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Simulating Initial Attack With Two Fire Containment Models

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Given a variable rate of fireline construction and an elliptical fire growth model, two methods for estimating the required number of resources, time to containment, and the resulting fire area were compared. Five examples illustrate some of the computational differences between the simple and the complex methods. The equations for the two methods can be used and programmed to estimate fire size and perimeter, time-to-containment, and the number of resources required as a function of spread rate.

Retrieval Terms: fire control, fire suppression, planning, fire containment, dispatching

An ellipse of a specified length-to-width ratio can be used to estimate fire size and shape for suppression modeling purposes and also for field use.[1,2] A 4-to-1 length-to-width ratio was suggested for grass fires[3] and a 2-to-1 ratio for a forest fire burning under a canopy.[4] Mathematical and geometric models[5,6] have been developed to examine the sensitivity of final fire size and time-to-containment to suppression force allocations. The models have been extended to the elliptical model with a constant rate of fireline construction.[7] Given a variable rate of fireline construction and an elliptical fire growth model, either of two models—simple or complex—can be used to estimate the required number of resources, the time-to-containment, and the resulting fire area.

In the complex model, the area and perimeter of the expanding ellipse are computed at multiples of some time increment (specified by the user) and partial containment at time t_i contributes to the possible complete containment at time t_{i+1}. A typical fire at times t_i, t_{i+1}, t_{i+2}, t_{i+3} will look like an ellipse that continually changes *(fig. 1A)*. The complex containment model takes full advantage of the smaller size of the ellipse at time t_i compared with the sizes at later times. Two computer simulation models—FOCUS and FEES—use this method in their initial attack evaluations. FOCUS (Fire Operational Characteristics Using Simulation) evaluates alternative fire suppression programs at the Forest or District level,[8] and FEES (Fire Economics Evaluation System) is being developed to evaluate fire program options for nonsite specific areas.[9]

A simpler technique determines the containment time t_c such that the total length of line produced at time t_c equals or exceeds the fire perimeter at time t_c. The line built up to time t_c is compared with the perimeter of the ellipse at time t_c and line built around the smaller perimeter at earlier time points is not considered *(fig. 1B)*. This model will be referred to as the simple containment model.

This note describes the formulation and development of the procedures used in both the simple and complex containment models using an ellipse of a given length-to-width ratio. Five tables illustrate the difference between the two models in terms of resulting fire areas,

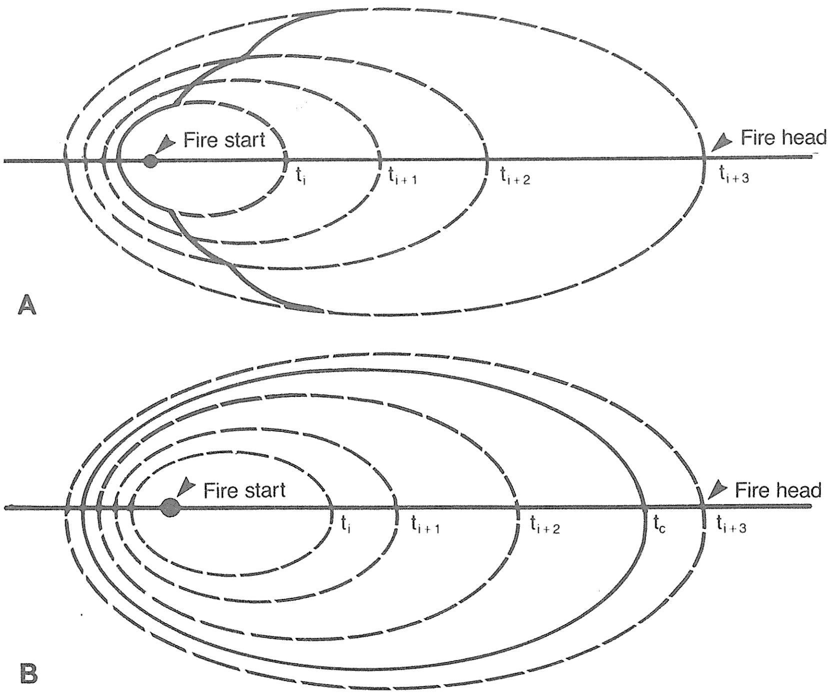

Figure 1—(A) In the complex containment model, fireline construction starts at time t_i and continues along the perimeter of the ellipse evaluated at times t_{i+1}, t_{i+2}, and t_{i+3} specified by the user. (B) In the simple containment model, times t_i, t_{i+1}, t_{i+2}, t_{i+3} represent arrival times of resources, and t_c represents time to control. At that time, fireline computed equals or exceeds the fire perimeter.

number of resources used, and time required to contain each fire. Given resource arrivals, assumed production rates, and a range of spread rates, outputs of both computer simulation models indicate that variations in the time-to-containment and the number of resources used may lead to substantial differences in suppression cost estimates.

ASSUMPTIONS

Some simplifying assumptions were made to calculate the number of required resources, area, and time-to-containment for each fire, given a forward spread rate. Unless otherwise indicated, all assumptions apply to both containment models:

1. The shape of a free-burning fire is an ellipse with constant length-to-width ratio. The point of origin is defined as one of the focal points. Initial area at the time each fire is reported is one-tenth of an acre (0.04 ha).
2. The forward rate-of-spread (at the head of the fire) is constant during the time required for containment or when the fire exceeds 100 acres.
3. The rate of fireline construction is resource-specific and is constant for each resource during the time required for containment or when the fire exceeds 100 acres.
4. Airtankers are not used because of the resulting complexity in fire shape and the difficulty of interpreting their effectiveness.
5. In the complex containment model, fireline construction proceeds on both sides of the ellipse and may be applied at unequal rates. For example, a five-person handcrew may be split into a two-person and a three-person crew working on opposite flanks of the ellipse. The complex model can use head-attack computations if the forward spread rate is small enough relative to the line construction rate from the available resources.[8] Head attack begins at the head of the fire and the resources may be applied at unequal rates on both sides of the ellipse.
6. All suppression work is assumed to be 100 percent effective, and a fire does not spread beyond its contained perimeter.
7. A list of resources is available for each fire, and each resource must be described in terms of its type (handcrew, engine, bulldozer, helitack, smokejumpers, tractor-plow), arrival time (measured from the reported time of the fire), and production rate (chains per hour).
8. Resource units are used as they arrive on the fire and their total line production is computed as the product of total time on the fire by their production rate.

MATHEMATICAL DEVELOPMENT

Complex Containment Model

The complex containment model assumes an elliptical fire such that the spread rate V from any point on the perimeter at polar angle ϕ, measured from the direction of most rapid spread $V_h(t)$, is given by *(fig. 2)*

$$V(\phi, t) = V_h(t) * (1 - \epsilon) / [1 - \epsilon * \cos(\phi)] \quad (1)$$

in which ϵ is the eccentricity of the fire ellipse

$$\epsilon = \sqrt{1 - (\text{width}/\text{length})^2}.$$

Equation 1 can be integrated with respect to time along constant ϕ to give perimeter distance R from the origin of the fire at time t:

$$R(\phi, t) = [(1 - \epsilon) / (1 - \epsilon * \cos(\phi)] * h(t)$$

in which h(t) is the distance of the fire head from the origin, given by

$$h(t) = \int_0^t V_h(t)\,dt \quad (2)$$

A fire perimeter location y can be expressed in rectangular coordinates [x(t), y(x(t), t)] in which

$$y[x(t), t] = \pm A * \sqrt{h^2(t) - z^2(x, t)} \quad (3)$$

and

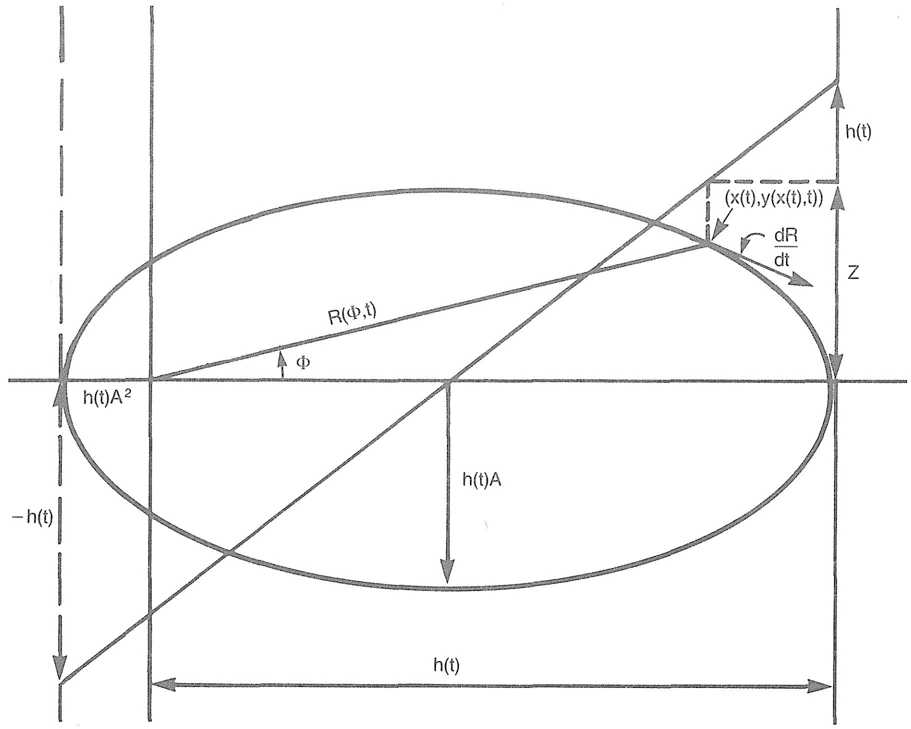

Figure 2—In the complex model, line construction is calculated separately for lower and upper halves of the ellipse and can proceed toward the rear or head of the fire.

$$A = \sqrt{(1 - \epsilon) / (1 + \epsilon)}$$

and

$$z[x(t), t] = (1 + \epsilon) * x(t) - \epsilon * h(t)$$

is an auxiliary variable.

Starting at time t_0 and a perimeter point $\{x(t_o), y[x(t_o)]\}$, control line construction can proceed toward the rear or the head of the fire. Let the ratio of line construction rate $V_L(t)$ to the forward spread rate of the head $V_h(t)$ be P at the time the fire is at h(t). The position vector $R(\phi, t)$ and its derivative with respect to time are *(fig. 2)*

$$R = x(t) * i + y[x(t), t] * j$$

$$\frac{dR}{dt} = \dot{x}(t) * i + [y_x * \dot{x}(t) + \dot{y}] * j$$

in which a dot indicates the partial derivative with respect to time and y_x is the partial derivative of y with respect to x.

Setting the line construction rate $V_L(t)$ at time t equal to $\frac{dR}{dt}$ gives

$$\dot{x}^2 + (y_x * \dot{x} + \dot{y})^2 = V_L^2(t)$$

Solving for $\dot{x}$

$$\dot{x} = \frac{dx}{dt} = \frac{-y_x\dot{y} \pm \sqrt{V_L^2(t) * (1 + y_x)^2 - \dot{y}^2}}{1 + y_x{}^2}$$

or

$$\frac{dx}{dt} = \frac{-y_x\dot{y} \pm \sqrt{V_L^2(t) * (1 + y_x)^2 - \dot{y}^2}}{(1 + y_x{}^2) * h^2(t)}$$

$$= \frac{-y_x y_h \pm \sqrt{P^2 * (1 + y_x)^2 - y_h{}^2}}{1 + y_x{}^2}$$

in which $P = V_L(t) / V_h(t)$.

The derivatives of y with respect to x and h written in terms of A, h, and z, lead to

$$\frac{dx}{dh} = \frac{(1 - \epsilon) * z \pm \sqrt{(P^2 * \frac{h(t) - \epsilon z}{h(t) + \epsilon z} - A^2)}}{h(t) - \epsilon z}$$

$$* \sqrt{h^2(t) - z^2} \qquad (4)$$

in which

$$P^2 \geq A^2 * \frac{h(t) + \epsilon z}{h(t) - \epsilon z}$$

The forward rate-of-spread $V_h(t)$ is assumed to be constant and is matched against a variable line construction rate $V_L(t)$. Equation 4 can be integrated numerically to calculate construction progress as a function of h. The sign in equation 4 is positive if progress is toward the head of the ellipse; the sign is negative otherwise.[10]

Equations 2 and 3 are used to compute the (x, y) position of progress and are calculated independently for the lower and upper halves of the ellipse as a function of the variable construction rates for each half. Head or rear attack is chosen on the basis of a specified ratio of rate-of-spread to rate-of-available-line-construction. Unlike the simple containment model, equation 4 is evaluated and integrated starting at the first arrival time and thereafter at 1-minute increments. Therefore, the available line construction rate is applied almost continuously as the ellipse expands with time.

Simple Containment Model

In the simple containment[10] model the elliptical fire starts at time $t_0 = 0.0$ and is reported at time t_r *(fig. 3)*. The fire is contained at time t_c if the perimeter at time t_c is less than or equal to the line built around the fire at time t_c, i.e.,

$$C(\epsilon) * V_h * t_c = P(t_c) = \sum_{i=1}^{k} R_i(t_c - t_i)$$

in which $P(t_c)$ is the perimeter at time t_c, and k is the number of resources dispatched to generate the required perimeter at time t_c. The corresponding area at time t_c will be

$$(V_h * t_c)^2 * \pi * \sqrt{1 - \epsilon^2 / (1 + \epsilon)^2}.$$

Solving for t_c gives:

$$t_c = \frac{t_r \sum_{i=1}^{k} R_i + \sum_{i=1}^{k} R_i\, \gamma_i}{\sum_{i=1}^{k} R_i - C(\epsilon) * V_h}$$

in which

R_i = line production rate of the *i*th resource (chains per minute)

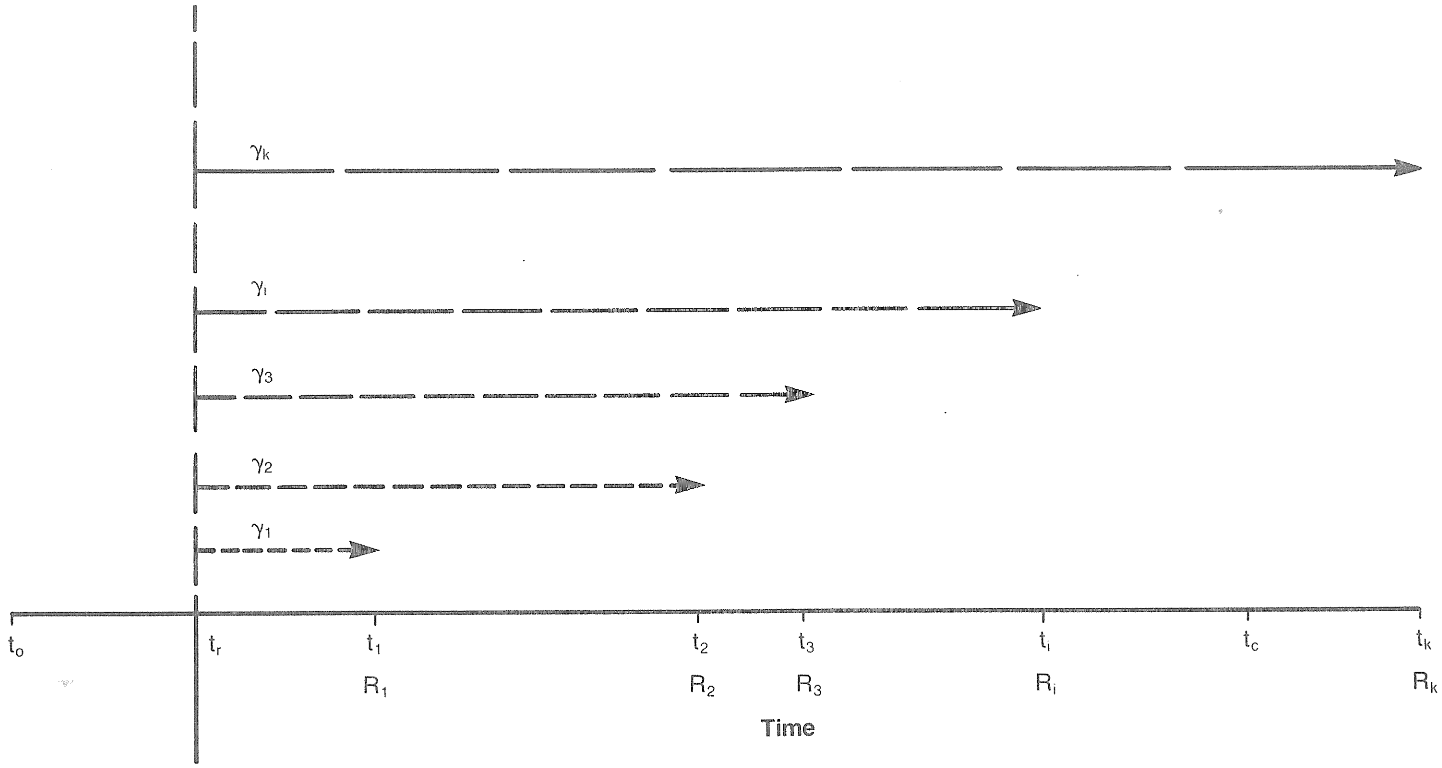

Figure 3—A time sequence explains variables in the simple model: a fire started at time t_o is reported at time t_r and controlled at time t_c; resources arrive at time t_i with production rate R_i and travel time γ_i to the fire site.

t_r = time the fire was reported (minutes)
$\gamma_i = t_i - t_r$ = travel time for the *i*th resource (minutes)
V_h = forward rate of spread (chains per minute)

$$C(\epsilon) = \frac{4 * E(\epsilon^2)}{1 + \epsilon} \approx 5.83 - 3.76 * \epsilon$$

$$E(\epsilon^2) = \int_0^{\pi/2} \sqrt{1 - \epsilon^2 * \sin^2(\phi)} d\phi$$

E (ϵ^2) is an elliptical integral, which exists only in tabular form. The linear function $5.83 - 3.76\epsilon$ is used as an approximation for C (ϵ) in the range of interest. C (ϵ) is a unitless quantity.

The number of resources dispatched k is determined by $\gamma_k \leq t_c \leq \gamma_k + 1$, or k is equal to the maximum number of resources available.

ANALYSIS AND RESULTS

The simple and complex containment model equations were each incorporated into a computer program that calculated area at containment, time to containment, and number of resources used, at 13 spread rates. The programs were used to evaluate five different examples, which varied in available resources, type of attack, and length-to-width ratio of the fire. In all cases, dispatch procedures and spread rates were the same.

In the first case, the following five resources were available for each fire:

Time of arrival (min)	Type	Assumed production rate
		Chains/hour
23	Handcrew (2 persons)	6.8
23	Handcrew (2 persons)	6.8
41	Engine crew (2 persons, 200 gal)	16
50	Engine crew (2 persons, 200 gal)	16
52	Handcrew (2 persons)	6.8

Two of the handcrews were the same. If the arrival time of any resource exceeded the required containment time by resources already on the fire the resource was not used. The length-to-width ratios for the ellipse were 4:1 and 2:1. The contained areas and time to containment did not differ substantially between the two models for spread rates less than 10 chains per hour *(table 1)*.

In the second case, the following five resources were available for all fires:

Time of arrival (min)	Type	Assumed production rate
		Chains/hour
15	Engine crew (2 persons, 200 gal)	16
40	Bulldozer medium size	36
45	Handcrew (2 persons)	6.8
45	Handcrew (2 persons)	6.8
69	Engine crew (2 persons, 200 gal)	16

The length-to-width ratios for the ellipse were 4:1 and 2:1. Due to the high production of the bulldozer, the complex containment model used head attack calculations up to a spread rate of 10 chains per hour (see assumption 5). This attack option resulted in a reduction of acreage and number of crews used at the lower spread rates for the complex model *(table 2)*.

The third case was the same as the first case, except that the complex model used the head attack option. With the head attack option, area at containment and the number of resources used differed substantially *(table 3)*. At 5 chains per hour, the complex model shifted over to rear attack, and the results were almost identical for both models. Again, spread rates in excess of 10 chains per hour were needed to show any differences in contained area.

In the fourth and fifth cases, the resources were the same as for the second case, but production rates differed. For the fourth case they were one-fourth of those in the second case, and for the fifth case they were one-half of those in the second case:

Time of arrival (min)	Type	Assumed production rates Fourth case	Fifth case
		Chains/hour	
15	Engine crew (2 persons, 200 gal)	4	8
40	Bulldozer (medium)	9	18
45	Handcrew (2 persons)	1.7	3.4
45	Handcrew (2 persons)	1.7	3.4
69	Engine crew (2 persons, 200 gal)	4	8

Length-to-width ratios were 2:1. In the fourth case, area-at-containment varied with increasing spread rates *(table 4)*. For a spread of 8 chains per hour or more, the crews cannot match the perimeter growth rate in the simple model. For the complex model, the fire escapes (exceeds 100 acres) at 11 chains per hour.

Again in the fifth case, for spread rates in excess of 5 chains per hour, the complex model gave smaller areas at containment *(table 5)*.

Table 1—*Area at containment, time to containment, and resources used, by spread rate and length-to-width ratio, for simple and complex containment models*

Spread rate (ch/hr)	Area at containment Simple	Complex	Time to containment Simple	Complex	Area ratio (simple:complex)	Resources used Simple	Complex
	Acres		*Minutes*				
					4:1 length-to-width ratio		
1	0.18	0.17	46	46	1.08	3	3
2	.30	.28	50	49	1.08	3	3
3	.48	.40	53	52	1.19	5	4
4	.70	.60	55	54	1.17	5	5
5	1.01	.82	58	57	1.23	5	5
6	1.42	1.14	61	60	1.25	5	5
7	1.94	1.52	65	63	1.28	5	5
8	2.65	1.95	69	66	1.36	5	5
9	3.60	2.58	74	71	1.40	5	5
10	4.79	3.28	79	75	1.46	5	5
12	8.77	5.38	92	86	1.63	5	5
14	16.12	8.56	110	99	1.87	5	5
16	32.00	14.88	140	122	2.15	5	5
					2:1 length-to-width ratio		
1	.21	.20	44	44	1.05	3	3
2	.43	.37	49	48	1.13	3	3
3	.77	.60	52	51	1.20	5	4
4	1.20	.98	55	55	1.16	5	5
5	1.86	1.40	59	57	1.22	5	5
6	2.78	1.99	62	61	1.30	5	5
7	4.00	2.85	67	65	1.27	5	5
8	5.78	3.81	72	69	1.37	5	5
9	8.32	5.07	78	75	1.44	5	5
10	11.72	6.48	84	78	1.58	5	5
12	24.80	11.26	103	92	1.83	5	5
14	55.50	19.06	133	109	2.29	5	5
16	>100	34.31	183	135	3.09	5	5

CONCLUSIONS

No empirical data are available to verify the accuracy of the simple and complex containment models. The results are rather limited in scope, but they do illustrate some of the computational differences between the two models. A large number of possible combinations of dispatches, fire spread rates, and line construction rates would further bring out differences between these two models. Variations in the time-to-containment and the number of resources used may lead to substantial differences in suppression cost estimated by the two models.

The results indicate that:

- The models agree closely for elliptical fires in which the ratio of line production rate to perimeter increase rate is high.
- The use of the direct head attack option in the complex model significantly affects area at containment and the number of resources used.
- For those fires in which the production rate is close to the perimeter growth rate, the complex model gives substantially smaller containment areas and fewer escapes.
- For the average fire the simple model has an advantage of approximately 100 to 1 in computer running time over the complex model. This advantage increases as the time to containment goes up. The equations for the simple model can easily be programmed and adapted within other models.

Potential users of these models must consider these results, computational cost, ease of using the simple model, and the range of production rate versus perimeter growth rate, in deciding whether to use the simple or complex model.

END NOTES AND REFERENCES

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Table 2—*Area at containment, time to containment, and resources used, by spread rate and length-to-width ratio, for simple and complex containment models*

Spread rate (ch/hr)	Area at containment		Time to containment		Area ratio (simple:complex)	Resources used	
	Simple	Complex	Simple	Complex		Simple	Complex
	Acres		*Minutes*				
			4:1 length-to-width ratio				
1	0.16	0.14	38	36	1.16	1	1
2	.26	.20	41	40	1.30	2	2
3	.39	.27	43	41	1.44	2	2
4	.55	.36	45	43	1.52	4	2
5	.77	.46	47	44	1.67	4	2
6	1.04	.60	49	45	1.73	4	4
7	1.36	.73	51	46	1.86	4	4
8	1.78	.88	54	47	2.02	4	4
9	2.32	1.11	56	50	2.09	4	4
10	2.94	1.33	59	52	2.21	4	4
12	4.81	2.98	66	52	1.61	4	4
14	7.15	4.12	72	66	1.73	4	4
16	11.03	5.92	79	71	1.86	5	5
			2:1 length-to-width ratio				
1	.18	.15	33	33	1.20	1	1
2	.36	.25	40	38	1.44	2	1
3	.60	.36	43	41	1.66	2	2
4	.91	.54	45	42	1.68	4	2
5	1.34	.73	48	48	1.83	4	2
6	1.80	.97	50	45	1.85	4	4
7	2.52	1.30	51	47	1.93	4	4
8	3.60	1.65	56	49	2.18	4	4
9	4.89	2.09	59	52	2.35	4	4
10	6.58	2.52	63	57	2.61	4	4
12	11.27	6.04	71	65	1.86	5	4
14	18.12	8.85	79	70	2.04	5	5
16	28.98	12.90	89	76	2.25	5	5

Table 4—*Area at containment, time to containment, and resources used, by spread rate for simple and complex containment models. Length-to-width ratio of ellipse was 2:1*

Spread rate (ch/hr)	Area at containment		Time to containment		Area ratio (simple:complex)	Resources used	
	Simple	Complex	Simple	Complex		Simple	Complex
	Acres		*Minutes*				
1	0.26	0.22	58	56	1.18	4	4
2	.66	.45	70	65	1.46	5	4
3	1.50	.78	85	73	1.92	5	5
4	3.29	1.44	107	85	2.28	5	5
5	8.22	2.35	144	97	3.49	5	5
6	25.80	4.07	224	115	6.35	5	5
7	>100	7.46	463	143	18.35	5	5
8	>100	12.89	12,870	176	10,126.40	5	5
9		25.35		234		5	5
10		50.76		319		5	5
11		>100				5	5

Table 3—*Area at containment, time to containment, and resources used, by spread rate and length-to-width ratio, for simple and complex containment models*

Spread rate (ch/hr)	Area at containment		Time to containment		Area ratio (simple:complex)	Resources used	
	Simple	Complex	Simple	Complex		Simple	Complex
	Acres		*Minutes*				
	4:1 length-to-width ratio						
1	0.18	0.15	46	45	1.20	3	3
2	.30	.21	50	46	1.43	3	3
3	.48	.28	53	48	1.71	5	3
4	.71	.37	55	55	1.91	5	3
5	1.01	.82	58	57	1.23	5	5
6	1.43	1.14	61	60	1.25	5	5
7	1.94	1.52	65	63	1.28	5	5
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16	>100	34.31	183	135	3.09	5	5

Table 5—*Area at containment, time to containment, and resources used, by spread rate for simple and complex containment models. Length-to-width ratio of ellipse was 2:1*

Spread rate (ch/hr)	Area at containment		Time to containment		Area ratio (simple:complex)	Resources used	
	Simple	Complex	Simple	Complex		Simple	Complex
	Acres		*Minutes*				
1	0.22	0.29	45	44	0.76	4	2
2	.44	.34	49	48	1.29	4	4
3	.81	.54	55	51	1.50	4	4
4	1.37	.87	61	56	1.57	4	4
5	2.35	1.24	70	60	1.89	5	4
6	3.76	1.79	75	65	2.09	5	4
7	5.70	2.62	84	71	2.17	5	5
8	9.10	3.57	96	76	2.54	5	5
9	14.60	4.83	109	76	3.02	5	5
10	23.37	6.29	128	87	3.71	5	5
12	72.66	11.49	193	103	6.62	5	5
14	>100	20.58	413	125	21.03	5	5
16	>100	39.54	12,798	158	13,132.52	5	5

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The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.