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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 pre-
liminary fire control planning and as a dispatching aid. Copies of
a program for the Texas Instruments Model 59 calculator[2] are avail-
able 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 con-
tainment 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 capa-
bilities (Barrows 1951).

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[2]The use of trade, firm, or corporation names in this publication is for the in-
formation and convenience of the reader. Such use does not constitute an official en-
dorsement 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.
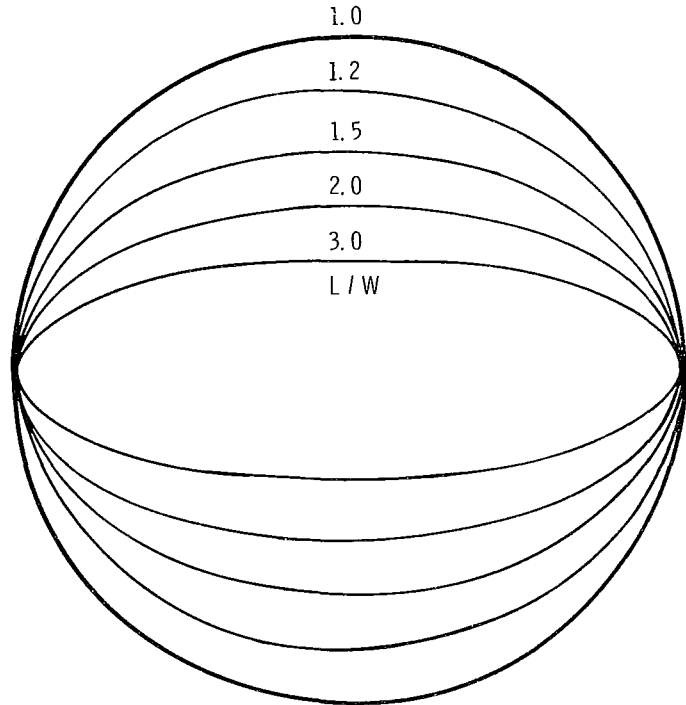
The last constraint is imposed simply to limit the scope of the cases considered.
Indirect attack tactics have been successfully treated (Albini and others 1978) so the
methodology could be extended if interest warrants it. That is, we could fit curves
to numerical results obtained using a well-placed 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 for-
mulated 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.

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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 (θ = 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

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

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

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

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.

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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.
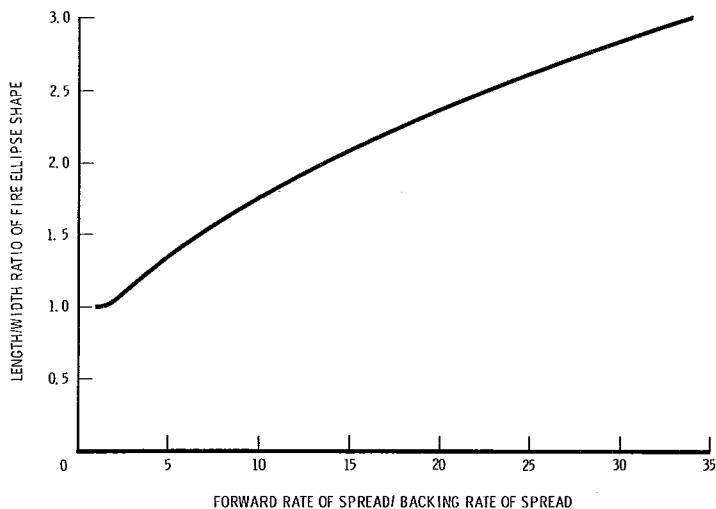
Figure 2.--Variation of length/width
ratio of elliptical fire shapes with
the ratio of forward rate of spread
to backing rate of spread.
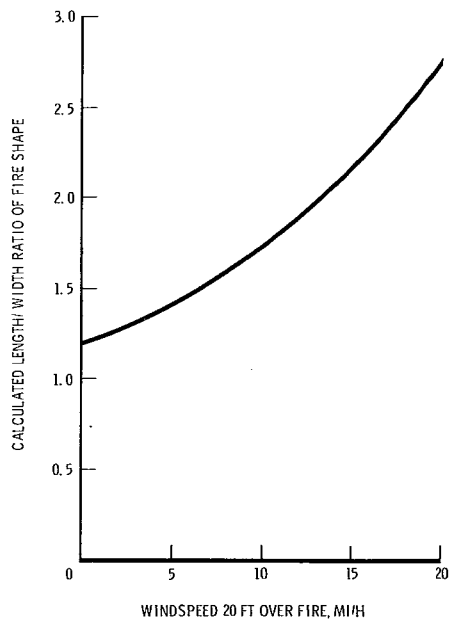
Figure 3.--Calculated length/
width ratios for fire shapes,
based on Hal Anderson's double-
ellipse equations.

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 ($1.2 \leq L/W \leq 3.0$)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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. $\begin{cases} \text{A':} & \text{Input } A_B \text{ (stop occurs if } A_B \le A_O) \\ & \text{-or-} \\ \text{B':} & \text{Input } V_L \text{ (stop occurs if } V_L \le V_F) \end{cases}$
6. Input L/W (stop occurs if out of range)

Computation Sequence

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

2. Calculate: ε, $r(0)$

3. <u>Case A</u>. Calculate and store A_{ij} coefficients

   <u>Option A'</u>. 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

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

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

   Calculate: A_B, P, Δt

   <u>Case B</u>. Calculate and store B_{ij} coefficients

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

   Calculate: V_L, P, Δt

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

   Calculate: A_B, P, Δt

4. Display results

   <u>Option A'</u>. V_L, P, Δt

   <u>Option B'</u>. 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. $\begin{cases} A': & \text{Input } A_B \text{ (stop occurs if } A_B \leq A_O\text{)} \\ & -or- \\ B': & \text{Input } V_L \text{ (stop occurs if } V_L \leq V_F\text{)} \end{cases}$

Computation Sequence

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

   Calculate: Z, A_B, P, Δt

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

   Calculate: Z, V_L, P, Δt

2. Display results:

   <u>Option A'</u>. V_L, P, Δt

   <u>Option B'</u>. 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: 2️⃣ 2nd 🅾️p 1️⃣ 7️⃣ .

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: 1️⃣ .
  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: 2️⃣ .
  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: 3️⃣ .
  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: 4️⃣ .
 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 (in-
     clude 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 .

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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] ,
     Mode of attack--rear: [B] }   continue

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

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

15

ELLIPTICAL
FIRE SHAPE

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

```
512  43 RCL    598  43 RCL    684  45 Yˣ     016  01  01    102  19  19    188  55  ÷
513  15  15    599  03  03    685  53  (     017  91 R/S     103  22 INV    189  43 RCL
514  54  )     600  65  ×     686  43 RCL    018  42 STO     104  23 LNX    190  04  04
515  65  ×     601  01  1     687  15  15    019  02  02     105  65  ×     191  95  =
516  43 RCL    602  93  .     688  55  ÷     020  22 INV     106  53  (     192  42 STO
517  18  18    603  05  5     689  53  (     021  77  GE     107  43 RCL    193  06  06
518  54  )     604  94 +/-    690  01  1     022  52  EE     108  19  19    194  87 IFF
519  33 X²     605  54  )     691  75  -     023  67  EQ     109  75  -     195  01  01
520  42 STO    606  22 INV    692  43 RCL    024  52  EE     110  01  1     196  54  )
521  13  13    607  23 LNX    693  14  14    025  61 GTO     111  54  )     197  58 FIX
522  55  ÷     608  65  ×     694  54  )     026  24  CE     112  85  +     198  01  01
523  01  1     609  03  3     695  54  )     027  76 LBL     113  01  1     199  43 RCL
524  00  0     610  93  .     696  45 Yˣ     028  17  B'     114  54  )     200  04  04
525  95  =     611  04  4     697  43 RCL    029  22 INV     115  55  ÷     201  91 R/S
526  42 STO    612  85  +     698  16  16    030  58 FIX     116  53  (     202  43 RCL
527  02  02    613  01  1     699  65  ×     031  86 STF     117  43 RCL    203  05  05
528  61 GTO    614  93  .     700  02  2     032  01  01     118  19  19    204  91 R/S
529  23 LNX    615  01  1     701  65  ×     033  47 CMS     119  22 INV    205  43 RCL
530  76 LBL    616  01  1     702  43 RCL    034  91 R/S     120  23 LNX    206  06  06
531  42 STO    617  02  2     703  18  18    035  42 STO     121  75  -     207  91 R/S
532  43 RCL    618  95  =     704  95  =     036  00  00     122  53  (     208  76 LBL
533  03  03    619  42 STO    705  42 STO    037  32 X:T     123  43 RCL    209  54  )
534  23 LNX    620  15  15    706  05  05    038  43 RCL    124  13  13    210  58 FIX
535  45 Yˣ     621  53  (     707  61 GTO    039  00  00    125  55  ÷     211  01  01
536  01  1     622  53  (     708  35 1/X    040  91 R/S     126  43 RCL    212  43 RCL
537  93  .     623  43 RCL    709  76 LBL    041  42 STO    127  12  12    213  02  02
538  00  0     624  03  03    710  54  )     042  01  1     128  54  )     214  91 R/S
539  01  1     625  65  ×     711  53  (     043  91 R/S     129  54  )     215  43 RCL
540  65  ×     626  02  2     712  43 RCL    044  42 STO     130  95  =     216  05  05
541  93  .     627  93  .     713  18  18    045  04  04     131  42 STO    217  91 R/S
542  09  9     628  03  3     714  55  ÷     046  22 INV     132  19  19    218  43 RCL
543  02  2     629  05  5     715  53  (     047  77  GE     133  97 DSZ    219  06  06
544  05  5     630  94 +/-    716  43 RCL    048  52  EE     134  06  06    220  91 R/S
545  85  +     631  54  )     717  14  14    049  67  EQ     135  22 INV    221  76 LBL
546  93  .     632  22 INV    718  45 Yˣ     050  52  EE     136  53  (     222  34 ΓX
547  08  8     633  23 LNX    719  43 RCL    051  76 LBL     137  53  (     223  53  (
548  02  2     634  65  ×     720  09  09    052  24  CE     138  02  2     224  53  (
549  05  5     635  02  2     721  65  ×     053  43 RCL    139  65  ×     225  43 RCL
550  95  =     636  93  .     722  43 RCL    054  01  01     140  89  ∏     226  04  04
551  42 STO    637  04  4     723  08  08    055  65  ×     141  55  ÷     227  55  ÷
552  07  07    638  06  6     724  85  +     056  01  1     142  43 RCL    228  43 RCL
553  43 RCL    639  94 +/-    725  43 RCL    057  00  0     143  19  19    229  00  00
554  03  03    640  85  +     726  07  07    058  95  =     144  54  )     230  54  )
555  45 Yˣ     641  93  .     727  54  )     059  42 STO    145  33 X²     231  33 X²
556  93  .     642  09  9     728  54  )     060  12  12    146  85  +     232  75  -
557  01  1     643  08  8     729  33 X²     061  43 RCL    147  01  1     233  01  1
558  02  2     644  08  8     730  42 STO    062  02  02     148  54  )     234  54  )
559  03  3     645  54  )     731  13  13    063  65  ×     149  34 ΓX     235  34 ΓX
560  04  4     646  35 1/X    732  55  ÷     064  01  1     150  65  ×     236  35 1/X
561  65  ×     647  42 STO    733  01  1     065  00  0     151  43 RCL    237  65  ×
562  05  5     648  16  16    734  00  0     066  95  =     152  00  00    238  02  2
563  93  .     649  87 IFF    735  95  =     067  42 STO    153  95  =     239  65  ×
564  09  9     650  02  02    736  42 STO    068  13  13     154  42 STO    240  89  ∏
565  06  6     651  54  )     737  02  02    069  53  (     155  04  04    241  95  =
566  94 +/-    652  53  (     738  61 GTO    070  43 RCL    156  76 LBL    242  42 STO
567  85  +     653  53  (     739  45 Yˣ     071  12  12    157  23 LNX    243  19  19
568  05  5     654  53  (     740  76 LBL    072  55  ÷     158  53  (     244  53  (
569  93  .     655  43 RCL    741  52  EE     073  89  ∏     159  53  (     245  43 RCL
570  01  1     656  18  18    742  00  0     074  54  )     160  43 RCL    246  19  19
571  95  =     657  55  ÷     743  35 1/X    075  34 ΓX     161  19  19    247  22 INV
572  42 STO    658  43 RCL    744  91 R/S    076  95  =     162  55  ÷     248  23 LNX
573  08  08    659  13  13    745  76 LBL    077  42 STO    163  02  2     249  75  -
574  43 RCL    660  34 ΓX     746  44 SUM    078  18  18     164  54  )     250  01  1
575  03  03    661  75  -     747  01  1     079  87 IFF    165  22 INV    251  54  )
576  23 LNX    662  43 RCL    748  94 +/-    080  01  01    166  23 LNX    252  55  ÷
577  45 Yˣ     663  07  07    749  34 ΓX     081  34 ΓX     167  75  -     253  43 RCL
578  93  .     664  54  )     750  91 R/S    082  53  (     168  01  1     254  19  19
579  00  0     665  55  ÷                    083  43 RCL    169  54  )     255  65  ×
580  09  9     666  43 RCL      CIRCULAR     084  13  13    170  65  ×     256  43 RCL
581  02  2     667  08  08    FIRE SHAPE     085  55  ÷     171  43 RCL    257  12  12
582  05  5     668  54  )     000  76 LBL    086  43 RCL    172  04  04    258  95  =
583  65  ×     669  22 INV    001  16  A'    087  12  12    173  55  ÷     259  42 STO
584  01  1     670  45 Yˣ     002  22 INV    088  54  )     174  43 RCL    260  13  13
585  93  .     671  43 RCL    003  58 FIX    089  23 LNX    175  00  00    261  55  ÷
586  09  9     672  09  09    004  22 INV    090  65  ×     176  65  ×     262  01  1
587  07  7     673  54  )     005  86 STF    091  02  2     177  02  2     263  00  0
588  02  2     674  42 STO    006  01  01    092  95  =     178  65  ×     264  95  =
589  75  -     675  14  14    007  47 CMS    093  42 STO    179  43 RCL    265  42 STO
590  93  .     676  35 1/X    008  91 R/S    094  19  19    180  18  18    266  02  02
591  08  8     677  65  ×     009  42 STO    095  06  6     181  95  =     267  61 GTO
592  01  1     678  43 RCL    010  00  00    096  42 STO    182  42 STO    268  23 LNX
593  03  3     679  00  00    011  91 R/S    097  06  06    183  05  05    269  76 LBL
594  95  =     680  95  =     012  42 STO    098  76 LBL    184  43 RCL    270  52  EE
595  42 STO    681  42 STO    013  01  01    099  22 INV    185  05  05    271  00  0
596  09  09    682  04  04    014  32 X:T    100  53  (     186  55  ÷     272  35 1/X
597  53  (     683  76 LBL    015  43 RCL    101  43 RCL    187  02  2     273  91 R/S
```

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)