New Directions in Fire Research in the US

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Capability vs. Needs

- **Capability: Rothermel (1972) – surface fire model**
  – Basis of dozens of fire behavior systems

- **Needs: crown fires (& shrub & grass)**
  – Live canopies
  – “Discontinuous”
  – Spread thresholds
  – Require wind/slope etc. to burn

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Assumptions in Rothermel 1972

- Continuous fuels
- Steady state spread, flames steady
- 'shallow' fuel beds (<30 cm)
- Depends on presence of dead fuel
- Extinction by assigning maximum moisture content
- Fuel beds must burn w/o wind-slope (w/s effect multiplied)

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Realizations

- Can't simply extend semi-empirical Rothermel model – no theory, no data
- Considerable research assuming radiation dominated spread, surface and crown fire
- Must completely rethink the approach to fire spread

Observations of Fire Spread

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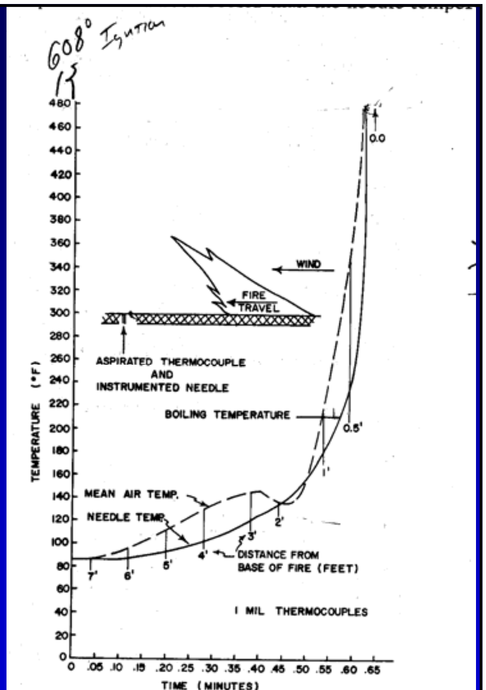
- Particles < pilot ignition temperature (~320 C, 608F) when flame gets there – must have flame contact (visible flames)
- Heating rate same for all fires (Latham)
- Radiation shield experiments



Rothermel and Anderson (1966)

Radiant Heating Experiment (Latham)

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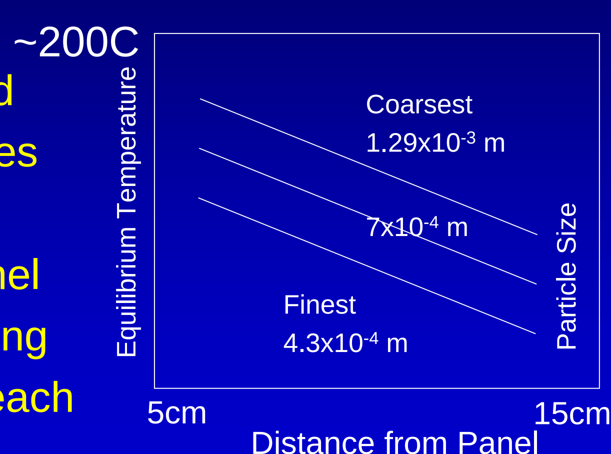
- Instrumented fuel particles
- Exposure to 1000C panel
  - Free cooling
  - Rapidly reach T_{eq}



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Examination of Assumptions

Our observations (and the literature) suggest that convection (flame contact), particularly from non-steady flame flow, significantly contributes heat for fire spread.

Steady Flame

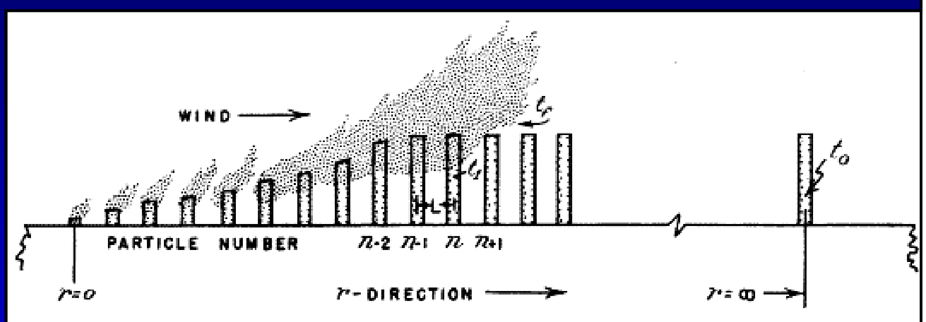
Non-steady Flame (common condition)

Figure 6.--Flame size in ponderosa pine needles at 704 ft./min. airspeed.

Research Target

- Fuel Discontinuous – gaps of similar order in size as fuel "clumps"
- Fuel Deep – vertical dimension not negligible
- Fuel Vertically arranged -no surface fuel
- Thresholds spread -- Depends on wind, slope, moisture, & fuel geometry for any spread at all

Small Scale Experiments



Fons, W. L. 1946. Analysis of Fire Spread in Light Forest Fuels. Journal of Agricultural Research 72:95.

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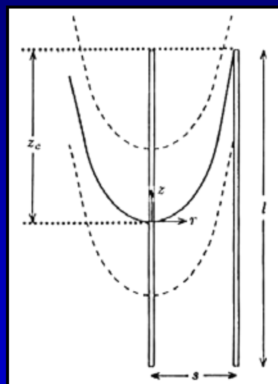
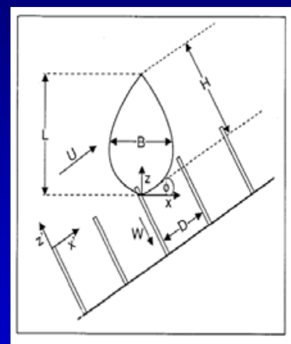
Small-Scale Models

Laminar flame structure



Weber, R. O. 1990. A Model for Fire Propagation in Arrays. Mathmatical Computation Modelling 13:95-102.



Beer, T. 1995. fire Propagation in Vertical Stick Arrays: The Effects of Wind. International Journal of Wildland Fire 5:44.

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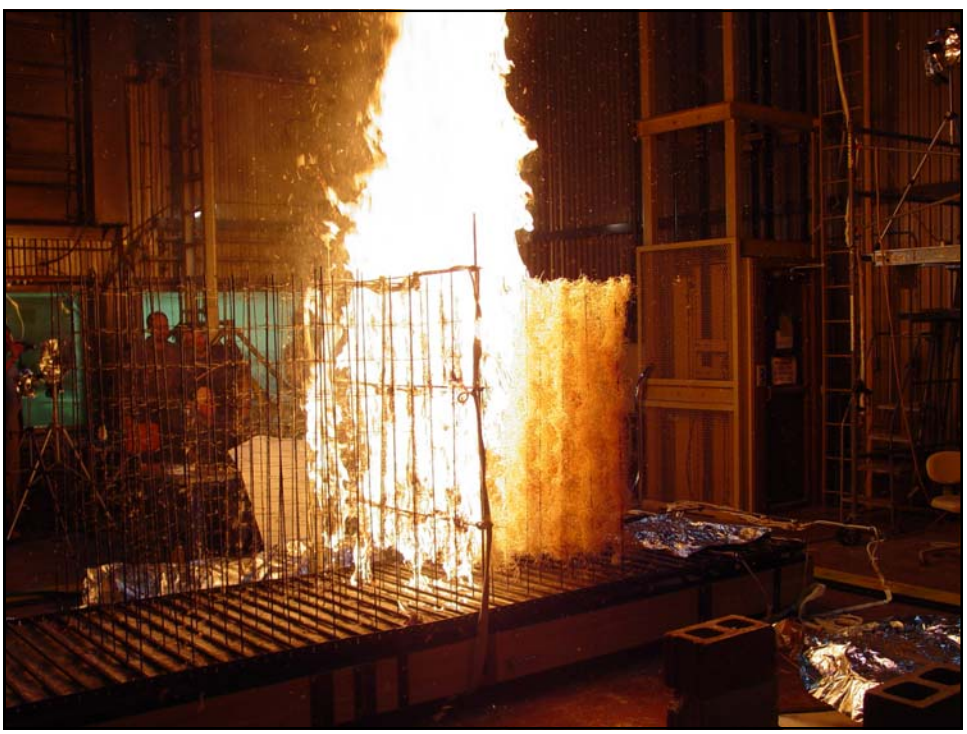
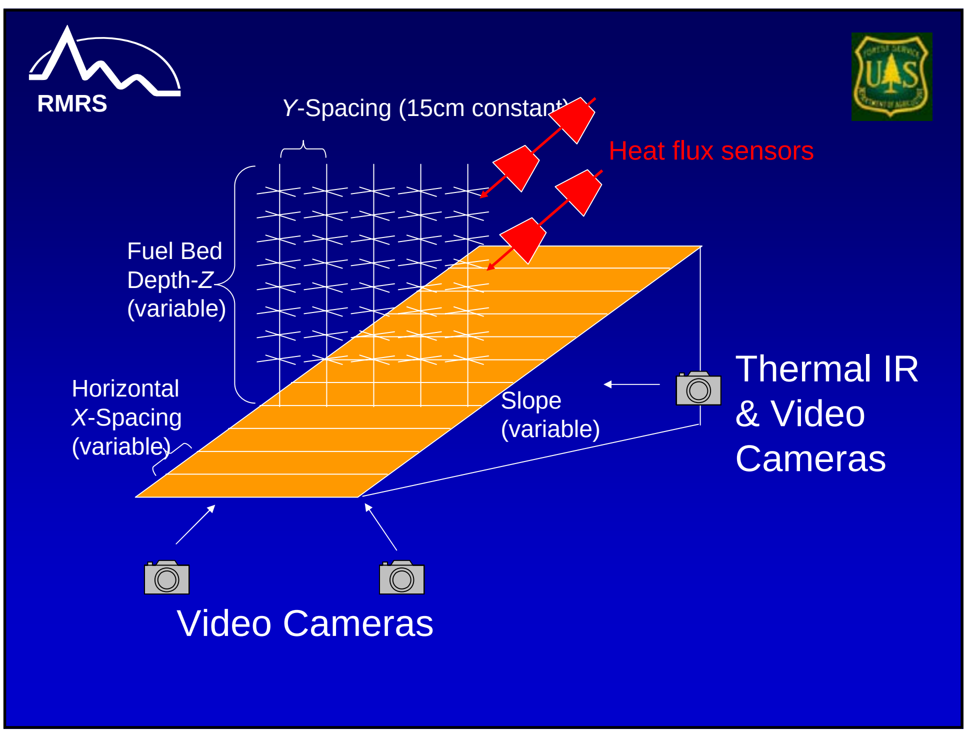
Laboratory Setup

- Rows of "deep" fuels
- Variables:
  - Slope (0-39 degrees)
  - Depth (30, 60, 120 cm)
  - Spacing (10-50 cm)
- Constants
  - Fuel moisture (~15%)
  - Lineal fuel loading (97g/meter)
  - Platform (1.2m x 4.8m)
- 112 experiments – ID threshold recording spread vs. no spread

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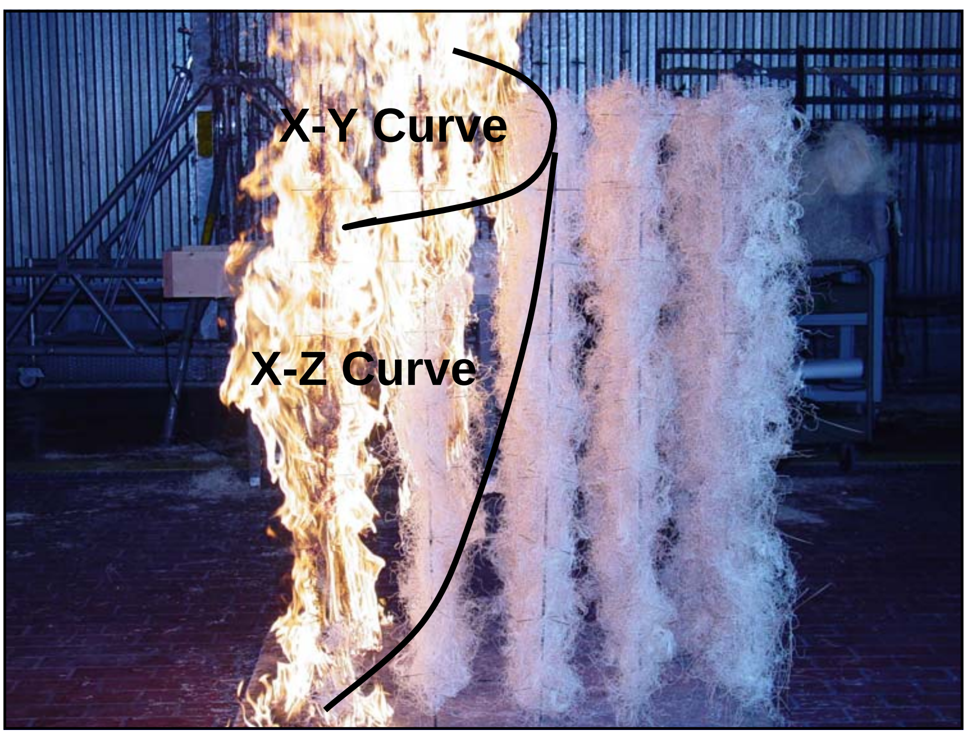
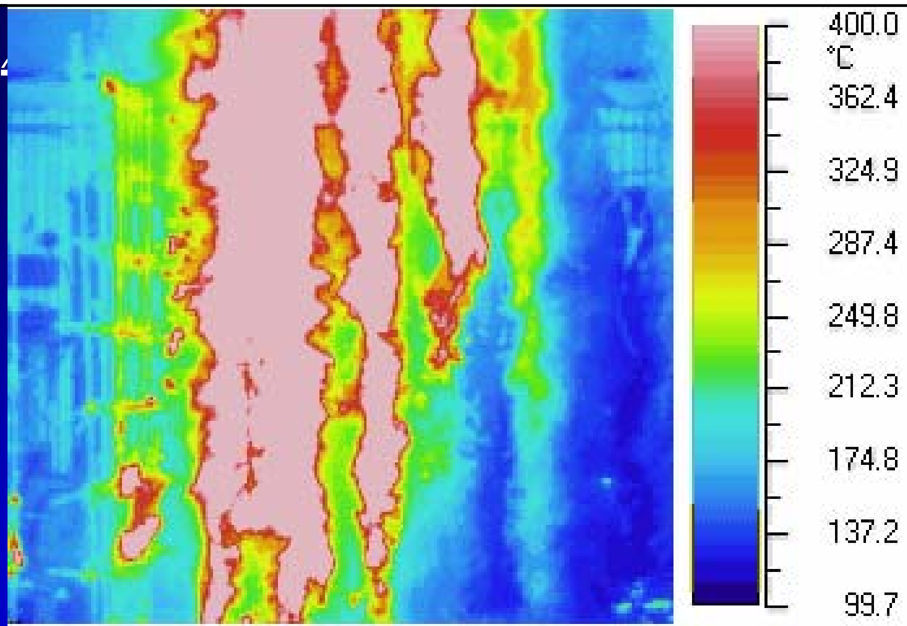
Y-Spacing (15cm constant)
Heat flux sensors
Fuel Bed
Depth-Z
(variable)
Horizontal
X-Spacing
(variable)
Slope
(variable)
Thermal IR
& Video
Cameras
Video Cameras


Fuel row ignited by flame contact near the top of the fuel bed
Inclined Combustion Interface


X-Y Curve
X-Z Curve



8-Seconds, 1/120th sec, Thermal Infrared

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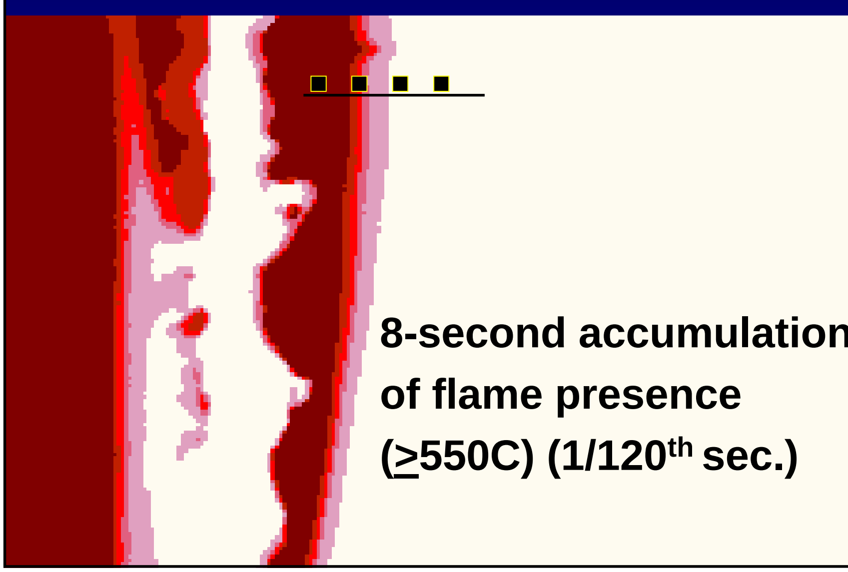
Intermittent Flames



8-second accumulation of flame presence ($\geq$550C) (1/120th sec.)

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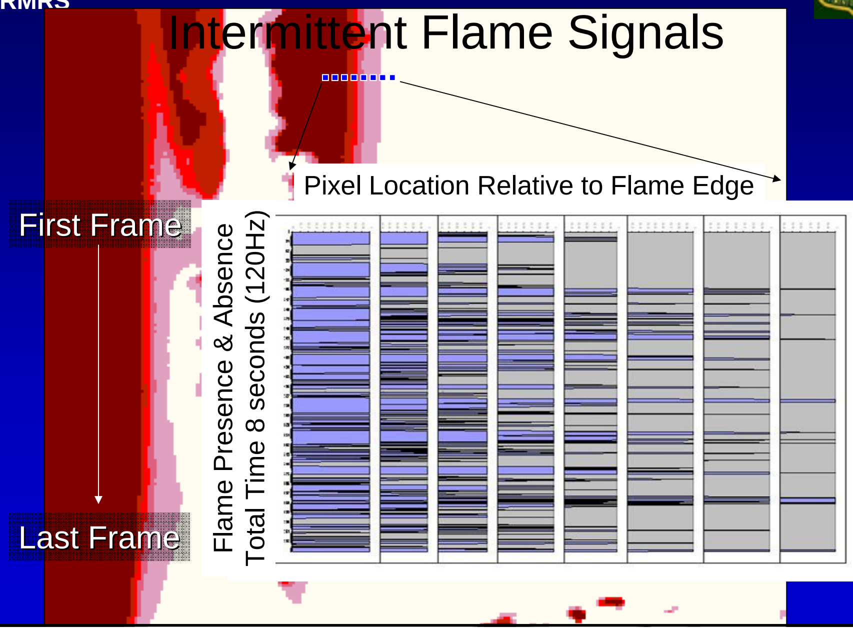
Intermittent Flame Signals



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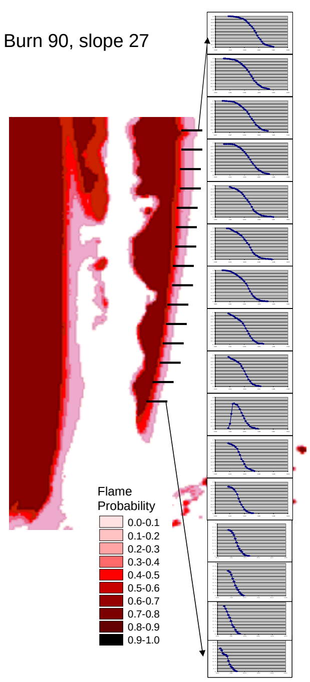
Time-averaged distribution of visible flame (>550 C)

- Gaussian Probability Distribution
- Increasing Variance with height

Burn 90, slope 27



Height	Mean X-pos	Variance
0.95	119	44
0.91	117	37
0.87	117	38
0.83	117	37
0.78	118	29
0.74	117	31
0.70	116	27
0.66	116	24
0.61	115	20
0.57	116	13
0.53	114	14
0.49	113	11
0.44	112	9
0.40	111	6
0.36	108	7
0.32	105	8

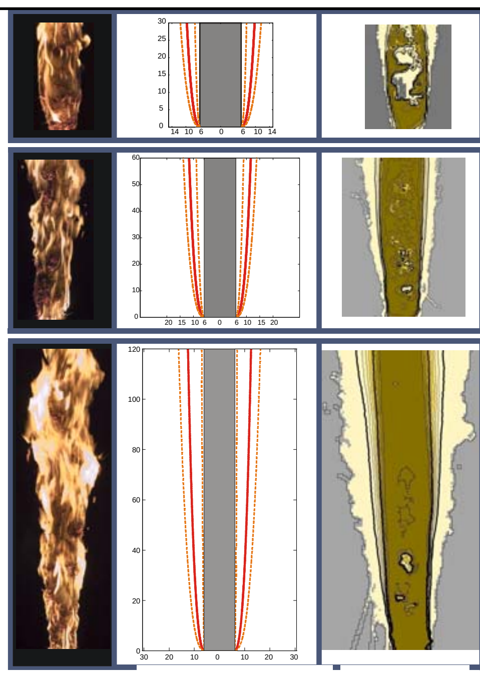
Results: Flame Geometry & Statistics

- **Fuel row ignited by flame contact near the top of the fuel bed**
- **Burned from the top-down, curved profile**
  - **XY, XZ**
- **Flame edge not stationary**
  - Gaussian distribution
  - Higher variance with height
  - Fuel particles experience intermittent flame bathing prior to ignition

I (30cm)

II (60cm)

III (120cm)



Laminar model | probability

Mass loss

I: 5.92 g m^{-1} s^{-1}

II: 7.03 g m^{-1} s^{-1}

III: 6.07 g m^{-1} s^{-1}

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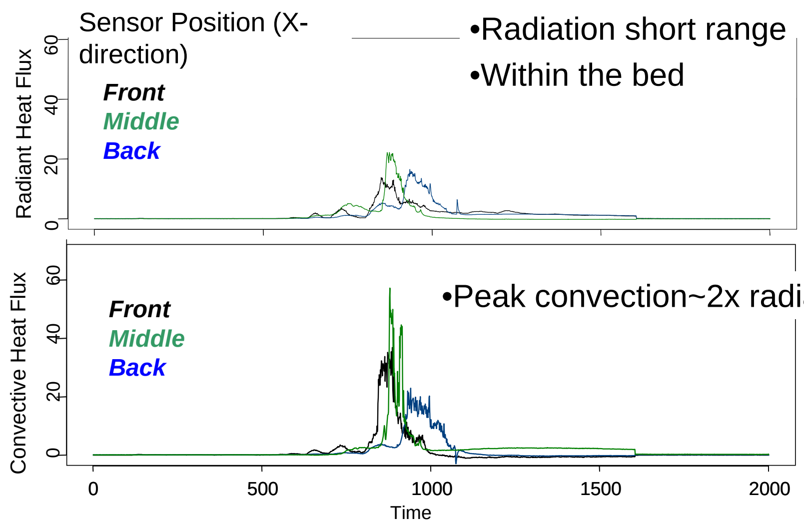
Radiation and Convection



- •Radiation short range
- •Within the bed
- •Peak convection~2x radiation

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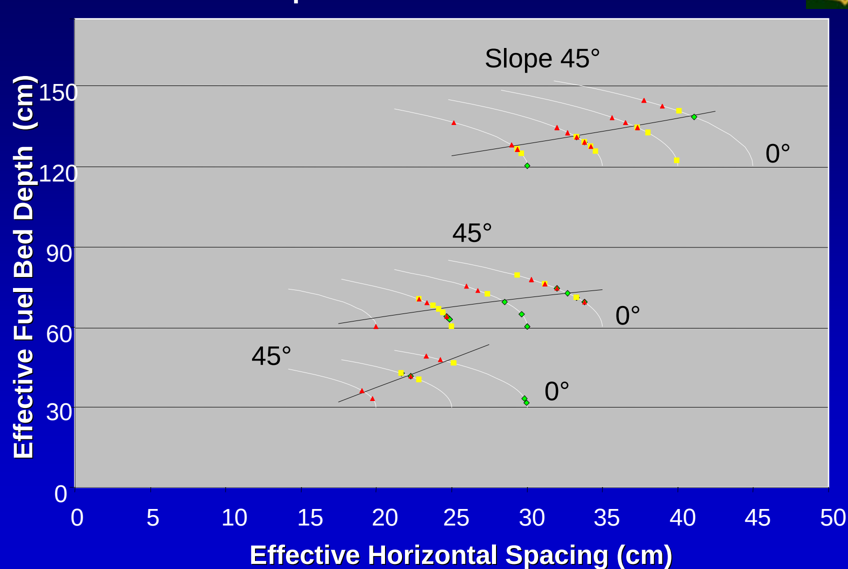
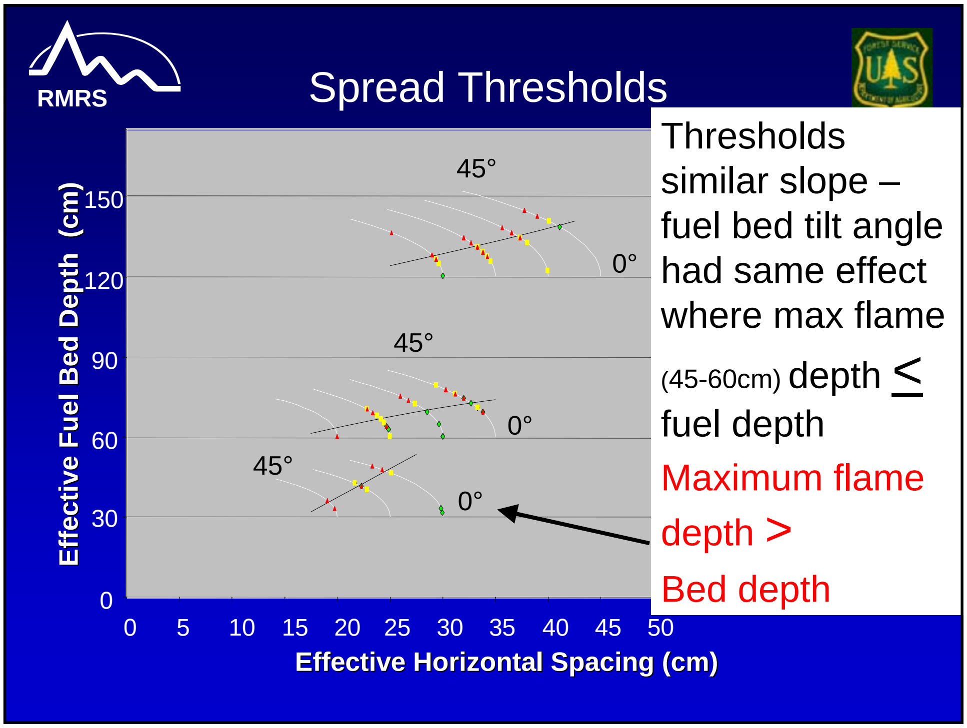
Spread Thresholds

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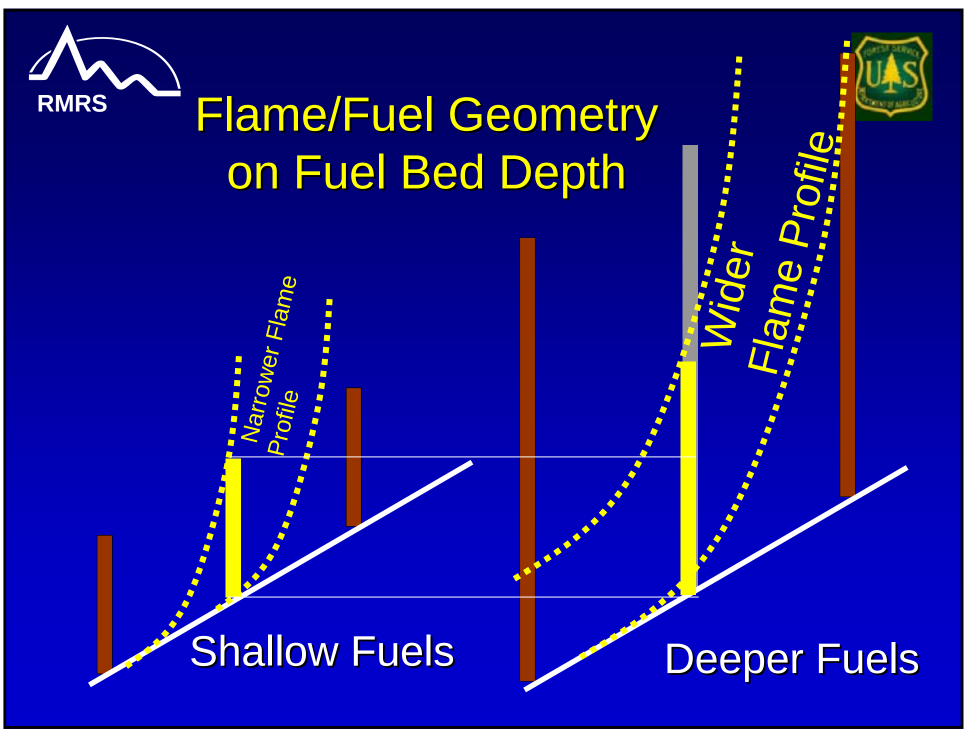
Spread Thresholds
Thresholds similar slope – fuel bed tilt angle had same effect where max flame (45-60cm) depth ≤ fuel depth
Maximum flame depth > Bed depth
45°
0°
45°
0°
45°
0°
Effective Fuel Bed Depth (cm)
0
30
60
90
120
150
0
5
10
15
20
25
30
35
40
45
50
Effective Horizontal Spacing (cm)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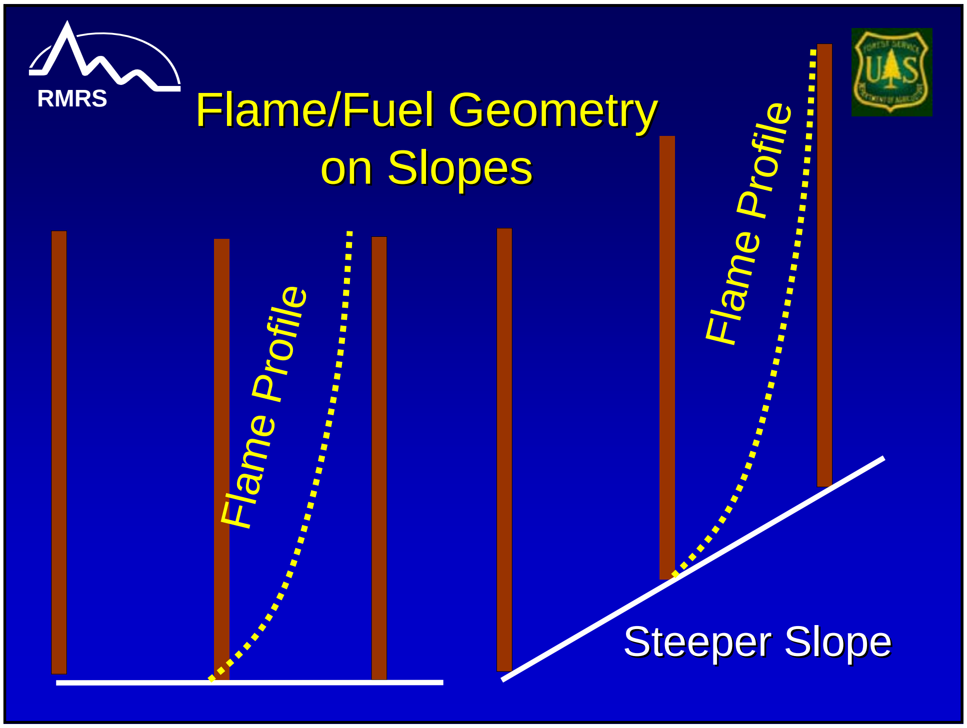
Flame/Fuel Geometry on Fuel Bed Depth
Narrower Flame Profile
Wider Flame Profile
Shallow Fuels
Deeper Fuels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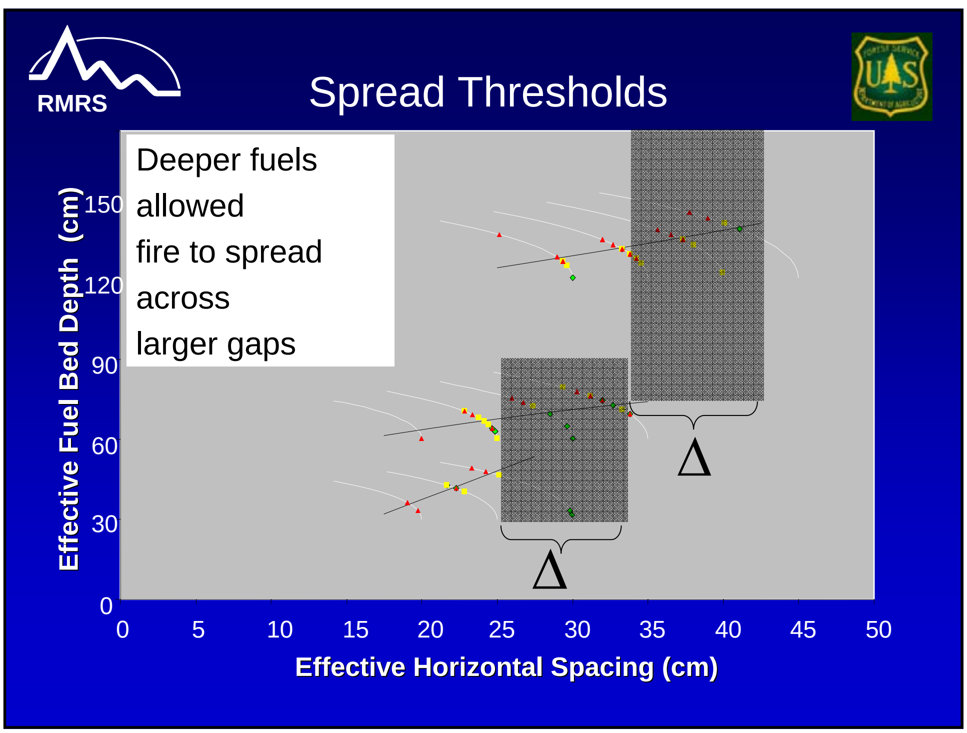
Flame/Fuel Geometry on Slopes
Flame Profile
Flame Profile
Steeper Slope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Spread Thresholds
Deeper fuels allowed fire to spread across larger gaps
Effective Fuel Bed Depth (cm)
0
30
60
90
120
150
0
5
10
15
20
25
30
35
40
45
50
Effective Horizontal Spacing (cm)
Δ
Δ

Conclusions

- **Strong role of flame/fuel geometry inside fuel bed (just like toothpicks & matches – *but not laminar flame edge*)**
- **Bulk fuel properties alone not meaningful to spread/no-spread (*i.e*. bulk density, cover)**
  - **Gap sizes critical to spread & variability**
  - **What's <u>not</u> there is as important as what is there**
- **Fuel bed depth is a critical independent factor (beyond effects on packing)**

Implications for Modeling

Ignition and fire spread stochastic—
the function of a conditional probability:

- The probability of the fuel characteristics—presence and attributes,
- The probability of the flame attributes particularly flame contact (determined by "internal" factors and external factors like wind variability).
- Fire is a sampling process—it samples for the ignition requirements.

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Wind Tunnel Burn