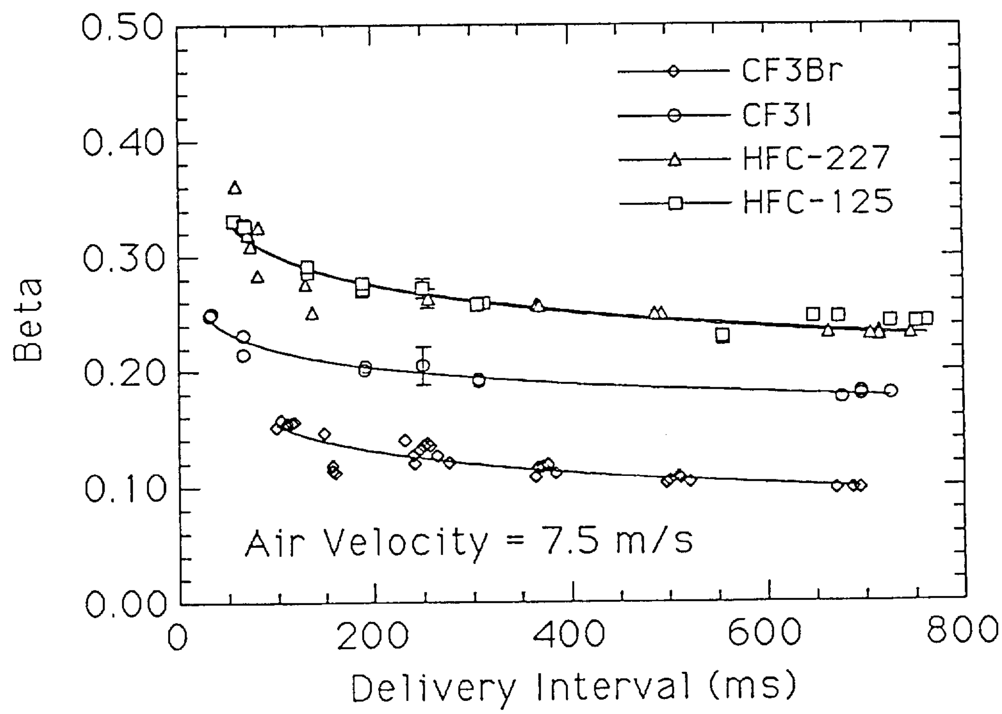

Figure 2. The critical agent mass fraction at extinction as a function of agent delivery interval.

These data can be explained in terms of a phenomenological model first developed by Longwell *et al.* (1953) to explain blow-off of premixed flames by treating the recirculation zone as a well-stirred reactor. The characteristic mixing time of reactants to entrain from the free stream into the recirculation zone is a key parameter in the model. Here, the model is extended to treat agent entrainment into the recirculation zone and subsequent flame extinction. The assumptions used to develop the model are as follows. The flame is stabilized in the recirculation zone behind the obstacle. To extinguish the flame, the agent (volume based) concentration (X) must obtain a critical value. The recirculation zone is homogeneous and mixing of the agent in the zone is instantaneous. Spray characteristics are considered unimportant. As agent entrains into the recirculation zone, the concentration there is given by:

$$X = X_f \left[1-e^{(-\Delta t/\tau)}\right] \quad (1)$$

where X_f is the free stream agent mole concentration, Δt is the agent injection duration, and τ is the characteristic mixing time for entrainment into the recirculation zone. For very long injection times ($\Delta t >> \tau$), the concentration in the recirculation zone will approach the free stream agent concentration, X_f. Experiments reported by Bovina (1958) confirm the form of Eq. 1. The well stirred reactor model requires that for flame extinction, the agent concentration in the recirculation zone must obtain the same critical value, regardless of agent injection duration. Thus, the model suggests that the critical agent concentration in the <u>free stream</u> required to achieve extinction, $X_c(\Delta t)$, for a finite injection interval (Δt) is related to the critical agent concentration in the free stream, $X_\infty(\Delta t >> \tau)$, for long injection intervals ($\Delta t >> \tau$) and an exponential term associated with the extent of mixing:

$$X_c(\Delta t) = \frac{X_\infty(\Delta t \gg \tau)}{1-e^{(-\Delta t/\tau)}} \quad (2)$$

For long injection durations, the denominator in Eq. 2 takes a value of ≈ 1.0 and X_c is equal to X_∞. For short injection intervals, very high agent concentrations are required to obtain extinction.

In addition, X_c is constrained such that $X_c \leq 1$. This implies that there exists a critical injection duration (Δt_c) such that when $X_c = 1$, Δt_c is given by:

$$\Delta t_c = -\tau \ln(1-X_\infty) \quad (3)$$

For τ equal to 100 ms, representative of conditions in the spray burner for an air velocity of 3 m/s, and X_∞ equal to 0.1, Eq. 3 yields a value of $\Delta t_c \approx 11$ ms. Unfortunately, the minimum solenoid opening time was much larger than this value, so the veracity of Eq. 3 was not tested.

Bovina (1958) found that τ in Eq. 2 is related to the baffle diameter (d) and the upstream velocity (V):

$$\tau \approx \frac{d}{V} \quad (4)$$

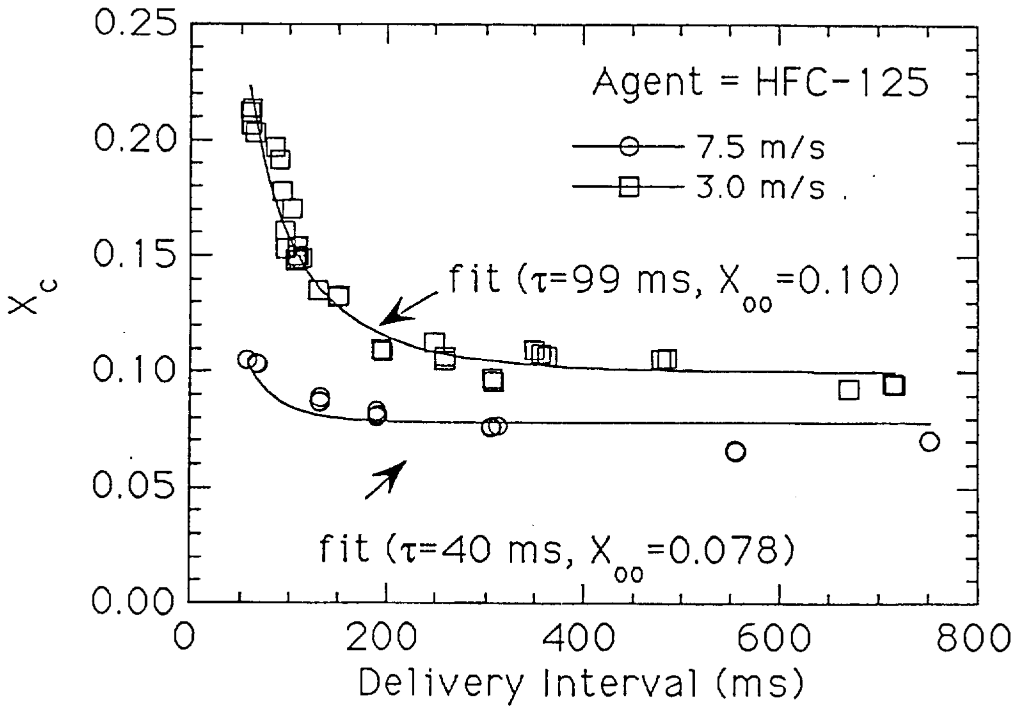

Figure 3. The critical mole fraction of HFC-125 at extinction for air velocities of 3.0 and 7.5 m/s.

Winterfeld (1965) verified Eq. 4 for both combusting and non-combusting conditions for Reynolds numbers extending from $\approx 1.5 \cdot 10^4$ to $2.2 \cdot 10^5$. Winterfeld (1965) also found that the time constant was a function of the blockage ratio and the geometry of the flame holder.

A two parameter fit to the extinction data shown in Fig. 2 (after conversion to mole from mass fraction) allows determination of the parameters X_∞ and τ in Eq. 2. The critical mole fraction of HFC-125 at extinction for air velocities of 3.0 and 7.5 m/s is shown in Fig. 3 using a portion of the data presented in Fig. 2. Interpreting the curves in terms of Eq. 2 shows that a best two parameter fit for the V= 3.0 m/s data yields τ= 99 ms and X_∞= 0.10. Because Eq. 4 suggests that $\tau \propto (1/V)$, the 7.5 m/s data should be well represented by τ=40 ms (=99 ms/2.5). A plot using 40 ms for τ leads to a reasonable fit of the V=7.5 m/s data shown in Fig. 5. The fit yields a value of 0.078 for X_∞. The value of X_∞ itself is a strong function of the air velocity and is thus a function of $(1/\tau)$ as described below.

3.2 Effect of Air Velocity. Figure 4 shows the critical mass fraction (ß) of CF_3Br and the three alternative agents at extinction as a function of air velocity for a constant injection duration equal to 700 ms. This value of the injection duration was selected because $X_c \approx X_\infty$. CF_3Br required the smallest mass fraction to extinguish the flames, followed by CF_3I, and the other two agents, HFC-125 and HFC-227, which were measured to have nearly identical effectiveness. As the air velocity increased from 3 m/s, ß decreased. At high air velocities, the flames were less stable and easier to extinguish, i.e. less

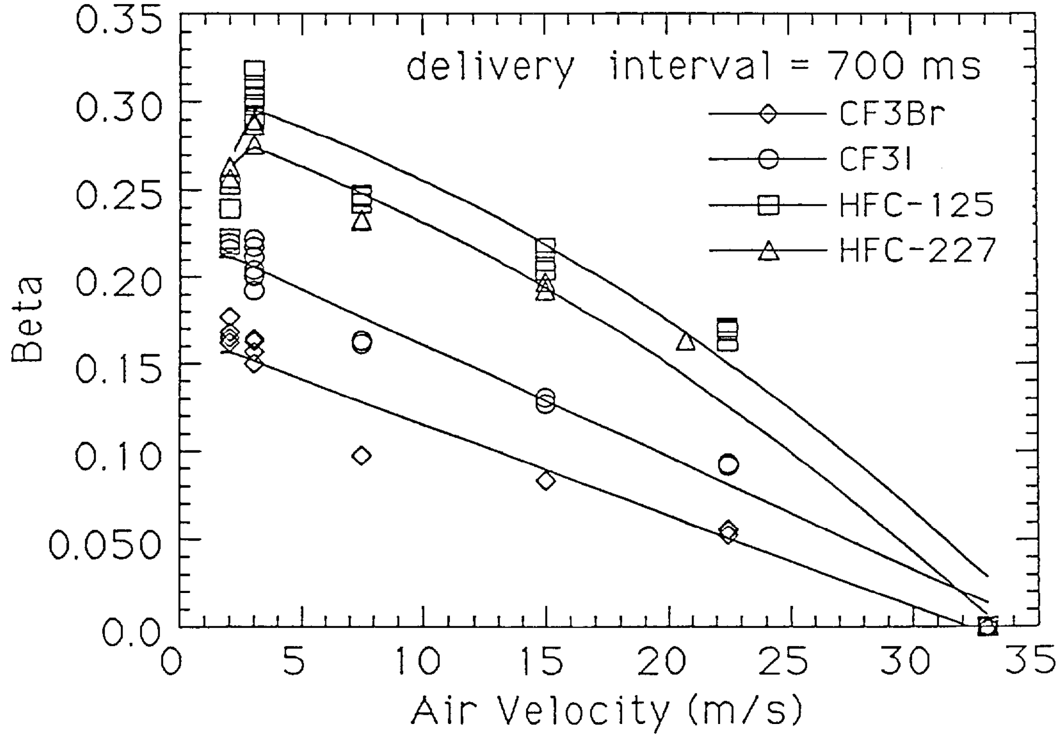

Figure 4. The critical agent mass fraction at extinction as a function of air velocity.

agent was required to extinguish them. At V= 33 m/s, air with no agent addition caused flame extinction. For very low air velocities (2 m/s), ß decreased or remained nearly the same as the results for V= 3 m/s. For all agents, the values of ß for the low air velocity spray flame results are very similar to agent extinction concentrations measured in cup burner flames and in opposed flow diffusion flames (OFDF) at low (25 s^{-1}) strain rates (Hamins *et al.*, 1994). Table 1 documents the correspondence between the flame extinction measurements in the three burners. All tests were conducted with JP-8 fuel. Table 1 shows that a correspondence also exists between the critical agent mass fractions for moderate (80 s^{-1}) strain rates in the OFDF burner (Hamins *et al.*, 1994) and moderate air velocities (15 m/s) in the spray burner. The same correspondence holds for high (22.5 m/s) air velocities in the spray burner and high (175 s^{-1}) strain rates in the OFDF burner. The practical implication of the results shown in Table 1 is that it is not necessary to rank the suppression effectiveness of agents in every possible configuration, a single test apparatus is sufficient. The correspondence between extinction concentrations in the spray burner, cup burner, and OFDF implies that a relationship exists in terms of the critical Damköhler number criterion for flame extinction.

3.3 Effect of Fuel Flow, Pressure, and Air Temperature. Other experiments showed that more agent mass was required to extinguish flames when the air was heated. This trend was anticipated, since heating the air adds enthalpy to a flame, and a flame with a higher enthalpy is expected to be more stable.

However, increasing the air temperature altered the agent ranking. For temperatures below 150 °C, CF_3I was the most effective agent. For temperatures above 150 °C, the three agents, CF_3I, HFC-125 and HFC-227 were approximately equally effective.

Experiments using a butterfly valve placed on the downstream end of the burner showed that the system pressure did not impact the agent concentration required to obtain extinction over the pressure range tested (101-135 kPa). Other suppression measurements showed that the fuel flow had little effect on the agent concentration required to achieve flame extinction.

Of the three candidate replacement agents evaluated in the turbulent spray burner, CF_3I was consistently the most effective compound. CF_3I required the least amount of gaseous agent to extinguish the flames on both a mass and volume basis. The other two alternative agents tested, HFC-125 and HFC-227, were measured to have nearly identical suppression effectiveness, and were significantly less efficient than CF_3I in extinguishing the flames. On a mass basis, none of the agents performed as well as halon 1301.

Table 1 Agent mass fraction at extinction with JP-8 fuel

Agent	Cup Burner	Air Velocity (m/s) in Spray Burner			Strain Rate (s^{-1}) in OFDF burner		
		3.0	15	22	25	80	175
CF_3Br	0.14	0.16	0.085	0.05	0.13	0.080	0.050
CF_3I	0.18[b]	0.21	0.13	0.09	a	a	a
HFC-125	0.28	0.30	0.21	0.17	0.28	0.22	0.16
HFC-227	0.27	0.28	0.20	0.15	0.26	0.20	0.14

a Not measured

b Measured with heptane as fuel. The agent concentration required to extinguish heptane and JP-8 cup burner flames are within 4% (Grosshandler *et al.*, 1994).

3.4 Suppression of Baffle Stabilized Pool Fires. Measurements on the suppression of baffle stabilized pool fires were conducted at Walter Kidde Aerospace under NIST direction. A detailed description of the experimental apparatus can be found in Gann (1995). The test results showed that the mixing time (τ) was relatively large in baffle stabilized pool fires as compared to the baffle stabilized spray fires. The characteristic mixing times from the data fits were 0.5 s for HFC-125 (with the air velocity approximately equal to 3 m/s) and 0.7 s for HFC-227 (with the air velocity approximately equal to 1.5 m/s). The minimum critical agent concentration required to achieve flame extinction was significantly larger than the concentration required to suppress cup burner flames under similar conditions, consistent with the results of Hirst *et al.*

(1976) and Dyer *et al.* (1977). The minimum critical agent concentrations approximately corresponded to the amount of agent required to suppress hydrocarbon flames at their peak flammability limits.

4. Conclusions

A comparison of flame stability in pool fires and spray flames showed that for similar air flows and baffle sizes, baffle stabilized pool fires were more difficult to extinguish than the baffle stabilized spray fires. Larger agent concentrations and longer characteristic agent mixing times were required to achieve suppression in the pool fires due to the structure of the recirculation zone.

Two dimensional isothermal fluid flow calculations showed that the characteristic time for an agent to entrain into a recirculation zone behind a bluff body depends on the location of the baffle in relation to the wall. The characteristic entrainment time is significantly larger for a baffle abutting a wall as compared to a baffle in the center of the flow field. The experimental findings were therefore consistent with the flow calculations.

5. Acknowledgements

This study was funded by the U.S. Army, Navy, Air Force and FAA. The author is grateful to T. Cleary and K. McGrattan for performing the pool fire experiments and flow field calculations, respectively, and C. Presser and L. Melton for assisting with the spray burner suppression measurements.

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Discussion

Naoshi Saito: In your paper, you said in order to compare the individual suppressant performance, you can just use one formula. I wonder if this is true. It reminds us of the time when we determined the size of the cup burner, but depending on the fuel, we could not get consistent results.

Anthony Hamins: What we showed is the most dangerous situation. In order to extinguish such a configuration, one must consider final events.