Research Note

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FIRE CONTAINMENT EQUATIONS FOR POCKET CALCULATORS

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ABSTRACT

Presents simplified equations for solving the fire containment problem. Equations can be used on a programmable pocket calculator to derive the burned area, given forward rate of spread, initial area, fire shape length/width ratio, and control-line construction rate. Equations can also be used to find the line construction rate needed to hold the burned area to a fixed value, knowing the other variables listed. Potential uses seen for this capability are preliminary fire control planning and as a dispatching aid. Copies of a program for the Texas Instruments Model 59 calculator[2] *are available on request.*

KEYWORDS: Fire containment, fire control, fire suppression,
planning, dispatching, calculator program

Prefire planning and initial attack dispatching are fire management activities that require the solution to the classical fire containment problem: How much containment capability is needed? The question can be phrased in a variety of ways and answered in many ways. Often there are additional considerations that modify or even override the answer to the strictly-limited question, but it is still necessary to estimate potential fire sizes and potential requirements for fire suppression capabilities (Barrows 1951).

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[2] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

Concern over rising costs of wildland fire suppression has stimulated more intensive planning for fire control.[3] The computer program FOCUS (Storey 1972) was designed to test fire control plans and force dispositions for the purpose of increasing efficiency and reducing costs. This program uses tables of numbers that give the final area and perimeter of an easily controlled fire in terms of its initial area, length/width ratio, and ratio of control line construction rate to forward rate of spread (Bratten 1978).

For preliminary planning work and as a ready aid for dispatcher use, a simplified mechanized process for solving the fire containment problem may be useful. This note presents simple equations that can be used on a programmable pocket calculator for this purpose. The structure of an appropriate program for such application is given. This structure has been used to program a Texas Instrument Model 59 calculator to solve the equations presented here.

SIMPLIFYING ASSUMPTIONS

In its general (real-life) form, the mathematical problem of calculating the time required to construct a control line around a spreading fire, working at the fire edge, is intractably complicated. By making a series of simplifying assumptions, the problem can be reduced to one that can be solved. The applicability of the results must then be judged according to how closely the real situation conforms to the idealized model of it. So that the reader may make such judgment, the assumptions used in setting up the mathematical problem are spelled out below:

1. The unconstrained spread of the fire would not change its shape. That is, while the fire may spread at different rates in different directions, its growth would resemble the enlargement of a photograph.

2. The rate of spread of the fire is constant over the time that control line construction takes place. In practical terms this implies that the fire is contained within one burning period and that the fuels, topography, and weather remain essentially the same from the time work starts until it is finished.

3. The shape of the free-burning fire is that of an ellipse, with the point of origin at a focus. Of course it need not be exactly an ellipse, but an elliptical shape must roughly describe the location of the fire edge. Note that an ellipse with a length/width ratio of unity is a circle, so this case is included. See figure 1 for ellipses of various length/width (L/W) ratios.

4. The rate of line construction is constant. Of course this is never exactly correct, but the analysis depends on treating the rate as a constant. By using different, constant, values in example calculations, one can explore how sensitive the results are to the validity of this assumption in each case considered.

5. Work proceeds simultaneously on both sides of the fire at an equal pace. That is, the line-construction force is split into two equal parts (in terms of line construction rates) and they separate at the point of attack--either the head or the rear of the fire--and work around the flanks to meet at the opposite end.

6. The containment line is constructed at the edge of the fire. No indirect containment tactics are handled in this simplified analysis, so this constraint indirectly limits the intensity level of fires that can be analyzed; only fires of low and moderate intensity permit direct suppression (Albini 1976).

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[3] "Fire management analysis for forest planning," National Fire Management Planning Task Force, USDA For. Serv. Working Draft No. 1; May 1979 (to be revised). Authors: James F. Mann, Richard A. Henry, Richard A. Chase, Randall J. Van Gelder.

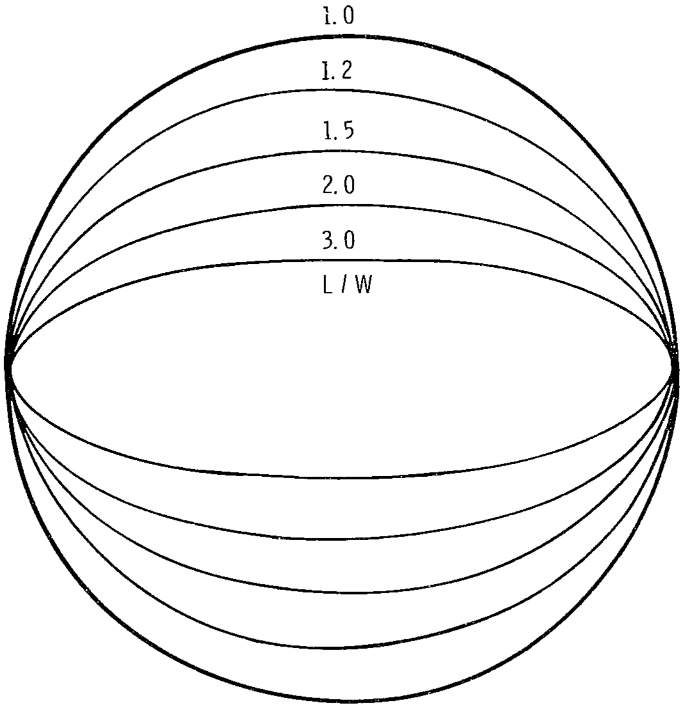

Figure 1.--Ellipses of various length/width (L/W) ratios.

The last constraint is imposed simply to limit the scope of the cases considered. Indirect attack tactics have been successfully treated (Albini and others 1978) so the methodology could be extended if interest warrants it. That is, we could fit curves to numerical results obtained using a well-placed barrier before the head of the fire as done by Albini and others (1978).

7. An implicit assumption here is that the containment or suppression work is 100 percent effective. That is, the fire does not spread beyond the control line once constructed.

METHODOLOGY

The problem described above, with the simplifying assumptions outlined, was formulated mathematically and reduced to the numerical evaluation of two integrals (Albini and others 1978). The exact expressions to be computed are:

$$P/2R(\theta_o) = \int_{\theta_o}^{\theta_o+\pi} G(\theta)F(\theta)d\theta \qquad (1)$$

$$A/R^2(\theta_o) = \int_{\theta_o}^{\theta_o+\pi} F^2(\theta)d\theta \qquad (2)$$

where

P = the final perimeter of the burned area (= the total length of control line constructed)

A = the burned area

$R(\theta_o)$ = the distance from the fire's point of origin to the point on its edge where control line construction started, designated by the angle θ_o.

The function F describes the shape of the final burned area in radial coordinates,[4] and the product GF is the derivative of perimeter length with respect to the angle θ. The size and shape of the free-burning fire is described in radial coordinates, with origin at the point of origin of the fire, by the function $r(\theta,t)$, where

$r(\theta,t)$ = distance from the point of origin to the fire edge at time t in the direction θ
θ = an angle measured from the direction of the maximum rate of spread ($\theta = 0$ toward the head of the fire), counterclockwise
t = time since start of the fire.

In terms of the function r, its time derivative $\dot{r}$, its derivative with respect to the angle r', and rate of control line construction on each flank, V_L, the function F can be written as

$$F(\theta) = \exp\left(\int_{\theta_0}^{\theta} f(\theta')d\theta'\right) \tag{3}$$

where

$$f = \frac{\dot{r}/V_L + (r'/r)\left(1 + (r'/r)^2 - (\dot{r}/V_L)^2\right)^{1/2}}{-(r'/r)(\dot{r}/V_L) + \left(1 + (r'/r)^2 - (\dot{r}/V_L)^2\right)^{1/2}}. \tag{4}$$

Because of simplifying assumptions 1, 2, and 4, the function f is independent of time. Likewise, function $G(\theta)$ is time-independent:

$$G = \left(1 + (r'/r)^2\right)/\left(-(r'/r)(\dot{r}/V_L) + \left(1 + (r'/r)^2 - (\dot{r}/V_L)^2\right)^{1/2}\right). \tag{5}$$

By assumption 3 above the outline of the free-burning fire can be expressed as

$$r(\theta) = r(0)(1 - \varepsilon)/(1 - \varepsilon \cos \theta) \tag{6}$$

where r(0), the distance from the point of origin to the head of the fire is given by

$$r(0) = V_F t \tag{7}$$

and V_F is the forward rate of spread. The factor ε in equation 6 is the eccentricity of the elliptical fire outline. It is related to the length/width ratio, L/W, by the formula

$$\varepsilon = \left((L/W)^2 - 1\right)^{1/2}/(L/W). \tag{8}$$

If control line construction starts at the head of the fire, θ_0 is zero; if at the rear, θ_0 is π:

$$R(\theta_0) = \begin{cases} r(0), & \theta_0 = 0 \\ r(0)(1 - \varepsilon)/(1 + \varepsilon), & \theta_0 = \pi \end{cases} \tag{9}$$

The value of r(0) can be related to the area of the fire at the time line construction begins, A_0, and the length/width ratio:

$$r(0) = (1 + \varepsilon)\left((L/W)A_0/\pi\right)^{1/2}. \tag{10}$$

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[4] The interested reader should consult Albini and others (1978) for the development of equations 1-5. These equations are given here only for completeness of this presentation.

APPROXIMATE FORMS

The equations above were programmed for calculation on the CDC7600 computer at Lawrence Berkeley Laboratories' facility on the University of California campus at Berkeley. The results, expressed in the dimensionless forms of equations 1 and 2, were tabulated against the ratios V_F/V_L and L/W. The tabular entries were then fitted by simple functional forms.

Holding L/W constant, nonlinear regressions yielded functions of V_F/V_L. Keeping the functional forms constant allowed the tabulation of the regression coefficients in terms of the fire shape parameter L/W. These tables were, in turn, fitted to simple forms by regressions. The expressions resulting from this sequence are listed in the equation summary below.

The approximate forms for elliptical fire shapes are accurate to within about 5 percent for all length/width ratios in the range 1.2 to 3.0 inclusive. Outside this range the expressions begin to deviate rapidly from "exact" results. The upper limit of 3.0 is probably not overly restrictive, because fires with greater eccentricity than this will probably not be contained on initial attack or within one burning period (recall assumptions 1 and 2 above). This is so because usually only very rapidly spreading fires will have large length/width ratios.

Because the fire shape used here is an ellipse and the point of origin of the fire is at a focus of the ellipse, a length/width ratio of 3.0 represents a fire spreading very much more rapidly in the forward direction than in the backing direction. The graph in figure 2 shows how the length/width ratio varies with the ratio of forward to backing rates of spread.[5] From this figure one can see that a fire with length/width ratio exceeding 3.0 would probably escape initial attack. Figure 3 shows the variation of length/width ratio with windspeed, based on Hal Anderson's double-ellipse formulas for wind-driven fire shapes (Albini 1976, erratum). This graph indicates that the windspeed at 20-foot height must exceed 20 mi/h before a length/width ratio of 3 is exceeded.

To extend the lower limit (L/W = 1.2), exact results for a circular fire shape are used. When the unconstrained fire grows as a circle, functions f (equation 4) and G (equation 5) become constants and equations 1 and 2 are simple to evaluate. These results are listed in the summary of equations. Whenever the length/width ratio of an elliptical fire shape is less than 1.2, the circular fire shape results can be used to obtain approximate results.

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[5] The spread rate ratio is the ratio of distance from the focus of origin to the forward and backward edges of the ellipse.

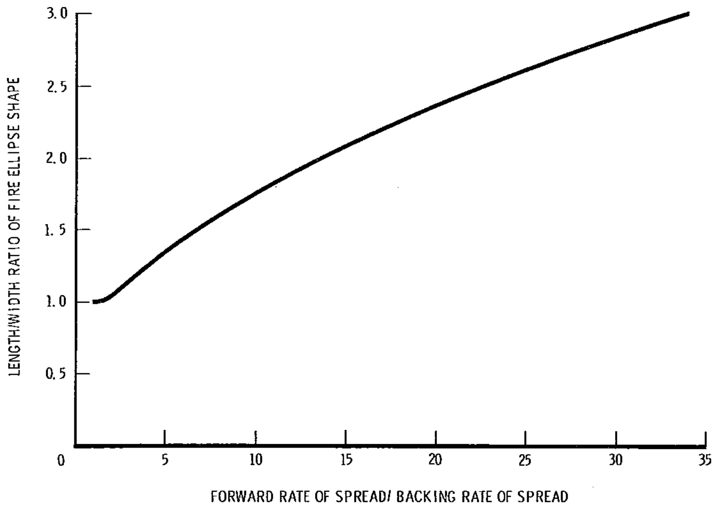

Figure 2.--Variation of length/width ratio of elliptical fire shapes with the ratio of forward rate of spread to backing rate of spread.

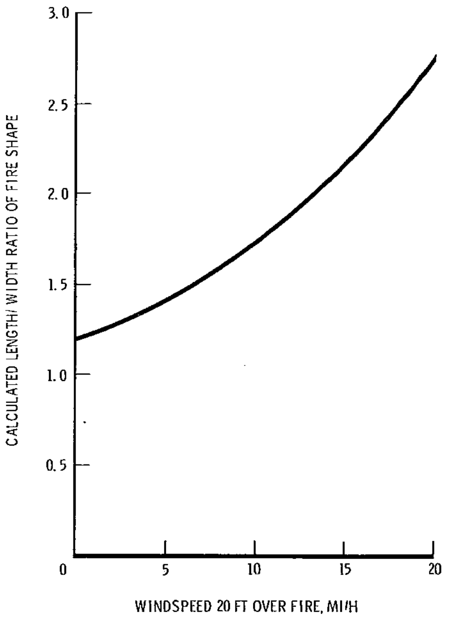

Figure 3.--Calculated length/width ratios for fire shapes, based on Hal Anderson's double-ellipse equations.

SUMMARY OF EQUATIONS FOR FIRE CONTAINMENT

Symbols

A_o = area of fire at the time containment work begins

$r(0)$ = distance from point of origin to head of fire when containment work begins

L/W = length/width ratio of elliptical shape of free-burning fire

V_F = forward rate of spread of free-burning fire

V_L = rate of construction of control line on each flank

A_B = final area of contained fire

P = perimeter of burned area (= length of control line built)

Δt = elapsed time to contain the fire

All Cases

$$r(0) = (1 + \varepsilon)\left((L/W)A_o/\pi\right)^{1/2}$$

$$\varepsilon = \left((L/W)^2 - 1\right)^{1/2}/(L/W)$$

$$\Delta t = P/(2V_L)$$

Case A, Work Starts at Head of Fire $(1.2 \le L/W \le 3.0)$

$$P/A_B^{1/2} = 3.52 + 0.044(L/W)^{2.4}$$

$$A_B^{1/2}/r(0) = \begin{cases} A_{11} + A_{12}(V_F/V_L)^{A_{13}}, & 0 \le V_F/V_L \le 0.95 \\ A_{21} + A_{22}\left(-\frac{1}{3}\ln(1 - V_F/V_L)\right)^{A_{23}}, & 0.95 < V_F/V_L < 1 \end{cases}$$

$$A_{11} = \left(2.341 - 3.126\exp(-0.6284\ L/W)\right)^{-1}$$

$$A_{12} = \left(4.799(L/W)^{0.774} - 5.047\right)^{-1}$$

$$A_{13} = \left(1.02 - 1.62\exp(-0.82\ L/W)\right)^{-1}$$

$$A_{21} = 0.45 + 2/(L/W)^3$$

$$A_{22} = 0.55(L/W - 1) - 2/(L/W)^3$$

$$A_{23} = 0.091 + 1.76/(L/W)^2$$

Case B. Work Starts at Back of Fire $(1.2 \le L/W \le 3.0)$

$$r(0)/A_B^{1/2} = B_{11} + B_{12}(V_F/V_L)^{B_{13}}$$

$$P/2r(0) = \left(B_{21}/(1.0 - V_F/V_L)\right)^{B_{22}}$$

$$B_{11} = 0.825 + 0.925\left(\ln\ (L/W)\right)^{1.01}$$

$$B_{12} = 5.1 - 5.96(L/W)^{0.1234}$$

$$B_{13} = -0.813 + 1.972\left(\ln\ (L/W)\right)^{0.0925}$$

$$B_{21} = 1.112 + 3.4\exp(-1.5L/W)$$

$$B_{22} = \left(0.988 - 2.46\exp(-2.35L/W)\right)^{-1}$$

Case C. Circular Fire Shape $(1 \le L/W < 1.2)$

$$A_B/A_o = \left(\exp(Z) - 1\right)/Z$$

$$P/2r(0) = \left(\exp(Z/2) - 1\right)(V_F/V_L)$$

$$Z = 2\pi/\left((V_F/V_L)^2 - 1\right)^{1/2}$$

The equations given in the summary can be inverted to express the rate of line construction required (V_L) to keep the burned area (A_B) to a specified value. In the pocket calculator program structure shown below, this option is selectable.

In the circular fire case, the equation for A_B/A_o in terms of Z can be solved for Z using the iteration:

$$Z_1 = 2 \ln (A_B/A_o) \tag{11}$$

$$Z_{n+1} = \left(1 + (Z_n - 1)\exp(Z_n)\right)/\left(\exp(Z_n) - A_B/A_o\right). \tag{12}$$

That is, use equation (11) to calculate a first estimate (Z_1) for Z, and use equation (12) to calculate successively better approximations Z_2, Z_3, etc., using the last estimate (Z_n) to generate the next one (Z_{n+1}). Repeating equation (12) six times gives convergence of Z to within one percent for A_B/A_o of 1,000. The iteration is strongly convergent.

Note that all the equations given in the summary are in dimensionless form. That is, the burned area is always divided by the initial area or appears as the square root divided by r(0); V_F and V_L always appear in ratio, etc. This was done for the convenience of the user, so that any system of units could be used. While the choice of units is up to the user, the user is reminded that internal consistency demands that the square of the unit of length be the unit of area. So if one chooses to express rate of spread and line construction rate in chains per hour, the unit of area (initial area and burned area) is squared chains. In this case it would be necessary to multiply areas measured in acres by a factor of 10 to convert them to squared chains. If the rate units are feet per minute (or per second or per hour) the area units are square feet, etc.

The conversion factor desired can be included in the program for a pocket calculator; this was done for a version programmed at the Northern Forest Fire Laboratory. In this version (see appendix), the units are assumed to be chains per hour and acres, the most common American forestry units, so a factor of 10 was programmed to multiply area entries to convert them to squared chains internally. For display, calculated areas are converted to acres. In the list of symbols shown in the appendix, the initial area in squared chains is denoted by A_o* while the same area in acres is called A_o. The asterisk implies the same conversion for burned area, A_B.

CALCULATOR PROGRAM STRUCTURE

The equations listed in the summary can be solved using a programmable pocket calculator. Exhibits 1 and 2 show appropriate program structures for the elliptical and circular fire shapes, respectively. These structures have been used to program the Texas Instruments Model 59 calculator. The combined cases A and B fit within the storage capability of that calculator, and required two magnetic-strip cards to record. Case C is much more compact, but could not be combined with either case A or B, so was recorded separately. Copies of these programs on magnetic strips are available from the authors at the Northern Forest Fire Laboratory. See the appendix for program listings and instructions for using them.

OPERATING STEPS, ELLIPTICAL FIRE SHAPE PROGRAM

1. Select case: A = head attack; B = rear attack
2. Select option: A' = compute line construction rate; B' = compute burned area
3. Input V_F
4. Input A_o
5. A': Input A_B (stop occurs if $A_B \leq A_o$)
   -or-
   B': Input V_L (stop occurs if $V_L \leq V_F$)
6. Input L/W (stop occurs if out of range)

Computation Sequence

1. Test: $1.2 \leq L/W \leq 3.0$ (stop out of range)

2. Calculate: ε, $r(0)$

3. Case A. Calculate and store A_{ij} coefficients

   Option A'. Test: $A_B/A_o > 1.0$ (stop out of range)

   Test: $A_B^{1/2}/r(0) < A_{21} + A_{22}$ (choose equation for V_L)

   Calculate: V_L, P, Δt

   Option B'. Test: $V_F/V_L > 1.0$ (stop out of range)

   Test: $V_F/V_L \leq 0.95$ (choose equation for V_L)

   Calculate: A_B, P, Δt

   Case B. Calculate and store B_{ij} coefficients

   Option A'. Test: $A_B/A_o > 1.0$ (stop out of range)

   Calculate: V_L, P, Δt

   Option B'. Test: $V_F/V_L < 1.0$ (stop out of range)

   Calculate: A_B, P, Δt

4. Display results

   Option A'. V_L, P, Δt

   Option B'. A_B, P, Δt

Exhibit 1.--Pocket calculator program structure and operating steps for solving the fire containment problem for elliptical fire shapes.

OPERATING STEPS, CIRCULAR FIRE SHAPE PROGRAM

1. Select option: A' = compute line construction rate; B' = compute burned area.
2. Input V_F
3. Input A_o
4. $\left\{\begin{array}{l}\text{A': Input } A_B \text{ (stop occurs if } A_B \leq A_o\text{)} \\ \text{-or-} \\ \text{B': Input } V_L \text{ (stop occurs if } V_L \leq V_F\text{)}\end{array}\right.$

Computation Sequence

1. Option A'. Test: $A_B/A_o > 1.0$ (stop out of range)

   Calculate: Z, A_B, P, Δt

   Option B'. Test: $V_F/V_L < 1.0$ (stop out of range)

   Calculate: Z, V_L, P, Δt

2. Display results:

   Option A'. V_L, P, Δt

   Option B'. A_B, P, Δt

Exhibit 2.--Pocket calculator program structure and operating steps for solving the fire containment problem for circular fire shapes.

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APPENDIX: OPERATING PROCEDURE FOR SOLVING FIRE CONTAINMENT PROBLEMS ON THE TI-59 CALCULATOR

I. Preliminaries

1. Turn calculator on.
2. Press: 2 2nd Op 1 7 .

II. Selection of program

1. Press: 2nd CP INV 2nd Fix .
2. Select set of cards to be used (see fig. 1 to help you select the right value for L/W).
   a. If L/W ≥ 1.2, use elliptical program, a set of 2 cards with sides 1 through 4.
   b. If L/W < 1.2, use circular program, a single card with sides 1 and 2.
3. Press: 1 .
4. Feed into lower slot side 1 of program strip of option chosen (circular or elliptical). The motor will start and stop automatically. A 1. should appear in the display after the strip is read. If the display flashes, press CLR and go back to step 3.
5. Press: 2 .
6. Feed in side 2 of program strip. (Keep printed side up, just start at the other end.) A 2. should appear in the display after the strip is read. If the display flashes, press CLR and go back to step 5.
7. (OMIT STEPS 7-10 FOR CIRCULAR OPTION.) Press: 3 .
8. Feed in side 3 similarly. The number 3. should appear in the display. If the display flashes, go back to step 7.
9. Press: 4 .
10. Feed in side 4 as above. When the number 4. appears in the display, you are ready to solve the problem. If the display flashes, press CLR and go back to step 9.

III. (OMIT PART III FOR CIRCULAR OPTION.) Select mode of attack on fire

1. If containment work is to begin at the *head* of the fire, press A .
2. If containment work is to begin at the *rear* of the fire, press B .

Each time a problem is solved, one *must* select either A or B. If A or B is pressed in the circular option, a flashing display will result. Press CLR and proceed.

IV. Choose type of problem to be solved.

1. To calculate line building rate required to hold burned area to a set acreage, press 2nd A' .
2. To calculate burned area when fire is contained with a set line building rate, press 2nd B' .

Each time a problem is solved, one *must* select either A' or B'.

A' Selected

1. Input forward rate of spread of fire in chains per hour. Press number keys (include decimal point if needed) and value will appear in the display. If an error is made, press CE and try again. When the desired number appears in the display, press R/S .

2. Input size of fire when containment work begins, in acres. When the desired number appears in the display, press R/S .
3. Input burned area target, in acres; press R/S . This value must be greater than the initial size or the display will flash 9's--go back to IV.
4. (OMIT STEP 4 IN CIRCULAR OPTION.) Input the length/width ratio of the fire shape at the time containment work begins. This number must be at least 1.2 and no more than 3.0. Press R/S . If L/W is outside the allowable range, display will flash 9's--go back to IV. If $1 \leq L/W < 1.2$, display will flash 1--go back to II and use circular option.
5. A flickering "C" should now appear in the display. If it does not, an error has occurred. Go back to III.
6. Calculation will cease with a number in the display. This number indicates the line-building rate (chains per hour) required on each flank of the fire. The total line-building rate capability, then, must be twice this number. Record this value for reference and then press R/S .
7. The number in the display indicates perimeter of the burned area (in chains) which is the same as the total length of control line constructed. Record this number for reference and then press R/S .
8. The number in the display indicates the time (in hours) that it will take to contain the fire. This completes the problem. To do another problem under the same option, go back to step III. To change options, go to part II.

B' Selected

1. Input forward rate of spread of fire in chains per hour. Press number keys (include decimal point if needed) and value will appear in display. If an error is made, press CE and try again. When desired number appears in the display, press R/S .
2. Input size of fire when containment work begins, in acres. When the desired number appears in the display, press R/S .
3. Input line-building rate capability (chains per hour) assigned equally to each flank of the fire. Press R/S . This must be more than the forward rate of spread or the display will flash 9's--go back to IV.
4. (OMIT STEP 4 IN CIRCULAR OPTION.) Input the length/width ratio of the fire shape at the time containment work begins. This number must be at least 1.2 and no more than 3.0. Press R/S . If L/W is outside the allowable range, display will flash 9's--go back to IV. If $1.0 \leq L/W < 1.2$, display will flash 1--go back to II and use circular option.
5. A flickering "C" should now appear in the display. If it does not, an error has occurred. Go back to III.
6. Calculation will cease with a number in the display. This number is the burned area, in acres, when the fire is contained. Record this value for reference and then press R/S .
7. The number in the display now is the perimeter of the burned area, which is the same as the total length of control line constructed, in chains. Record this number for reference and then press R/S .
8. The number in the display now will be the time, in hours, that it will take to contain the fire. This completes the problem. To do another problem under the same option, go back to step III. To change options, go to part II.

Condensed Instruction Steps

I. Press `2` `2nd` `Op` `1` `7` .

II. Press `2nd` `CP` `INV` `2nd` `Fix` .

Load: Press `1` , feed side 1, display 1. (flashing display: `CLR` try again)
Press `2` , feed side 2, display 2. (flashing display: `CLR` try again)
Etc.

III. Mode of attack--head: `A` } OMIT FOR CIRCULAR OPTION--Flashing display, `CLR` , continue
Mode of attack--rear: `B`

IV. Calculate line building rate: `2nd` `A'`
Calculate burned area: `2nd` `B'`

Option A'

Input
1. Forward rate of spread (ch/h), `R/S`
2. Initial fire size (acres), `R/S`
3. Burned area target (acres), `R/S`
4. Length/width ratio (1.2 - 3), `R/S`

Output
5. Line building rate per flank (ch/h): `R/S`
6. Total length of line (ch): `R/S`
7. Containment time (hours)

Error Indications

(3) Flashing 9's--number too small--go to IV

(4) a. Flashing 9's--number out of range--go to IV
  b. Flashing 1--wrong option--go to II and use circular option

Option B'

Input
1. Forward rate of spread (ch/h), `R/S`
2. Initial fire size (acres), `R/S`
3. Line building rate per flank (ch/h), `R/S`
4. Length/width ratio (1.2 - 3) `R/S`

Output
5. Burned area (acres): `R/S`
6. Total length of line (ch): `R/S`
7. Containment time (hours)

Error Indications

(3) Flashing 9's--number too small--go to IV

(4) a. Flashing 9's--number out of range--go to IV
  b. Flashing 1--wrong option--go to II and use circular option

Worked Examples

1. Suppose a fire has a size of 2 acres, a forward rate of spread of 15 chains per hour, and a length/width ratio of 2.5 when line construction begins. Assuming attack at the head of the fire, what line construction capability is required to contain the fire at 4 acres?

Step	Procedure	Enter	Display should be	Press	Display changes to
I.1	Turn calculator on				
I.2	Partition program memory			2 2nd Op 1 7	799.19
II.1	Clear memory; prepare decimal format			2nd CP INV 2nd Fix	ignore
II.2	Select elliptical program				
II.3	Prepare to read side 1	1	1		
II.4	Insert program side 1	(motor starts & stops automatically)			1.
II.5	Prepare to read side 2	2	2		
II.6	Insert program side 2	(motor starts & stops automatically)			2.
II.7	Prepare to read side 3	3	3		
II.8	Insert program side 3	(motor starts & stops automatically)			3.
II.9	Prepare to read side 4	4	4		
II.10	Insert program side 4	(motor starts & stops automatically)			4.
III.1	Select head attack			A	ignore
IV.1	Select calculation of line building rate			2nd A'	ignore
A'.1	Enter rate of spread	15	15	R/S	15.
A'.2	Enter size when fire containment begins	2	2	R/S	2.
A'.3	Enter burned area target	4	4	R/S	4.
A'.4	Enter length/width ratio	2.5	2.5	R/S	flickering C
A'.6	Record line construction rate on each flank (ch/h)				15.5 ←
A'.7	Record perimeter of		15.5	R/S	24.8 ←
A'.8	Record time required to contain fire (hours)		24.8	R/S	0.8 ←

Output: 15.5 = line construction rate on each flank (ch/h)
24.8 = perimeter of burned area (ch)
0.8 = time required to contain fire (hours)

2. Suppose that the size of a fire is 2 acres when containment begins and that the forward spread rate is 15 chains per hour. If the length/width ratio is 1 and line can be constructed at a rate of 25 chains per hour on each flank, what is the burned area when the fire is contained?

Step	Enter	Press	Display
II		2nd CP INV 2nd Fix	ignore
	1	(insert side 1)	1.
	2	(insert side 2)	2.
IV		2nd B'	ignore
	15	R/S	15.
	2	R/S	2.
	25	R/S	46.8 ←
		R/S	80.3 ←
		R/S	1.6 ←

Output: 46.8 = burned area (acres)
80.3 = perimeter of burned area (ch)
1.6 = time required to contain fire (hours)

Storage Registers

Register number	Elliptical shape	Circular shape
00	V_F	V_F
01	A_o	A_o
02	A_B	A_B
03	L/W	L/W
04	V_L	V_L
05	P	P
06	Δt	Δt
07	A_{11}, B_{11}	
08	A_{12}, B_{12}	
09	A_{13}, B_{13}	
10	B_{22}	
11	B_{23}	
12	A_o^*	A_o^*
13	A_B^*	A_B^*
14	V_F/V_L	V_F/V_L
15	A_{21}	
16	A_{22}	
17	A_{23}	
18	r(0)	r(0)
19		Z

ELLIPTICAL FIRE SHAPE

```
000  76 LBL
001  11  A
002  22 INV
003  58 FIX
004  22 INV
005  86 STF
006  01  01
007  22 INV
008  86 STF
009  02  02
010  47 CMS
011  91 R/S
012  76 LBL
013  12  B
014  22 INV
015  58 FIX
016  22 INV
017  86 STF
018  02  02
019  86 STF
020  01  01
021  47 CMS
022  91 R/S
023  76 LBL
024  16 A'
025  91 R/S
026  42 STO
027  00  00
028  91 R/S
029  42 STO
030  01  01
031  32 X:T
032  43 RCL
033  01  01
034  91 R/S
035  42 STO
036  02  02
037  22 INV
038  77  GE
039  52 EE
040  67  EQ
041  52 EE
042  43 RCL
043  02  02
044  91 R/S
045  61 GTO
046  24 CE
047  76 LBL
048  17 B'
049  86 STF
050  02  02
051  91 R/S
052  42 STO
053  00  00
054  32 X:T
055  43 RCL
056  09  00
057  91 R/S
058  42 STO
059  01  01
060  91 R/S
061  42 STO
062  04  04
063  22 INV
064  77  GE
065  52 EE
066  67  EQ
067  52 EE
068  91 R/S
069  76 LBL
070  24 CE
071  42 STO
072  03  03
073  32 X:T
074  01  1
075  32 X:T
076  22 INV
077  77  GE
078  52 EE
079  32 X:T
080  03  3
081  22 INV
082  77  GE
083  52 EE
084  01  1
085  93  .
086  02  2
087  32 X:T
088  43 RCL
089  03  03
090  22 INV
091  77  GE
092  44 SUM
093  53  (
094  53  (
095  43 RCL
096  03  03
097  65  ×
098  93  .
099  06  6
100  02  2
101  08  8
102  04  4
103  54  )
104  94 +/-
105  22 INV
106  23 LNX
107  65  ×
108  03  3
109  93  .
110  01  1
111  02  2
112  06  6
113  94 +/-
114  85  +
115  02  2
116  93  .
117  03  3
118  04  4
119  01  1
120  54  )
121  35 1/X
122  42 STO
123  07  07
124  53  (
125  43 RCL
126  03  03
127  45 Yˣ
128  93  .
129  07  7
130  07  7
131  04  4
132  65  ×
133  04  4
134  93  .
135  07  7
136  09  9
137  09  9
138  75  -
139  05  5
140  93  .
141  00  0
142  04  4
143  07  7
144  54  )
145  35 1/X
146  42 STO
147  08  08
148  53  (
149  53  (
150  43 RCL
151  03  03
152  65  ×
153  93  .
154  08  8
155  02  2
156  94 +/-
157  54  )
158  22 INV
159  23 LNX
160  65  ×
161  01  1
162  93  .
163  06  6
164  02  2
165  94 +/-
166  85  +
167  01  1
168  93  .
169  00  0
170  02  2
171  54  )
172  35 1/X
173  42 STO
174  09  09
175  53  (
176  53  (
177  43 RCL
178  03  03
179  45 Yˣ
180  03  3
181  54  )
182  35 1/X
183  65  ×
184  02  2
185  54  )
186  42 STO
187  19  19
188  85  +
189  93  .
190  04  4
191  05  5
192  95  =
193  42 STO
194  15  15
195  43 RCL
196  19  19
197  94 +/-
198  85  +
199  53  (
200  93  .
201  05  5
202  05  5
203  55  ÷
204  53  (
205  43 RCL
206  03  03
207  75  -
208  01  1
209  54  )
210  54  )
211  95  =
212  42 STO
213  16  16
214  43 RCL
215  03  03
216  33 X²
217  35 1/X
218  65  ×
219  01  1
220  93  .
221  07  7
222  06  6
223  85  +
224  93  .
225  00  0
226  09  9
227  01  1
228  95  =
229  42 STO
230  17  17
231  43 RCL
232  01  01
233  65  ×
234  01  1
235  00  0
236  95  =
237  42 STO
238  12  12
239  43 RCL
240  02  02
241  65  ×
242  01  1
243  00  0
244  95  =
245  42 STO
246  13  13
247  53  (
248  53  (
249  43 RCL
250  03  03
251  33 X²
252  35 1/X
253  94 +/-
254  85  +
255  01  1
256  54  )
257  34 ΓX
258  85  +
259  01  1
260  54  )
261  65  ×
262  53  (
263  43 RCL
264  03  03
265  65  ×
266  43 RCL
267  12  12
268  55  ÷
269  89  π
270  54  )
271  34 ΓX
272  95  =
273  42 STO
274  18  18
275  87 IFF
276  02  02
277  22 INV
378  87 IFF
279  01  01
280  42 STO
281  43 RCL
282  18  18
283  35 1/X
284  65  ×
285  43 RCL
286  13  13
287  34 ΓX
288  95  =
289  32 X:T
290  43 RCL
291  15  15
292  85  +
293  43 RCL
294  16  16
295  95  =
296  22 INV
297  77  GE
298  33 X²
299  76 LBL
300  32 X:T
301  53  (
302  53  (
303  53  (
304  43 RCL
305  13  13
306  34 ΓX
307  55  ÷
308  43 RCL
309  18  18
310  75  -
311  43 RCL
312  07  07
313  54  )
314  55  ÷
315  43 RCL
316  08  08
317  54  )
318  22 INV
319  45 Yˣ
320  43 RCL
321  09  09
322  54  )
323  35 1/X
324  65  ×
325  43 RCL
326  00  00
327  95  =
328  42 STO
329  04  04
330  87 IFF
331  01  01
332  45 Yˣ
333  76 LBL
334  23 LNX
335  53  (
336  43 RCL
337  03  03
338  45 Yˣ
339  02  2
340  93  .
341  04  4
342  65  ×
343  93  .
344  00  0
345  04  4
346  04  4
347  85  +
348  03  3
349  93  .
350  05  5
351  02  2
352  54  )
353  65  ×
354  43 RCL
355  13  13
356  34 ΓX
357  95  =
358  42 STO
359  05  05
360  76 LBL
361  35 1/X
362  43 RCL
363  05  05
364  55  ÷
365  02  2
366  55  ÷
367  43 RCL
368  04  04
369  95  =
370  42 STO
371  06  06
372  58 FIX
373  01  01
374  87 IFF
375  02  02
376  53  (
377  43 RCL
378  04  04
379  91 R/S
380  43 RCL
381  05  05
382  91 R/S
383  43 RCL
384  06  06
385  91 R/S
386  76 LBL
387  53  (
388  43 RCL
389  02  02
390  91 R/S
391  43 RCL
392  05  05
393  91 R/S
394  43 RCL
395  06  06
396  91 R/S
397  76 LBL
398  33 X²
399  43 RCL
400  00  00
401  55  ÷
402  53  (
403  01  1
404  75  -
405  53  (
406  53  (
407  03  3
408  94 +/-
409  65  ×
410  53  (
411  53  (
412  43 RCL
413  13  13
414  34 ΓX
415  55  ÷
416  43 RCL
417  18  18
418  75  -
419  43 RCL
420  15  15
421  54  )
422  55  ÷
423  43 RCL
424  16  16
425  54  )
426  22 INV
427  45 Yˣ
428  43 RCL
429  17  17
430  54  )
431  22 INV
432  23 LNX
433  54  )
434  54  )
435  95  =
436  42 STO
437  04  04
438  61 GTO
439  23 LNX
440  76 LBL
441  22 INV
442  43 RCL
443  00  00
444  55  ÷
445  43 RCL
446  04  04
447  95  =
448  42 STO
449  14  14
450  87 IFF
451  01  01
452  42 STO
453  32 X:T
454  93  .
455  09  9
456  05  5
457  22 INV
458  77  GE
459  43 RCL
460  53  (
461  53  (
462  43 RCL
463  14  14
464  45 Yˣ
465  43 RCL
466  09  09
467  65  ×
468  43 RCL
469  08  08
470  85  +
471  43 RCL
472  07  07
473  54  )
474  65  ×
475  43 RCL
476  18  18
477  54  )
478  33 X²
479  42 STO
480  13  13
481  55  ÷
482  01  1
483  00  0
484  95  =
485  42 STO
486  02  02
487  61 GTO
488  23 LNX
489  76 LBL
490  43 RCL
491  53  (
492  53  (
493  53  (
494  53  (
495  01  1
496  75  -
497  43 RCL
498  14  14
499  54  )
500  23 LNX
501  55  ÷
502  03  3
503  94 +/-
504  54  )
505  45 Yˣ
506  43 RCL
507  17  17
508  65  ×
509  43 RCL
510  16  16
511  85  +
```

```
512  43 RCL
513  15  15
514  54  )
515  65  ×
516  43 RCL
517  18  18
518  54  )
519  33 X²
520  42 STO
521  13  13
522  55  ÷
523  01  1
524  00  0
525  95  =
526  42 STO
527  02  02
528  61 GTO
529  23 LNX
530  76 LBL
531  42 STO
532  43 RCL
533  03  03
534  23 LNX
535  45 Yˣ
536  01  1
537  93  .
538  00  0
539  01  1
540  65  ×
541  93  .
542  09  9
543  02  2
544  05  5
545  85  +
546  93  .
547  08  8
548  02  2
549  05  5
550  95  =
551  42 STO
552  07  07
553  43 RCL
554  03  03
555  45 Yˣ
556  93  .
557  01  1
558  02  2
559  03  3
560  04  4
561  65  ×
562  05  5
563  93  .
564  09  9
565  06  6
566  94 +/-
567  85  +
568  05  5
569  93  .
570  01  1
571  95  =
572  42 STO
573  08  08
574  43 RCL
575  03  03
576  23 LNX
577  45 Yˣ
578  93  .
579  00  0
580  09  9
581  02  2
582  05  5
583  65  ×
584  01  1
585  93  .
586  09  9
587  07  7
588  02  2
589  75  -
590  93  .
591  08  8
592  01  1
593  03  3
594  95  =
595  42 STO
596  09  09
597  53  (
```

```
598  43 RCL
599  03  03
600  65  ×
601  01  1
602  93  .
603  05  5
604  94 +/-
605  54  )
606  22 INV
607  23 LNX
608  65  ×
609  03  3
610  93  .
611  04  4
612  85  +
613  01  1
614  93  .
615  01  1
616  01  1
617  02  2
618  95  =
619  42 STO
620  15  15
621  53  (
622  53  (
623  43 RCL
624  03  03
625  65  ×
626  02  2
627  93  .
628  03  3
629  05  5
630  94 +/-
631  54  )
632  22 INV
633  23 LNX
634  65  ×
635  02  2
636  93  .
637  04  4
638  06  6
639  94 +/-
640  85  +
641  93  .
642  09  9
643  08  8
644  08  8
645  54  )
646  35 1/X
647  42 STO
648  16  16
649  87 IFF
650  02  02
651  54  )
652  53  (
653  53  (
654  53  (
655  43 RCL
656  18  18
657  55  ÷
658  43 RCL
659  13  13
660  34 √X
661  75  -
662  43 RCL
663  07  07
664  54  )
665  55  ÷
666  43 RCL
667  08  08
668  54  )
669  22 INV
670  45 Yˣ
671  43 RCL
672  09  09
673  54  )
674  42 STO
675  14  14
676  35 1/X
677  65  ×
678  43 RCL
679  00  00
680  95  =
681  42 STO
682  04  04
683  76 LBL
```

```
684  45 Yˣ
685  53  (
686  43 RCL
687  15  15
688  55  ÷
689  53  (
690  01  1
691  75  -
692  43 RCL
693  14  14
694  54  )
695  54  )
696  45 Yˣ
697  43 RCL
698  16  16
699  65  ×
700  02  2
701  65  ×
702  43 RCL
703  18  18
704  95  =
705  42 STO
706  05  05
707  61 GTO
708  35 1/X
709  76 LBL
710  54  )
711  53  (
712  43 RCL
713  18  18
714  55  ÷
715  53  (
716  43 RCL
717  14  14
718  45 Yˣ
719  43 RCL
720  09  09
721  65  ×
722  43 RCL
723  08  08
724  85  +
725  43 RCL
726  07  07
727  54  )
728  54  )
729  33 X²
730  42 STO
731  13  13
732  55  ÷
733  01  1
734  00  0
735  95  =
736  42 STO
737  02  02
738  61 GTO
739  45 Yˣ
740  76 LBL
741  52 EE
742  00  0
743  35 1/X
744  91 R/S
745  76 LBL
746  44 SUM
747  01  1
748  94 +/-
749  34 √X
750  91 R/S
```

CIRCULAR
FIRE SHAPE

```
000  76 LBL
001  16 A'
002  22 INV
003  58 FIX
004  22 INV
005  86 STF
006  01  01
007  47 CMS
008  91 R/S
009  42 STO
010  00  00
011  91 R/S
012  42 STO
013  01  01
014  32 X:T
015  43 RCL
```

```
016  01  01
017  91 R/S
018  42 STO
019  02  02
020  22 INV
021  77 GE
022  52 EE
023  67 EQ
024  52 EE
025  61 GTO
026  24 CE
027  76 LBL
028  17 B'
029  22 INV
030  58 FIX
031  86 STF
032  01  01
033  47 CMS
034  91 R/S
035  42 STO
036  00  00
037  32 X:T
038  43 RCL
039  00  00
040  91 R/S
041  42 STO
042  01  01
043  91 R/S
044  42 STO
045  04  04
046  22 INV
047  77 GE
048  52 EE
049  67 EQ
050  52 EE
051  76 LBL
052  24 CE
053  43 RCL
054  01  01
055  65  ×
056  01  1
057  00  0
058  95  =
059  42 STO
060  12  12
061  43 RCL
062  02  02
063  65  ×
064  01  1
065  00  0
066  95  =
067  42 STO
068  13  13
069  53  (
070  43 RCL
071  12  12
072  55  ÷
073  89  π
074  54  )
075  34 √X
076  95  =
077  42 STO
078  18  18
079  87 IFF
080  01  01
081  34 √X
082  53  (
083  43 RCL
084  13  13
085  55  ÷
086  43 RCL
087  12  12
088  54  )
089  23 LNX
090  65  ×
091  02  2
092  95  =
093  42 STO
094  19  19
095  06  6
096  42 STO
097  06  06
098  76 LBL
099  22 INV
100  53  (
101  43 RCL
```

```
102  19  19
103  22 INV
104  23 LNX
105  65  ×
106  53  (
107  43 RCL
108  19  19
109  75  -
110  01  1
111  54  )
112  85  +
113  01  1
114  54  )
115  55  ÷
116  53  (
117  43 RCL
118  19  19
119  22 INV
120  23 LNX
121  75  -
122  53  (
123  43 RCL
124  13  13
125  55  ÷
126  43 RCL
127  12  12
128  54  )
129  54  )
130  95  =
131  42 STO
132  19  19
133  97 DSZ
134  06  06
135  22 INV
136  53  (
137  53  (
138  02  2
139  65  ×
140  89  π
141  55  ÷
142  43 RCL
143  19  19
144  54  )
145  33 X²
146  85  +
147  01  1
148  54  )
149  34 √X
150  65  ×
151  43 RCL
152  00  00
153  95  =
154  42 STO
155  04  04
156  76 LBL
157  23 LNX
158  53  (
159  53  (
160  43 RCL
161  19  19
162  55  ÷
163  02  2
164  54  )
165  22 INV
166  23 LNX
167  75  -
168  01  1
169  54  )
170  65  ×
171  43 RCL
172  04  04
173  55  ÷
174  43 RCL
175  00  00
176  65  ×
177  02  2
178  65  ×
179  43 RCL
180  18  18
181  95  =
182  42 STO
183  05  05
184  43 RCL
185  05  05
186  55  ÷
187  02  2
```

```
188  55  ÷
189  43 RCL
190  04  04
191  95  =
192  42 STO
193  06  06
194  87 IFF
195  01  01
196  54  )
197  58 FIX
198  01  01
199  43 RCL
200  04  04
201  91 R/S
202  43 RCL
203  05  05
204  91 R/S
205  43 RCL
206  06  06
207  91 R/S
208  76 LBL
209  54  )
210  58 FIX
211  01  01
212  43 RCL
213  02  02
214  91 R/S
215  43 RCL
216  05  05
217  91 R/S
218  43 RCL
219  06  06
220  91 R/S
221  76 LBL
222  34 √X
223  53  (
224  53  (
225  43 RCL
226  04  04
227  55  ÷
228  43 RCL
229  00  00
230  54  )
231  33 X²
232  75  -
233  01  1
234  54  )
235  34 √X
236  35 1/X
237  65  ×
238  02  2
239  65  ×
240  89  π
241  95  =
242  42 STO
243  19  19
244  53  (
245  43 RCL
246  19  19
247  22 INV
248  23 LNX
249  75  -
250  01  1
251  54  )
252  55  ÷
253  43 RCL
254  19  19
255  65  ×
256  43 RCL
257  12  12
258  95  =
259  42 STO
260  13  13
261  55  ÷
262  01  1
263  00  0
264  95  =
265  42 STO
266  02  02
267  61 GTO
268  23 LNX
269  76 LBL
270  52 EE
271  00  0
272  35 1/X
273  91 R/S
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The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 273 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

Field programs and research work units of the Station are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)