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WEIGHT REDUCTION STUDY ON THE 20MM, M61A1, VULCAN GUN BARREL

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FINAL REPORT

U.S. ARMY ARMAMENT COMMAND

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5. Wall Ratios

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A thermal analysis of the M61A1 VULCAN gun barrel was performed. This analysis included the calculation of bore boundary conditions by methods previously developed by the Research Directorate and the application of these boundary conditions to an outer barrel profile analysis. Pressure stress analyses were also performed. The final results are proposed outer barrel profiles for particular performance requirements.

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INTRODUCTION

Determination of the feasibility of a reduced barrel weight on the basis of thermal considerations requires experimental data. As a minimum, the outer barrel temperatures at various axial locations and the pressure versus time and distance data are required for the particular gun. Outside wall temperatures and pressure data[2] for the 20mm M61A1 barrel were obtained.

DISCUSSION AND ANALYSIS

The transient temperature data given above included outside temperatures at 5 axial locations - 5, 10, 18, 35.5, and 48 inches (measured from the breech end). The firing rate was 4000 spm for all 6 barrels or 667 spm for each barrel, 1050 total rounds fired or 175 rounds fired for each barrel. As a result of the application of both the technique and the computer programs developed by the Research Directorate[3] to the experimental temperature data obtained, effective propellant gas temperatures $\overline{T}_g$ and effective gas convection coefficients $\overline{h}_g$ were calculated for each of the above-mentioned axial locations. Good correlation between these experimental temperature curves and those curves obtained by utilization of the effective values ($\overline{h}_g$ and $\overline{T}_g$) was obtained, as shown in Figures 1-5.

Once the effective gas temperature and gas convection coefficient are known, any combination of firing rate and rounds fired can be simulated by use of the available computer programs[3]. In this study, the firing schedule established to satisfy the design criteria specified 540 rounds at a rate of 6000 spm or, 90 rounds at a rate of 1000 spm for each barrel. Since this firing rate is different from that of the experimental rate, the effective convection coefficients for the 1000 spm rate were adjusted accordingly. Since experimental results have shown that the convection coefficient is approximately linearly dependent upon the firing rate, the following relationship holds:

$$\overline{h}_{simulated} = \frac{\text{simulated rate}}{\text{experimental rate}} (\overline{h}_{experimental})$$

The effective gas temperature value remains fairly constant with change in firing rate for any particular axial location. Knowing the bore boundary values for the convection coefficient and for the gas temperature at all 5 axial locations provides the means to perform a parametric study of varying wall thickness at each axial location.

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[1]Adams, D. E., et. al., "Design Studies of the XM-140 Barrel", Cornell Aeronautical Laboratory, Inc., Feb. 1967.

[2]"20mm Barrel Erosion", Contract F09603-73-C-3263, TASK I, General Electric Co., Armament Systems Department, Burlington, Vermont.

[3]Benzkofer, P., "A theoretical and Experimental Thermal Analysis to Determine Wall Ratios for a 30mm Tactical Barrel", Technical Report R-TR-75-023.

The results of such a study for the 20mm, M61A1 Vulcan barrel with various wall ratios are given in Figures 6-25. The firing schedule, axial locations, $\bar{h}_g$, $\bar{T}_g$, inner radius, and various outer radii considered are given on the curves. For those figures which show temperature in ^oF versus time in seconds, note that temperature values may be either external, average or bore. Also, several figures give temperature versus distance from the bore. These temperatures are the final values at the end of the firing cycle. The present configuration of the M61A1 barrel is given in Figure 26.

Another aspect to consider is that of the stresses to which the gun barrel will be subjected. These stresses are of two types, thermal and pressure. One method or approach is that of combining these two stresses into a total equivalent stress. In the initial firing of a gun barrel, a large temperature difference exists across the barrel wall that induces large, negative, tangential thermal stresses which counteract the pressure stresses. Also, the timing of the peak thermal pulse is out of phase with the peak pressure pulse. One could conclude then, that by reduction of the wall thickness, the total equivalent stresses would be lower. This argument, however, does not hold in the situation in which heating is followed by cooling by which the large, negative, tangential thermal stresses increase in a positive sense because of lowered temperature gradients across the wall. Since the breech is subjected to considerably higher pressure, a safe method is that of considering a total equivalent stress on the basis of pressure and axial stress only. The resulting stresses[4] for a thick-walled cylinder due to the internal pressure are given by Lamé's solution

$$\sigma_r = \frac{r_i^2 P_i}{r_o^2 - r_i^2} \left(1 - \frac{r_o^2}{r^2}\right) \qquad (1)$$

and

$$\sigma_t = \frac{r_i^2 P_i}{r_o^2 - r_i^2} \left(1 + \frac{r_o^2}{r^2}\right) \qquad (2)$$

[4] Popov, E. P., "Mechanics of Materials", Prentice Hall, Inc., New Jersey, 1952.

Since $r_o^2/r^2 \geq 1$, σ_r is always a compressive stress and is maximum at $r = r_i$. Similarly, σ_t is always a tensile stress, and its maximum value occurs at $r = r_i$. Using the maximum shear theory of failure[4],

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} \qquad (3)$$

Because σ_t and σ_r are maximum principal stresses at the inner cylinder surface,

$$\tau_{max} = \frac{(\sigma_t)\ max - (\sigma_r)\ max}{2} = \frac{P_i\ R_o^2}{r_o^2 - r_i^2} \qquad (4)$$

Since the yield stress $Y = 2\ \tau_{max}$, and if one uses Tresca's yield condition[4] $(Y = \sigma_t - \sigma_r)$, then

$$Y = 2\ P_i/[1 - (r_i/r_o)^2] \qquad (5)$$

Now, the elastic yield stress at the bore surface can be calculated for any outer radius. A typical set of pressure data[5] for the M61A1 barrel is given in Table 1 and yield strength in KSI versus temperature in °F for CR-MO-V is given in Figure 27. Consider the 5 inch axial location as an example. This section is subjected to the maximum pressure of 55000 psi. Substituting this pressure value into Equation 5, one obtains:

$$Y = 2\ (55,000)/[1 - \left(\frac{.3937}{.78}\right)^2]$$

$$Y = 147,605\ psi$$

A comparison of this value against the dynamic yield strength values in Figure 27 shows that the elastic yield strength has been exceeded at the bore surface; that is, the bore region is acting in the plastic regime. With the use of a computer program[5] developed by the Research Directorate, total equivalent stresses for a radial cross-section of a gun barrel can be calculated, with a minor change to eliminate the thermal stress terms.

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[4]Popov, E. P., "Mechanics of Materials", Prentice Hall, Incorporated New Jersey, 1952.

[5]Thomsen, D. M., et. al., "Gun Barrel Thermal Structural Model", Progress Report, X. O. 512211 - 5007.

Now the depth of the plastic deformation into the radial section can be determined. Sound design practice allows for a small amount of plastic deformation. Therefore, one can vary the outer radius until approximately 10 per cent of the wall thickness is plastic for any particular temperature level desired from Figure 27. This temperature level is that temperature calculated for the prescribed firing schedule and outer radius in the parametric variation study, the results of which are given in Figures 6-25.

In summary, one can select an axial location, then use Equation 5 to determine the yield strength for the present outer radius. On the basis of this yield value, one can then determine whether the temperature value from Figure 27 is within the temperature range for the required firing schedule. The results for all axial locations are tabulated in Table 2. Further discussion of this data is presented later in this report.

A series of failure tests on a special reinforced, M197, 3-barrel weapon were conducted[2] by General Electric in 1973. The actual barrel configuration was identical to that of the VULCAN barrel. Characteristically, the new barrels failed near the muzzle end, and the worn barrels, at the breech end. Since temperature data were not recorded during the tests, data on the temperature levels attained are unavailable. However, the firing rate and the number of rounds to failure are known. Since the barrel configuration is identical to the M61A1, values calculated for $\bar{T}_g$ and h_g in a previous section can be used to determine the temperature reached at failure.

Two tests that resulted in muzzle end failure were analyzed. The firing rates were 1333 spm per barrel and 2000 spm per barrel, and the rounds fired per barrel were 267 and 290, respectively. With the use of the computer programs referenced in an earlier section, the outside and average barrel temperatures were determined to be in the range of 1350^{o} - 1400^{o}F. These temperature levels reflect large thermal stresses and as a consequence, a weakening of the barrel occurs that causes muzzle end droop and subsequent projectile exit through the side of the barrel. Clearly, the firing schedule was too severe for the barrel to sustain. As for the breech end problems, a different type of failure or combination of types of failures occurred. With the same procedure to determine barrel temperatures as used at the muzzle end, average and outside temperatures were found to be in the 800^{o}F - 1000^{o}F range. Bore inspection of the barrels showed radial cracking in the grooves and erosion measurements of .060 inch. Since this is the high-pressure region, pressure stresses are distinctly significant, and are most likely the cause of failure.

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[2]"20mm Barrel Erosion", Contract F09603-73-C-3263, Task I, General Electric Company, Armament Systems Department, Burlington, Vermont.

CONCLUSIONS AND RECOMMENDATIONS

An increase in material on the tapered down-section near the breech (Figure 26) would increase the factor of safety to avoid barrel rupture if the recommended firing schedule is exceeded. A rough estimate of plastic deformation for the 650°F - 1000°F operating temperatures is 10-16 per cent, as shown in Table 2. An increase of .2 to .4 inch to the diameter would substantially decrease the plastic penetration. This recommendation was also proposed by General Electric[2] in their erosion studies of the M61A1.

Generally, pressure stresses do not cause problems involving the middle-to-muzzle end of the barrel, but thermal stresses are significant. Since single-shot heat flux data are unavailable for the 20mm, M61A1 gun barrel, total equivalent stresses to include thermal stresses cannot be calculated. However, observing the temperature levels attained in the failure tests performed by General Electric, one notes that the firing schedule prescribed by SARRI-LW for this study is much less severe. On the basis of previous experience, one also notes that the temperature levels attained at the breech end for the present M61A1 barrel are within safe limits, if the firing schedule proposed is followed. Caution should be taken, however, when the barrel is designed for the middle-to-muzzle end on the basis of values from Table 2. This tabulation is only a pressure analysis and is meant to point out that pressure stresses are not of paramount importance in the middle-to-muzzle locations. Temperatures of 1300°F - 1400°F are within the elastic limit, as shown in Table 2. These temperature levels are high for CR-MO-V steel, as the failure tests previously discussed indicates.

Thus, several recommendations can be made. On the assumption that the firing schedule prescribed is realistic, then the present design can be changed to reduce barrel weight. A proposed barrel that reduces the existing weight by 14 per cent or by 2.5 pounds is shown in Figure 28. The temperature and pressure stress results for this design are still conservative; but, hardware requirements necessarily limit the reduction of wall ratios at certain points on the barrel. The tapered section at the 3.215 to the 6 inch region adds .4 pound to the barrel weight, but it provides a better margin of safety against breech rupture. The other changes in this barrel decrease barrel weight from the existing profile. The built-up section from 6 to 9.75 inches in the existing profile has been eliminated in this lightweight concept. If the lightweight concept is not adopted, then the present built-up section in the 6 to 10 inch area could be retained, and the reduction in total barrel weight would still be 1.5 pounds.

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[2] "20mm Barrel Erosion", Contract F09603-73-C-3263, Task I, General Electric Company, Armament Systems Dept., Burlington, Vermont.

Since the bore boundary conditions for the failure tests have been calculated for all 5 axial locations, upper limits for safe operating barrel temperatures can be calculated for more severe firing schedules. If complete redesign of the barrel is desired, then an optimum barrel profile could be defined prior to the design of the firing fixtures and hardware requirements. Additional constraints on design recommendations that include barrel material, propellant type, environmental conditions, and external loading (due to the motion of the aircraft) need to be considered prior to final design.

TABLE I

Time (ms)	Travel (in)	Pressure (psi)
0.00	0.0	0.
0.42	0.001	9100.
0.82	0.780	48000.
0.92	1.600	54500.
0.98	2.230	55000.
1.02	2.820	54180.
1.22	6.420	43200.
1.72	20.300	20100.
2.32	41.900	9650.
2.70	56.900	6760.

TABLE II

	Axial Locations (in)								
	5			10		18		35.5	48
r_o (in)	.78	.88	.98	.78	.694	.78	.694	.55	.55
P (psi)	55,000	55,000	55,000	43,200	43,200	30,156	30,156	10,000	9,000
Y (psi)	147,605	137,526	131,169	115,937	127,469	80,930	88,981	41,080	36,972
T (°F)	100	200	300	600	400	1300	1250	1400	1400
σ(psi) at bore	133,000	124,000	118,000	110,000	121,000	100% Elastic	100% Elastic	100% Elastic	100% Elastic
% plastic @650°F	10	6	2.5	100% Elastic	5	100% Elastic	100% Elastic	100% Elastic	100% Elastic
% plastic @ 1,000°F	16	8	3	100% Elastic	9	100% Elastic	100% Elastic	100% Elastic	100% Elastic

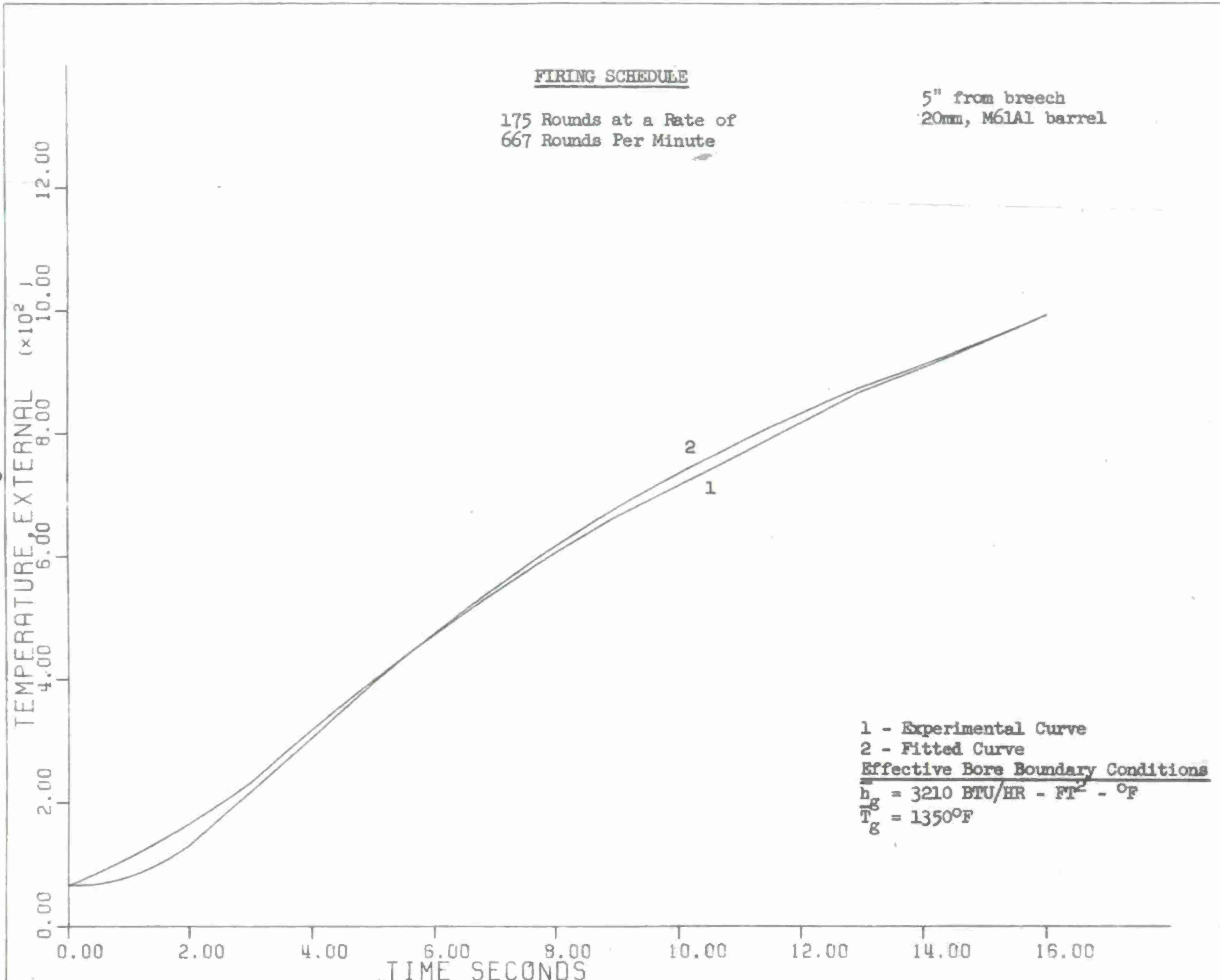

FIRING SCHEDULE
175 Rounds at a Rate of
667 Rounds Per Minute
5" from breech
20mm, M61A1 barrel
TEMPERATURE, EXTERNAL (×10²)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
TIME SECONDS
14.00
16.00
2
1
1 - Experimental Curve
2 - Fitted Curve
Effective Bore Boundary Conditions
$\bar{h}_g$ = 3210 BTU/HR - FT² - °F
$\bar{T}_g$ = 1350°F

FIGURE 1

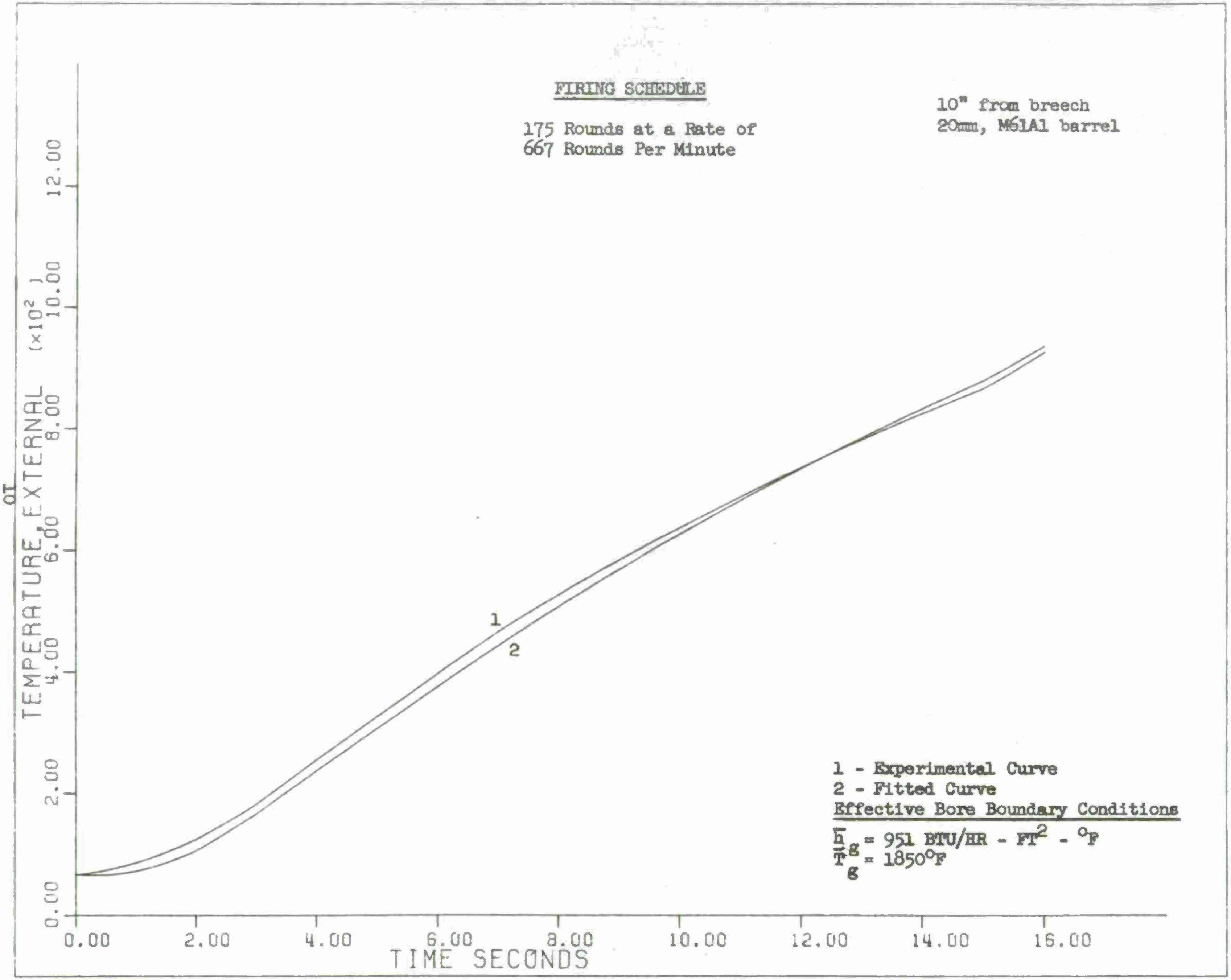

FIRING SCHEDULE
175 Rounds at a Rate of
667 Rounds Per Minute
10" from breech
20mm, M61A1 barrel
TEMPERATURE, EXTERNAL (×10²)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
TIME SECONDS
1
2
1 - Experimental Curve
2 - Fitted Curve
Effective Bore Boundary Conditions
h̄g = 951 BTU/HR - FT² - °F
T̄g = 1850°F

FIGURE 2

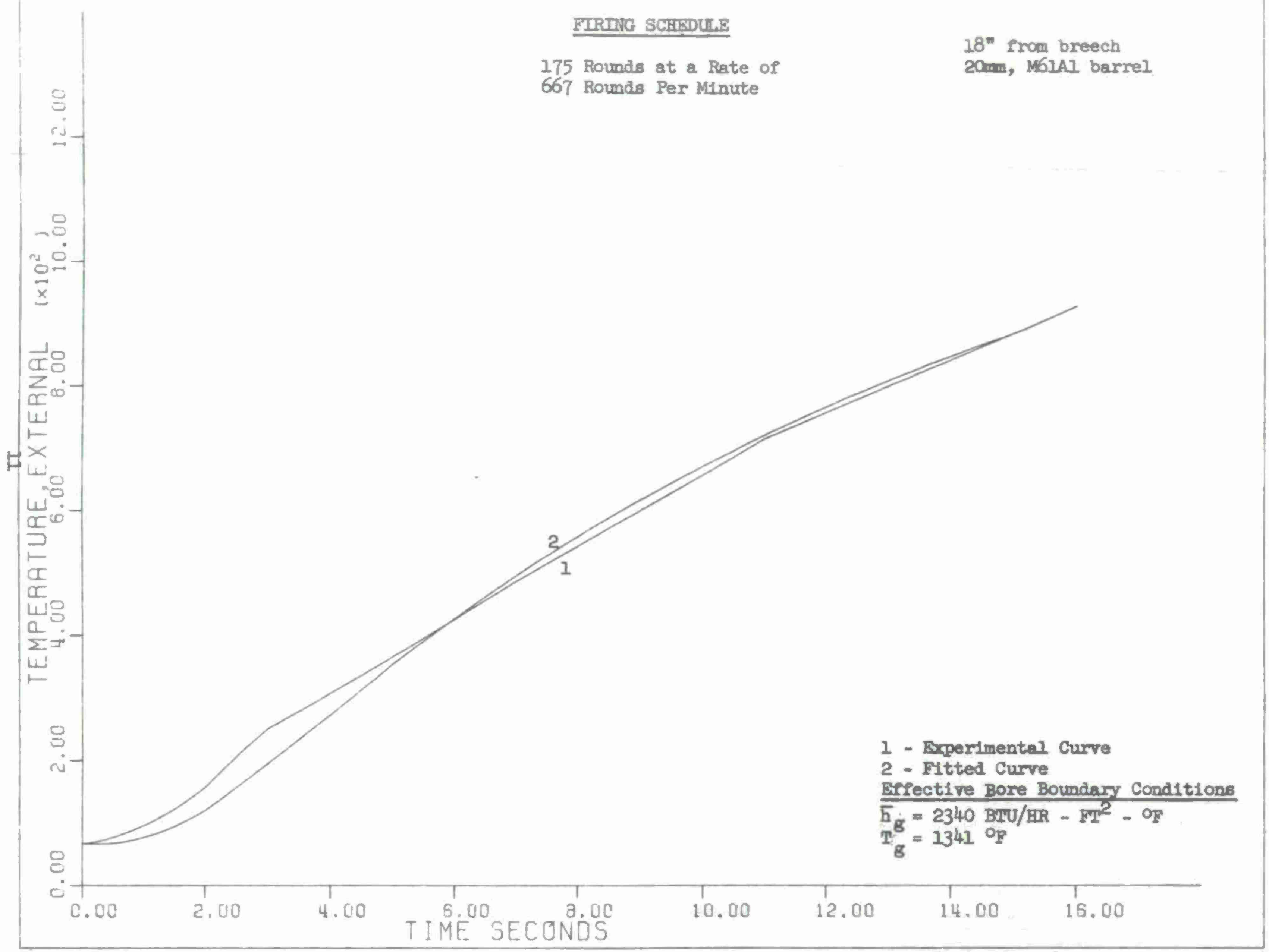

FIRING SCHEDULE
175 Rounds at a Rate of
667 Rounds Per Minute
18" from breech
20mm, M61A1 barrel
TEMPERATURE, EXTERNAL (×10²)
T1
TIME SECONDS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
1
2
1 - Experimental Curve
2 - Fitted Curve
Effective Bore Boundary Conditions
$\bar{h}_g$ = 2340 BTU/HR - FT^2 - °F
T_g = 1341 °F

FIGURE 3

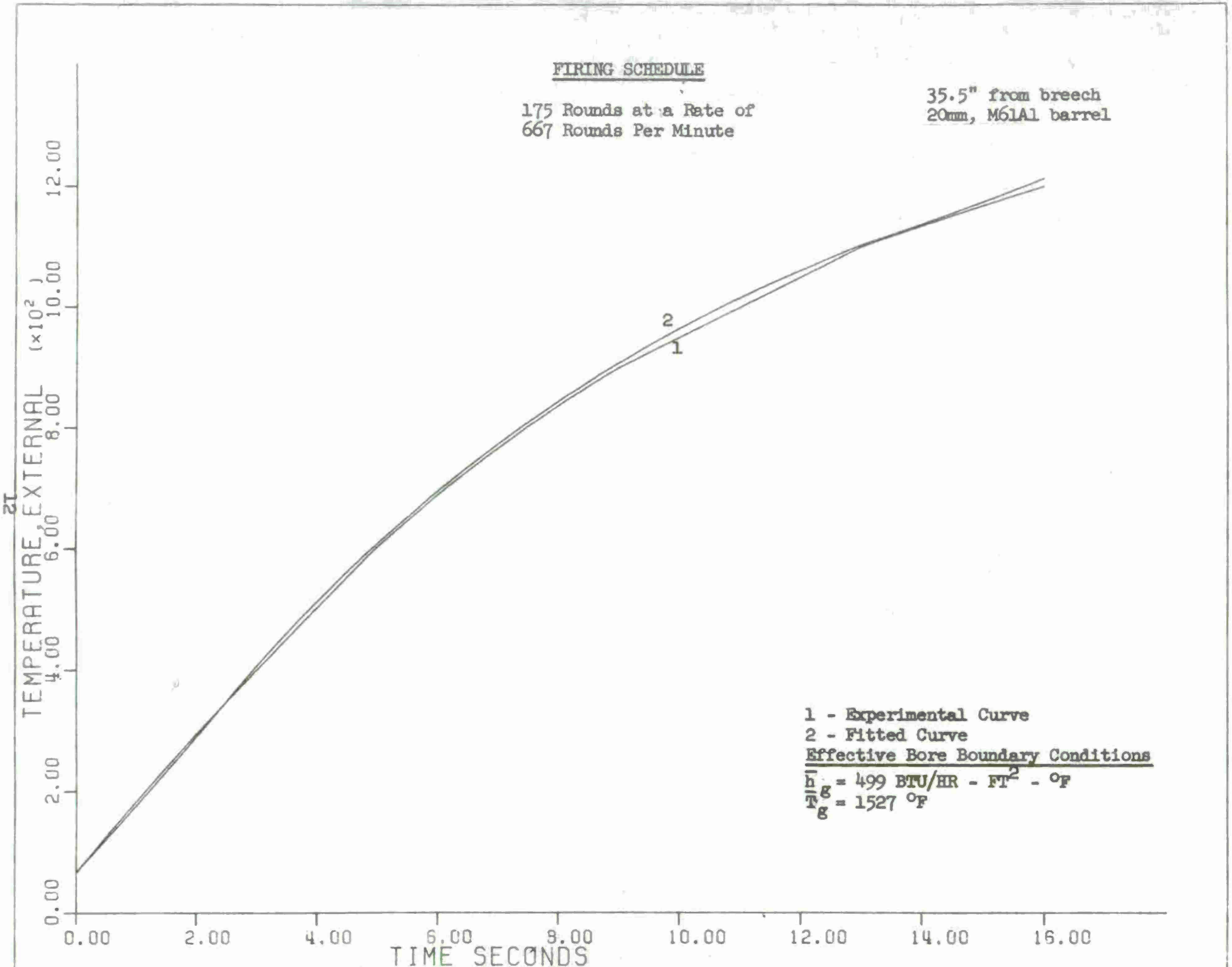

FIRING SCHEDULE
175 Rounds at a Rate of
667 Rounds Per Minute
35.5" from breech
20mm, M61A1 barrel
TEMPERATURE, EXTERNAL (×10²)
TIME SECONDS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
1
2
1 - Experimental Curve
2 - Fitted Curve
Effective Bore Boundary Conditions
$\bar{h}_g$ = 499 BTU/HR - FT^2 - °F
$\bar{T}_g$ = 1527 °F

FIGURE 4

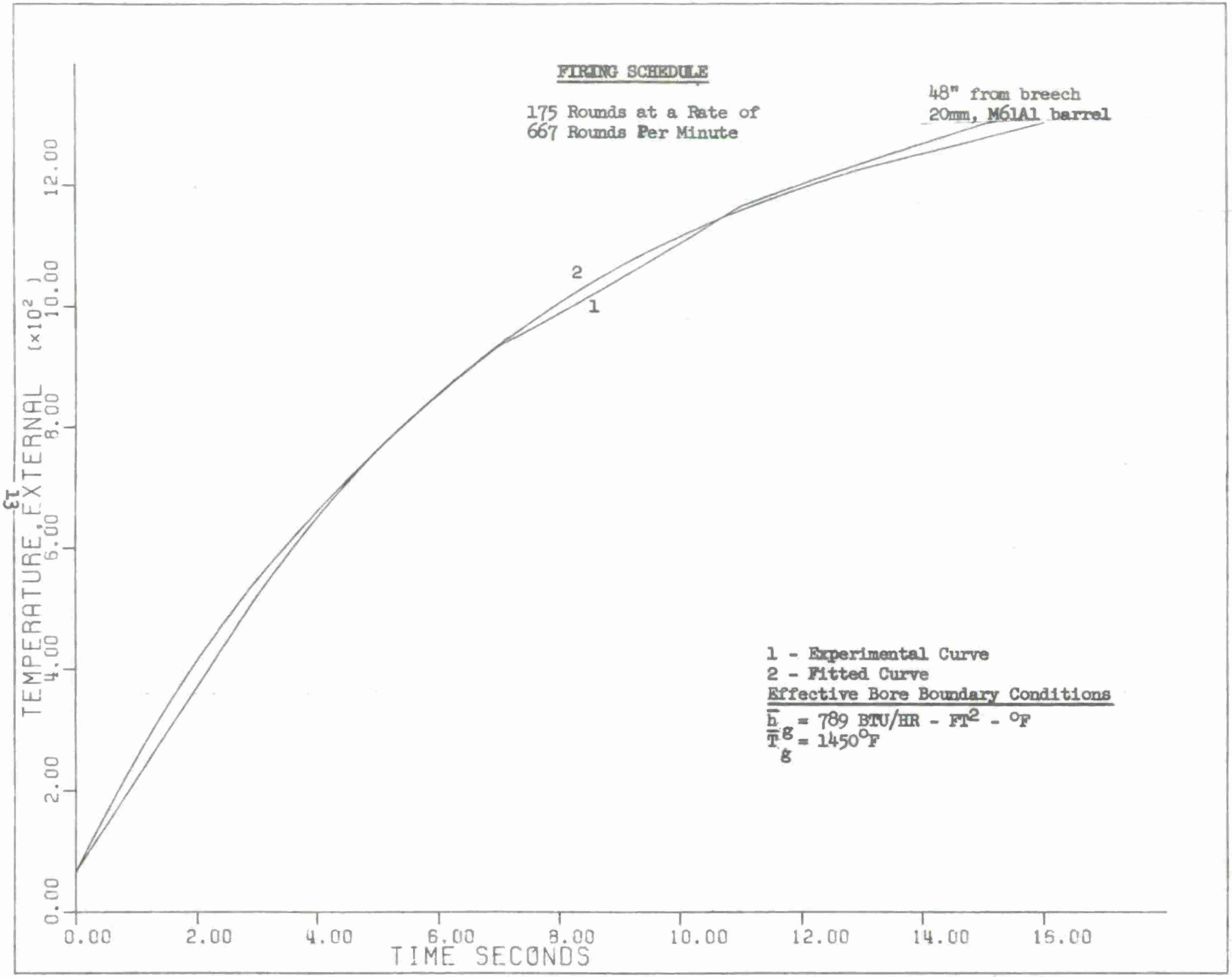

FIRING SCHEDULE
175 Rounds at a Rate of
667 Rounds Per Minute
48" from breech
20mm, M61A1 barrel
2
1
1 - Experimental Curve
2 - Fitted Curve
Effective Bore Boundary Conditions
$\bar{h}_g$ = 789 BTU/HR - FT^2 - ^{o}F
$\bar{T}_g$ = 1450^{o}F
TEMPERATURE, EXTERNAL (x10^2)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
TIME SECONDS

FIGURE 5

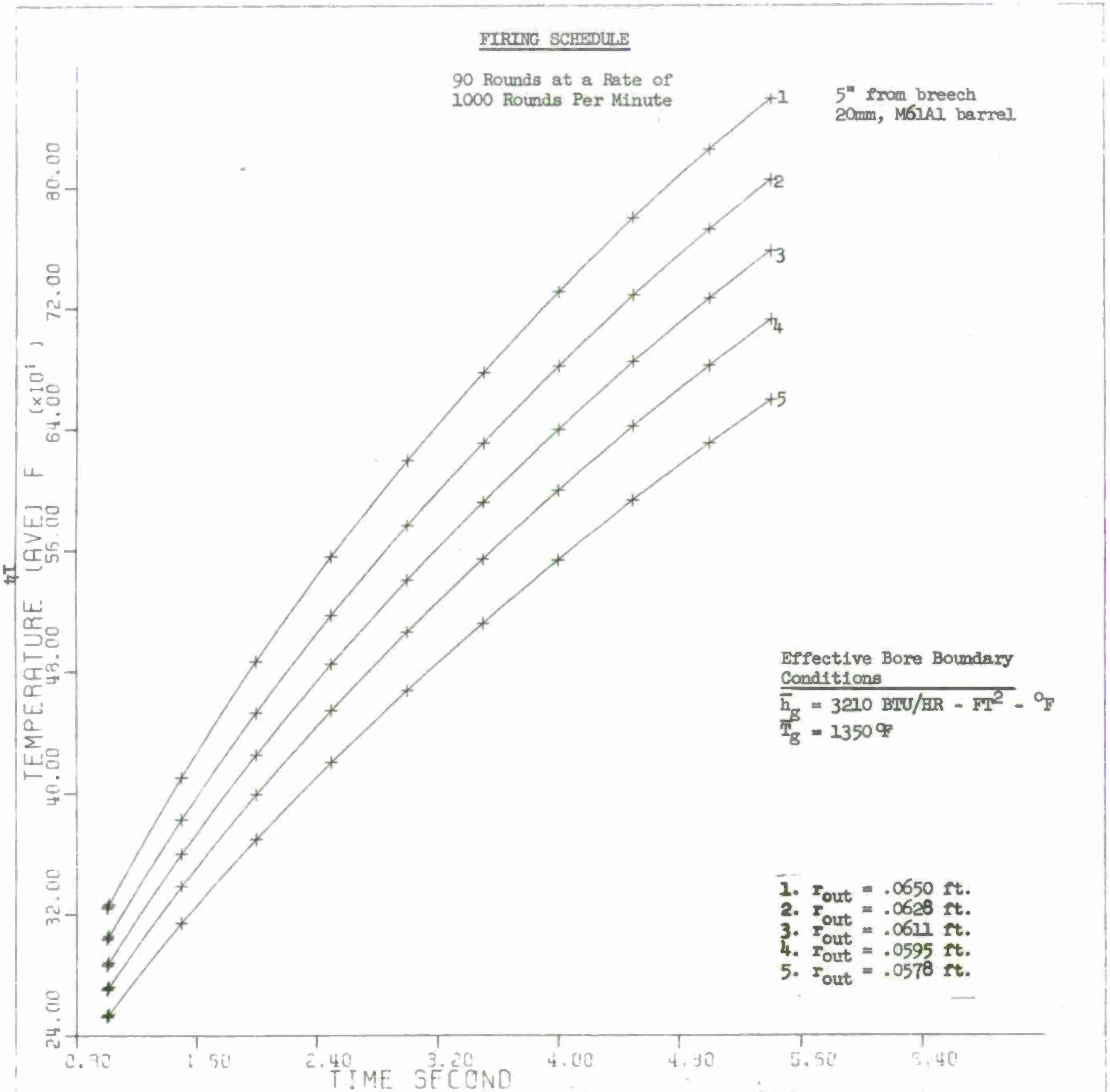
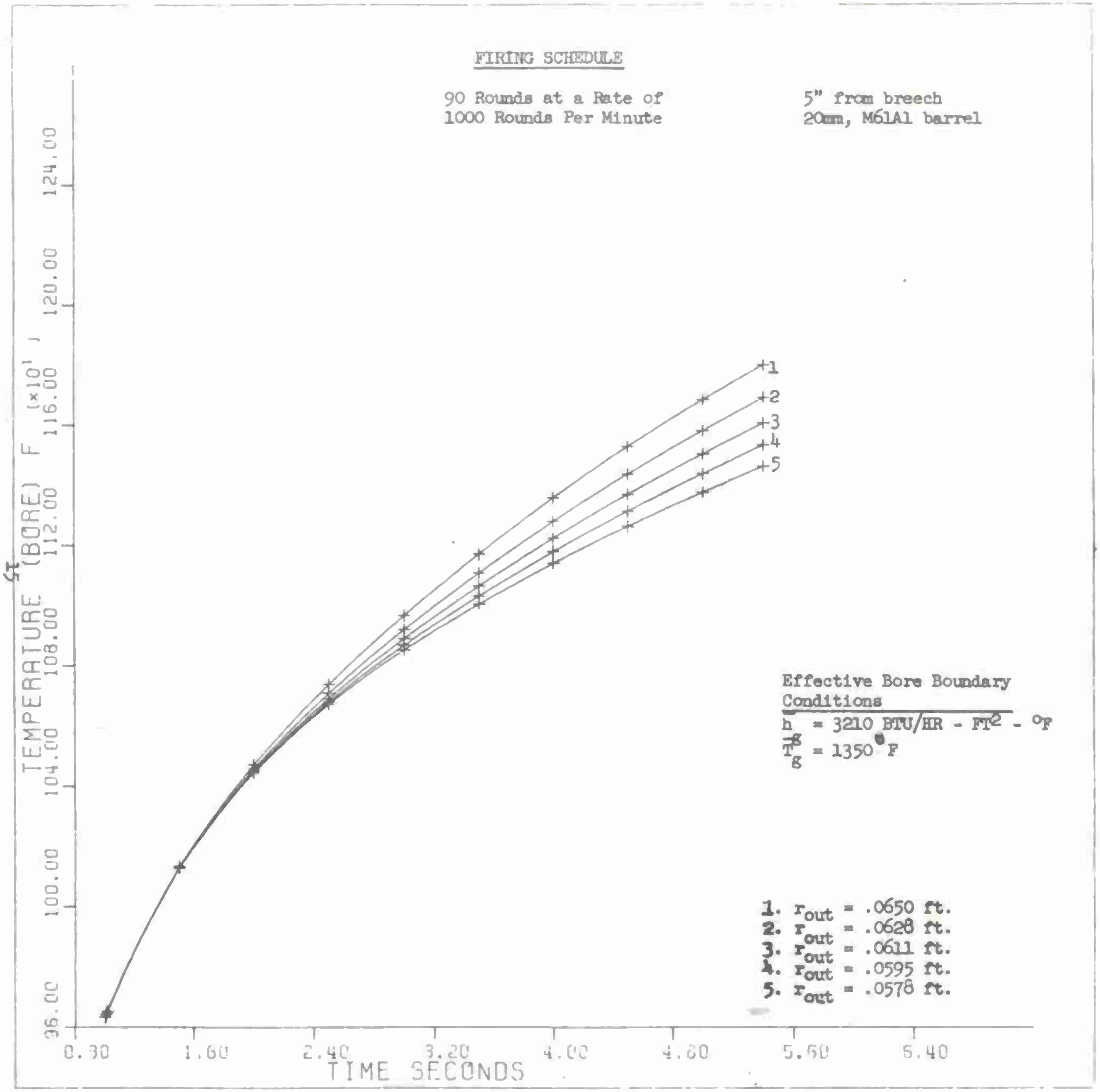
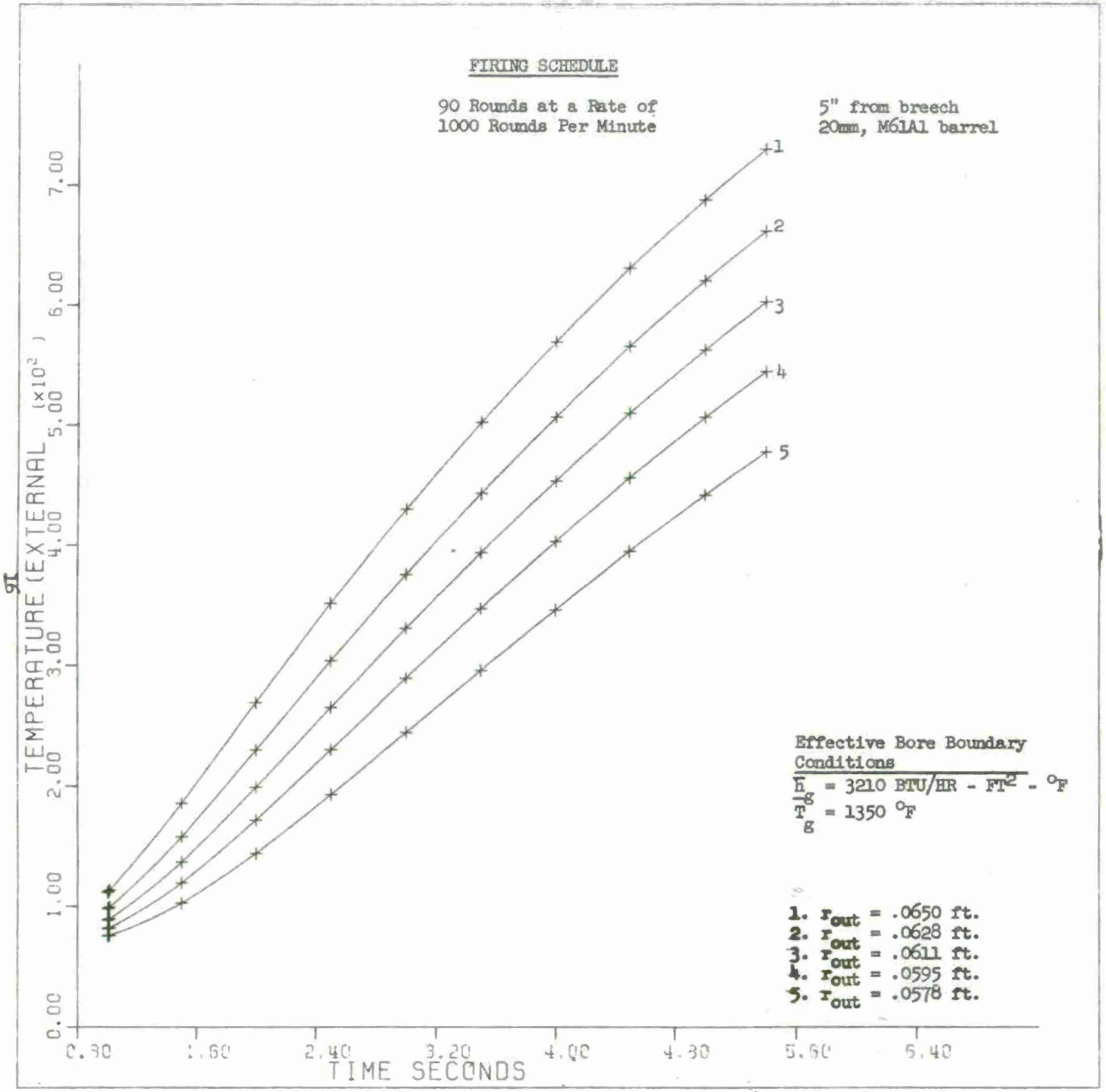

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
5" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
$\overline{h}_g$ = 3210 BTU/HR - FT^2 - °F
$\overline{T}_g$ = 1350 °F
1. r_{out} = .0650 ft.
2. r_{out} = .0628 ft.
3. r_{out} = .0611 ft.
4. r_{out} = .0595 ft.
5. r_{out} = .0578 ft.
TEMPERATURE (AVE) F (×10^1)
TIME SECOND
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5

FIGURE 6



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
5" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
h = 3210 BTU/HR - FT2 - oF
Tg = 1350 F
1. rout = .0650 ft.
2. rout = .0628 ft.
3. rout = .0611 ft.
4. rout = .0595 ft.
5. rout = .0578 ft.
TEMPERATURE (BORE) F (x10')
TIME SECONDS

FIGURE 7



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
5" from breech
20mm, M61A1 barrel
TEMPERATURE (EXTERNAL (x10²)
°F
TIME SECONDS
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
$\overline{h}_g$ = 3210 BTU/HR - FT² - °F
$\overline{T}_g$ = 1350 °F
1. r_{out} = .0650 ft.
2. r_{out} = .0628 ft.
3. r_{out} = .0611 ft.
4. r_{out} = .0595 ft.
5. r_{out} = .0578 ft.

FIGURE 8

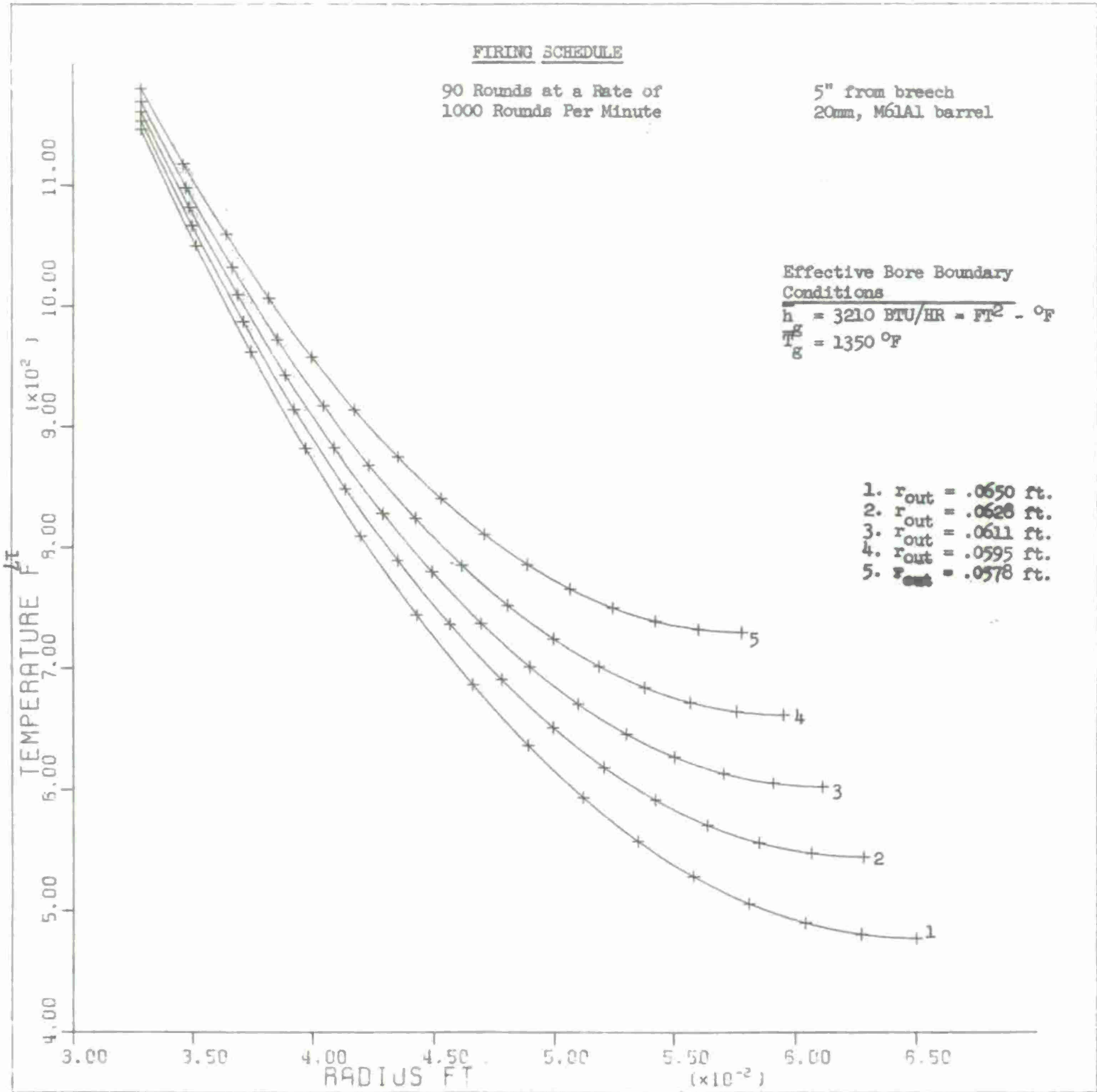
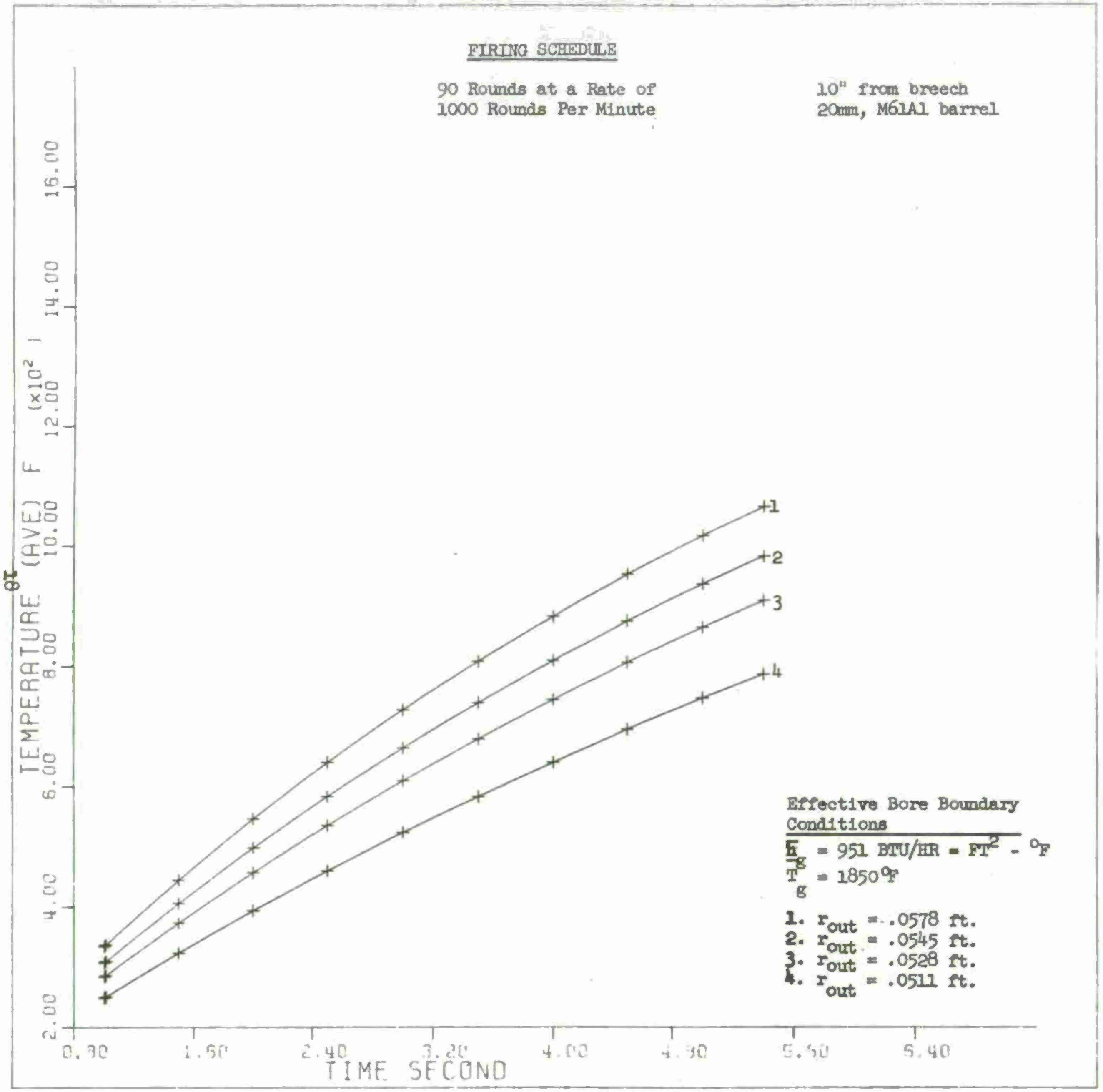
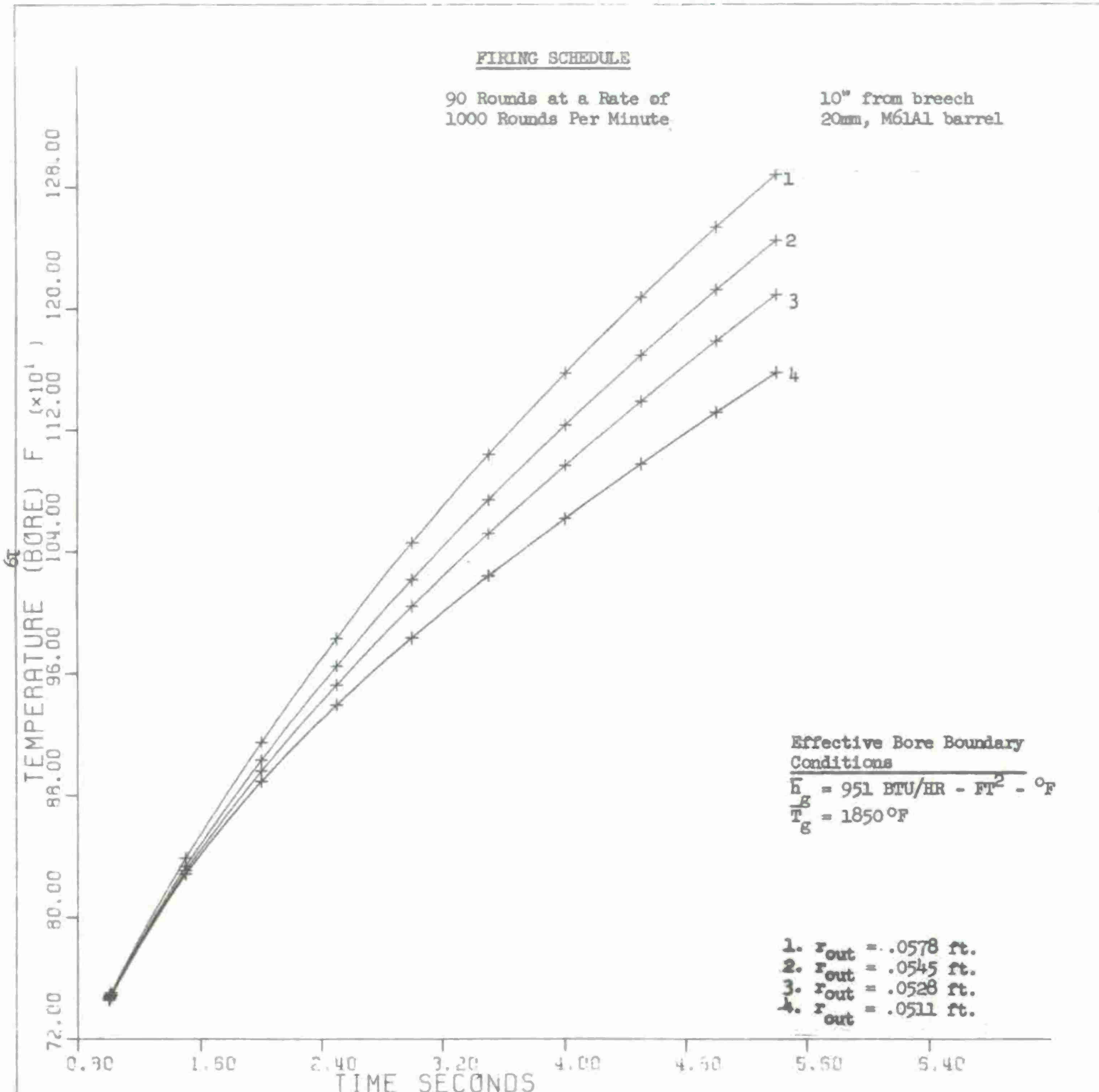

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
5" from breech
20mm, M61A1 barrel
Effective Bore Boundary
Conditions
h = 3210 BTU/HR - FT2 - °F
Tg = 1350 °F
1. rout = .0650 ft.
2. rout = .0628 ft.
3. rout = .0611 ft.
4. rout = .0595 ft.
5. rout = .0578 ft.
TEMPERATURE F (×10²)
RADIUS FT (×10⁻²)
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
3.00
3.50
4.00
4.50
5.00
5.50
6.00
6.50
1
2
3
4
5

FIGURE 9



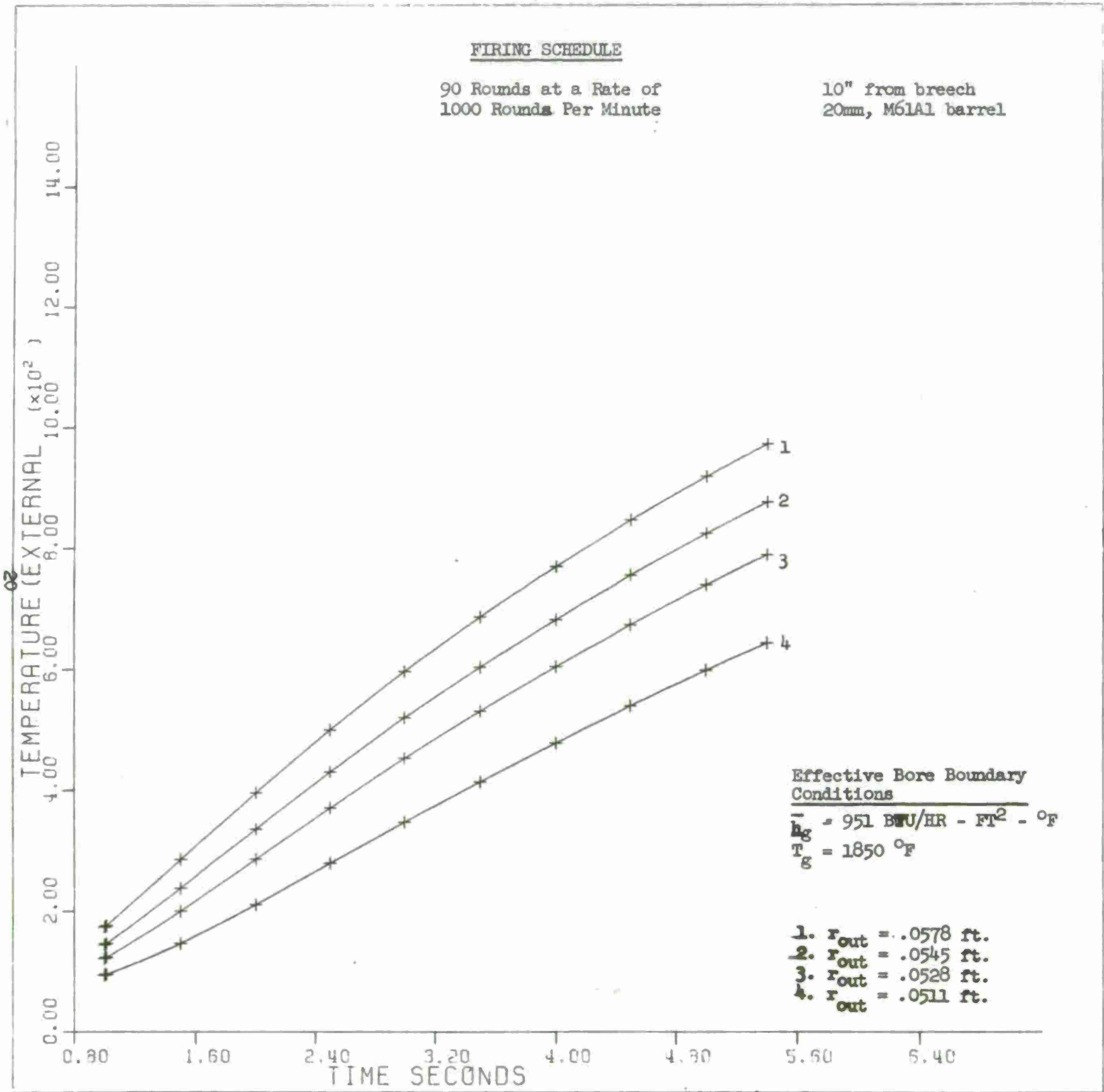
FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
10" from breech
20mm, M61A1 barrel
TEMPERATURE (AVE) F (×10²)
TIME SECOND
Effective Bore Boundary Conditions
$\bar{h}_g$ = 951 BTU/HR - FT² - °F
$\bar{T}_g$ = 1850°F
1. r_{out} = .0578 ft.
2. r_{out} = .0545 ft.
3. r_{out} = .0528 ft.
4. r_{out} = .0511 ft.

FIGURE 10



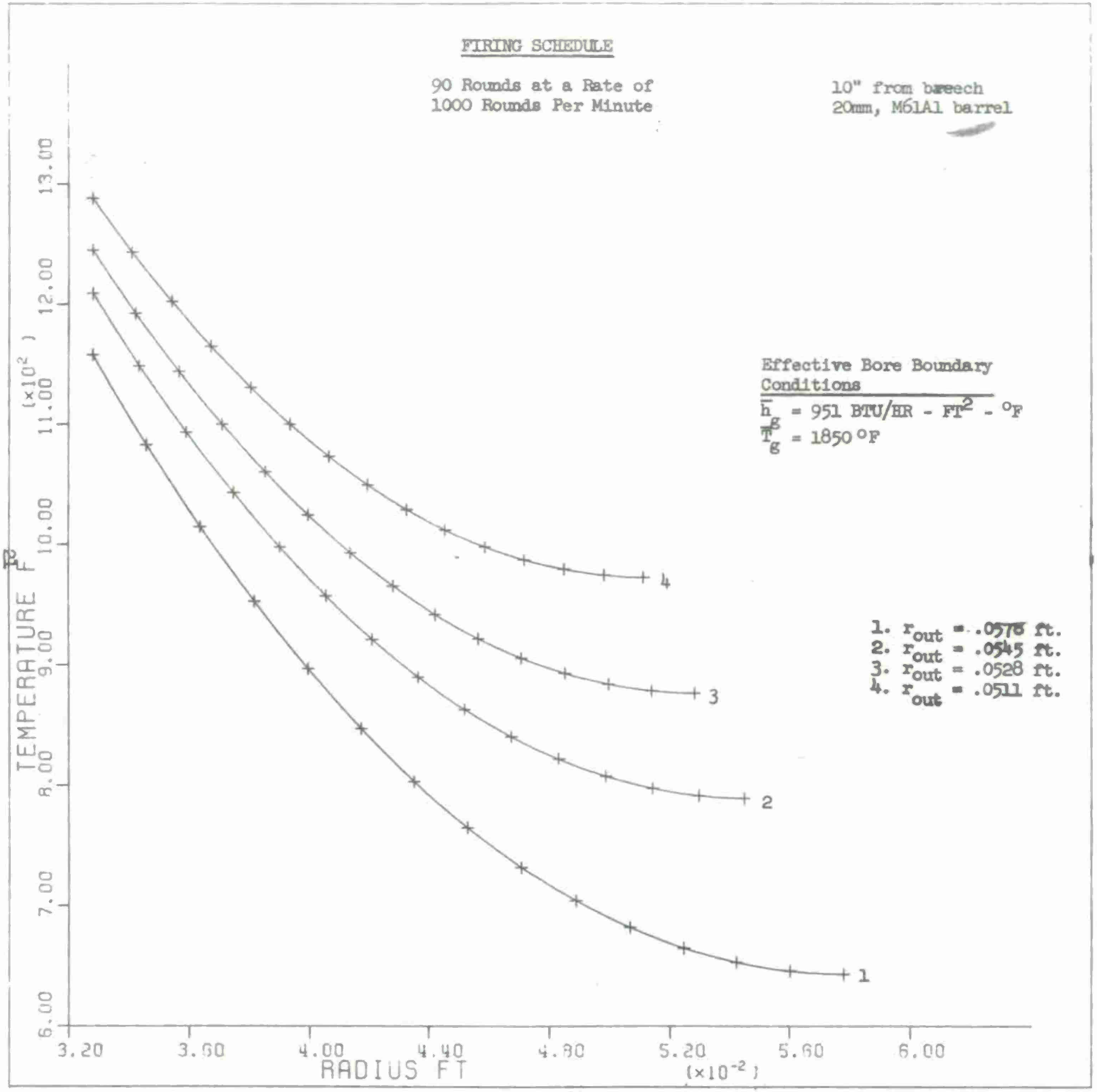
FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
10" from breech
20mm, M61A1 barrel
TEMPERATURE (BORE) F (×10¹)
TIME SECONDS
Effective Bore Boundary Conditions
$\overline{h}_g$ = 951 BTU/HR - FT² - °F
$\overline{T}_g$ = 1850 °F
1. r_{out} = .0578 ft.
2. r_{out} = .0545 ft.
3. r_{out} = .0528 ft.
4. r_{out} = .0511 ft.

FIGURE 11



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
10" from breech
20mm, M61A1 barrel
TEMPERATURE (EXTERNAL (x10²)
TIME SECONDS
Effective Bore Boundary Conditions
h̄g = 951 BTU/HR - FT² - °F
Tg = 1850 °F
1. rout = .0578 ft.
2. rout = .0545 ft.
3. rout = .0528 ft.
4. rout = .0511 ft.

FIGURE 12



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
10" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
$\overline{h}_g$ = 951 BTU/HR - FT^2 - °F
$\overline{T}_g$ = 1850 °F
1. r_{out} = .0578 ft.
2. r_{out} = .0545 ft.
3. r_{out} = .0528 ft.
4. r_{out} = .0511 ft.
TEMPERATURE F
(×10²)
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
RADIUS FT
(×10⁻²)
3.20
3.60
4.00
4.40
4.80
5.20
5.60
6.00
1
2
3
4

FIGURE 13

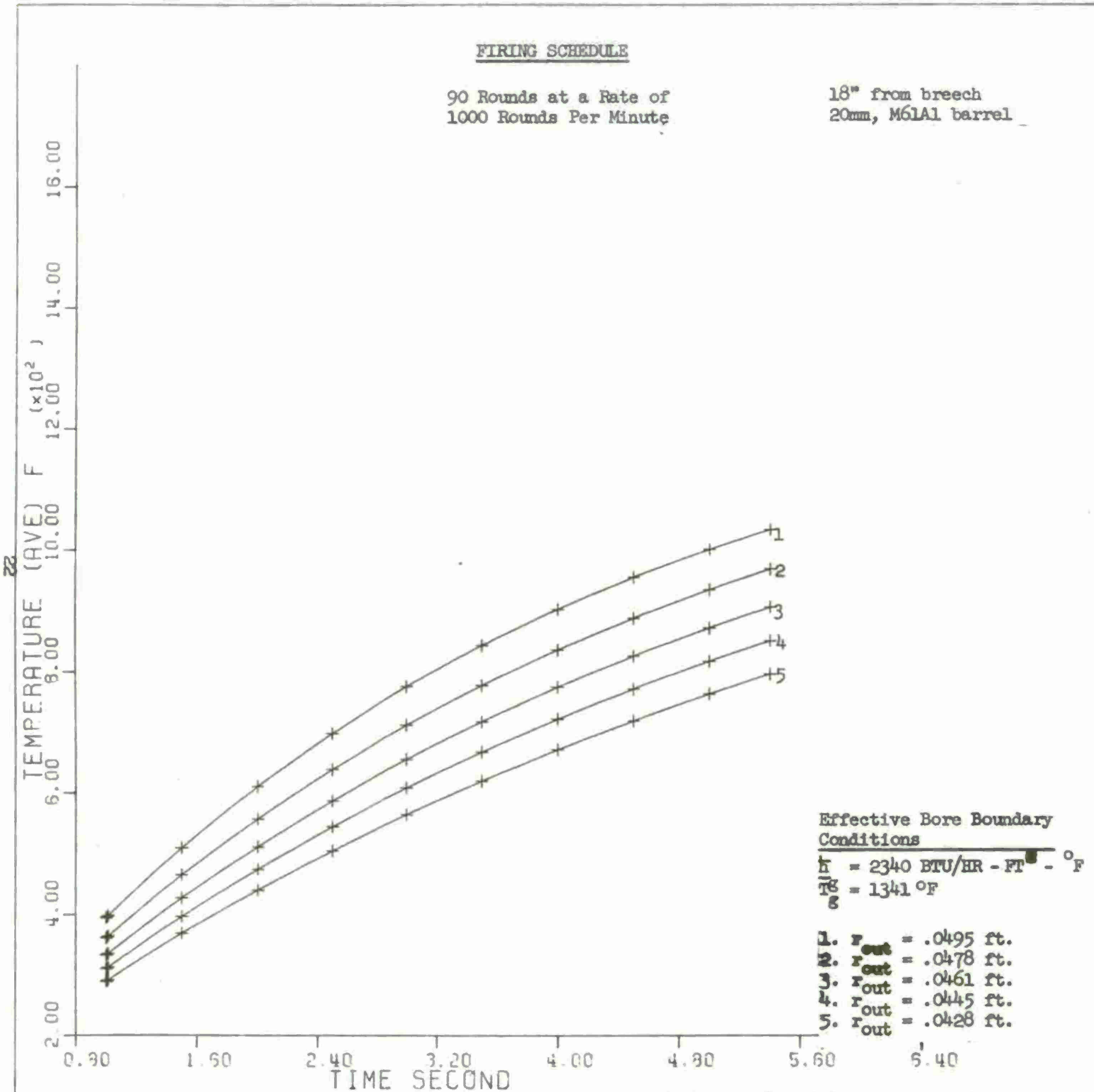

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
18" from breech
20mm, M61A1 barrel
TEMPERATURE (AVE) F (×10²)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
TIME SECOND
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
h̄ = 2340 BTU/HR - FT² - °F
T̄g = 1341 °F
1. r_out = .0495 ft.
2. r_out = .0478 ft.
3. r_out = .0461 ft.
4. r_out = .0445 ft.
5. r_out = .0428 ft.

FIGURE 14

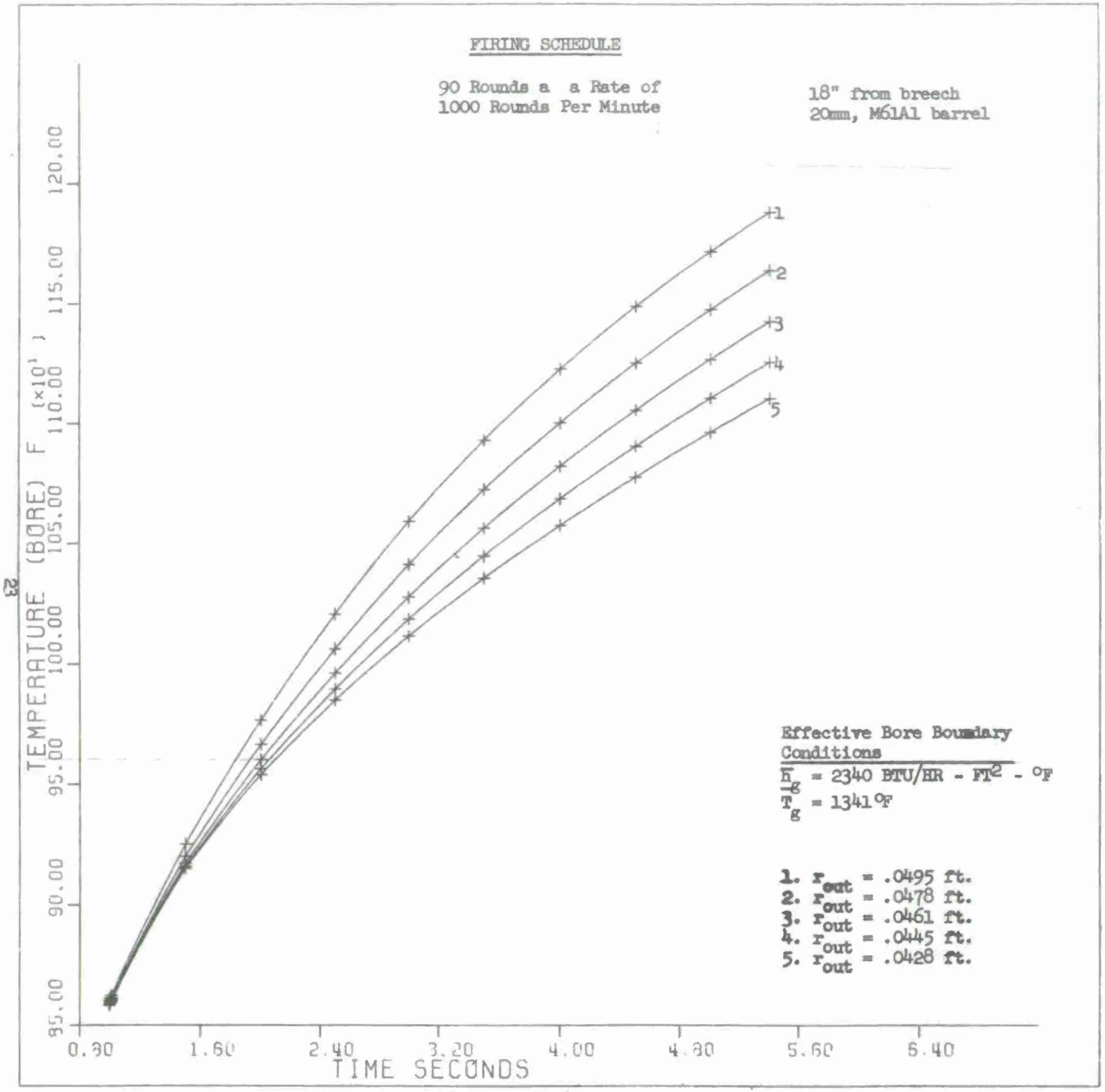

FIRING SCHEDULE
90 Rounds a a Rate of
1000 Rounds Per Minute
18" from breech
20mm, M61A1 barrel
TEMPERATURE (BORE) F (×10¹)
TIME SECONDS
85.00
90.00
95.00
100.00
105.00
110.00
115.00
120.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
h̄g = 2340 BTU/HR - FT² - °F
T̄g = 1341 °F
1. r out = .0495 ft.
2. r out = .0478 ft.
3. r out = .0461 ft.
4. r out = .0445 ft.
5. r out = .0428 ft.

FIGURE 15

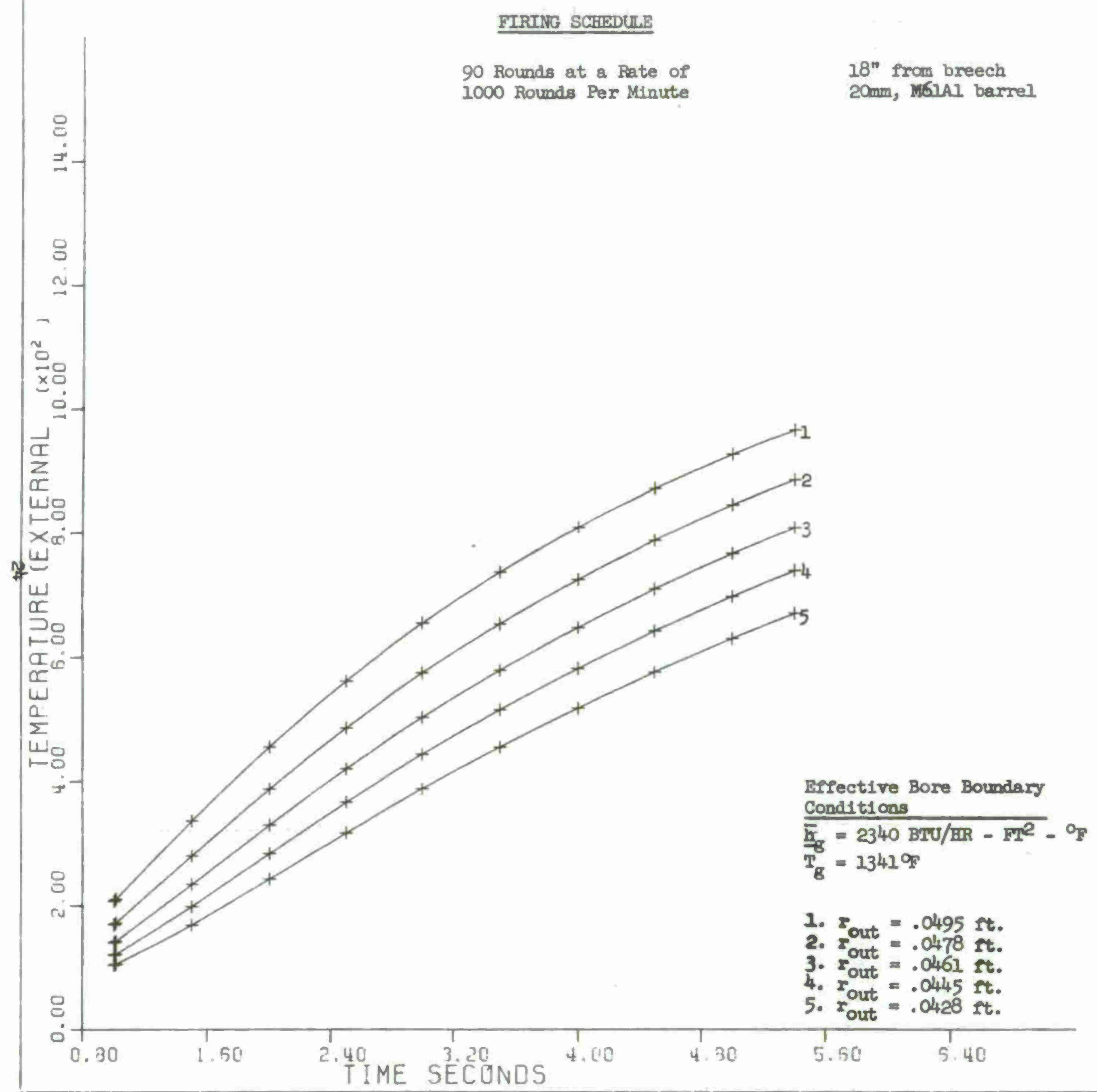

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
18" from breech
20mm, M61A1 barrel
TEMPERATURE (EXTERNAL (x10²)
TIME SECONDS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
h̄g = 2340 BTU/HR - FT² - °F
Tg = 1341°F
1. rout = .0495 ft.
2. rout = .0478 ft.
3. rout = .0461 ft.
4. rout = .0445 ft.
5. rout = .0428 ft.

FIGURE 16

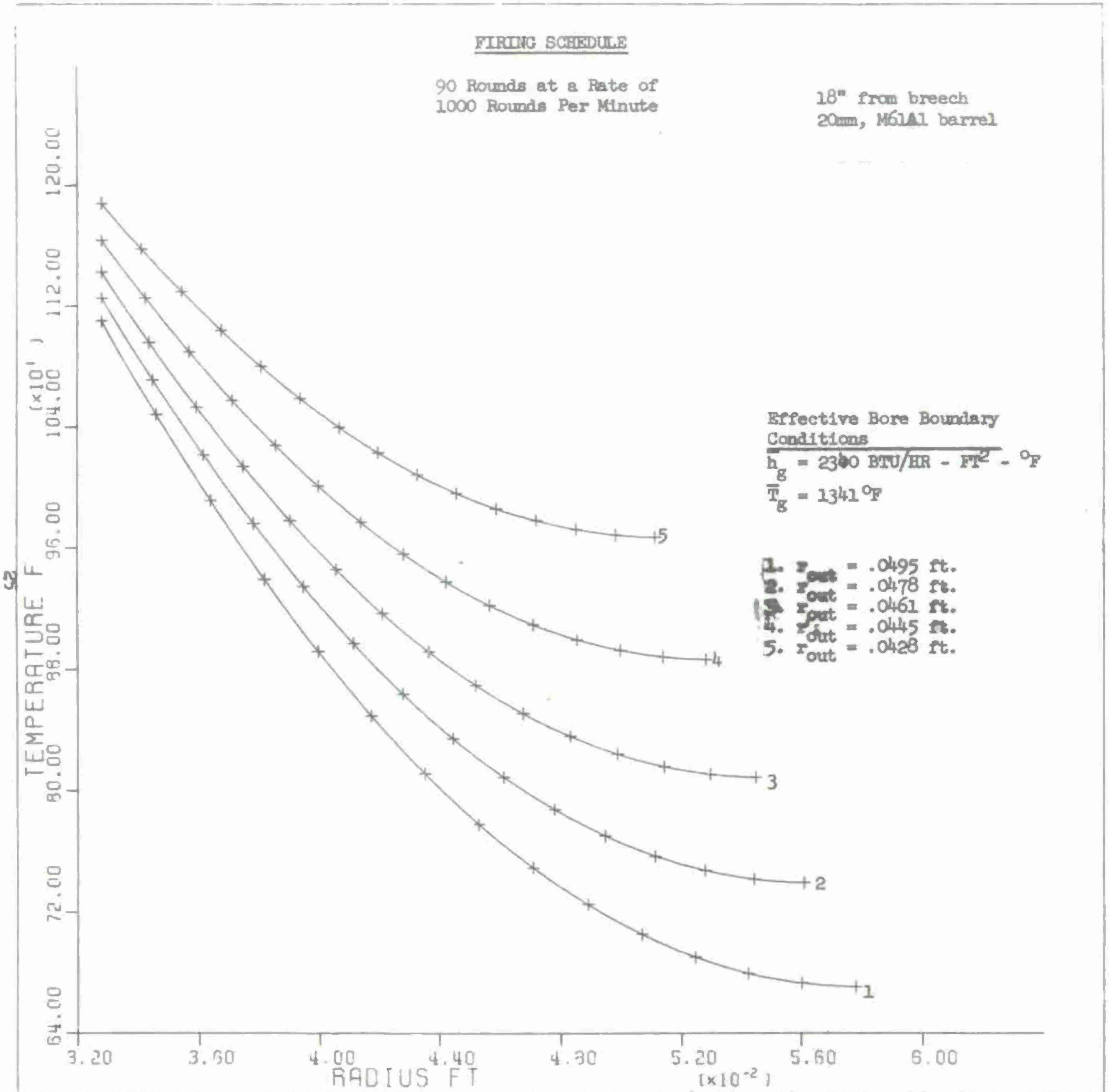
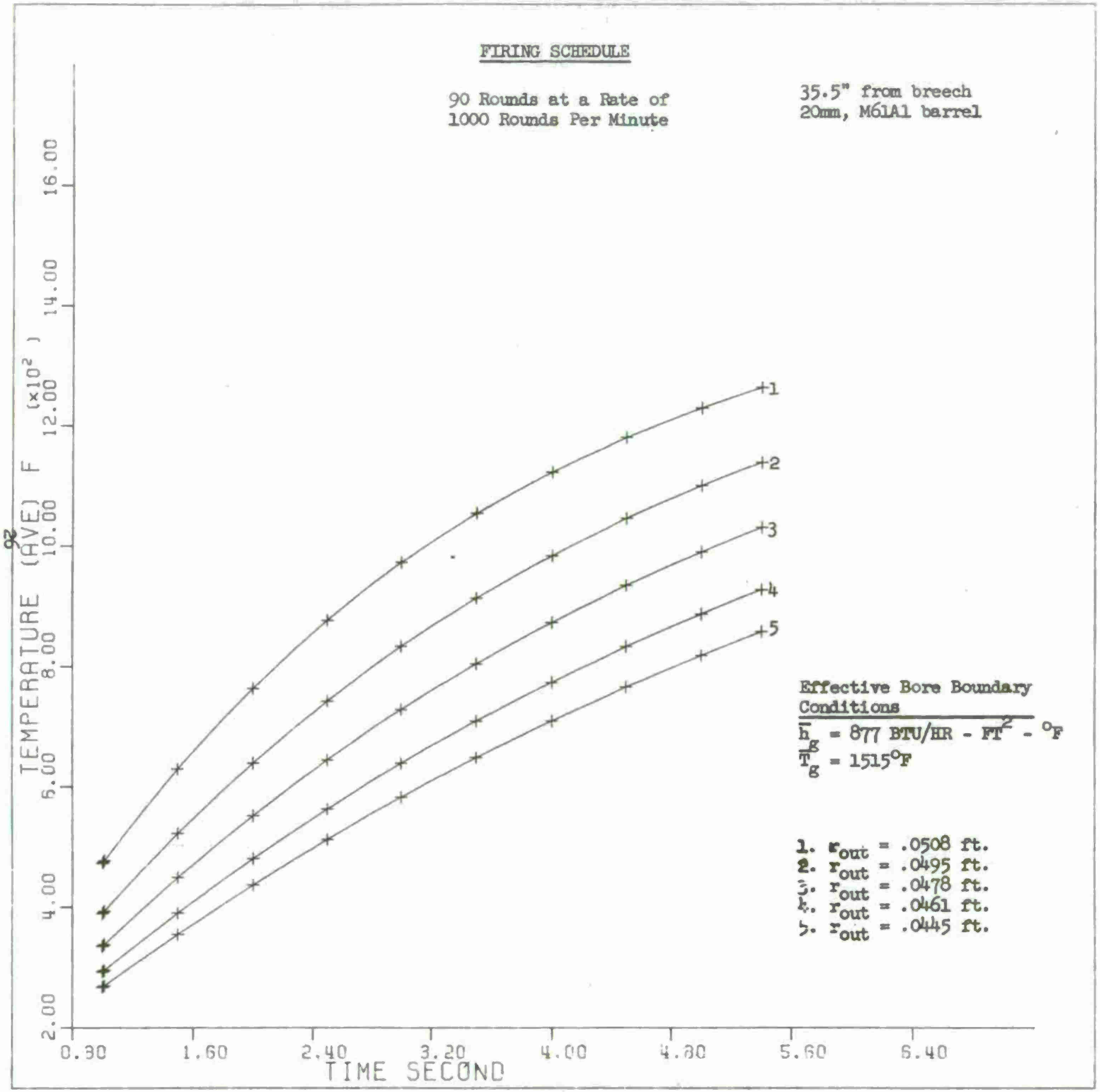

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
18" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
h_g = 2340 BTU/HR - FT^2 - $^{\circ}$F
$\overline{T}_g$ = 1341 $^{\circ}$F
1. r_{out} = .0495 ft.
2. r_{out} = .0478 ft.
3. r_{out} = .0461 ft.
4. r_{out} = .0445 ft.
5. r_{out} = .0428 ft.
TEMPERATURE F (x10^1)
64.00
72.00
80.00
88.00
96.00
104.00
112.00
120.00
RADIUS FT (x10^{-2})
3.20
3.60
4.00
4.40
4.80
5.20
5.60
6.00
1
2
3
4
5

FIGURE 17



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
35.5" from breech
20mm, M61A1 barrel
TEMPERATURE (AVE) F (x10²)
TIME SECOND
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
h̄g = 877 BTU/HR - FT² - °F
T̄g = 1515°F
1. rout = .0508 ft.
2. rout = .0495 ft.
3. rout = .0478 ft.
4. rout = .0461 ft.
5. rout = .0445 ft.

FIGURE 18

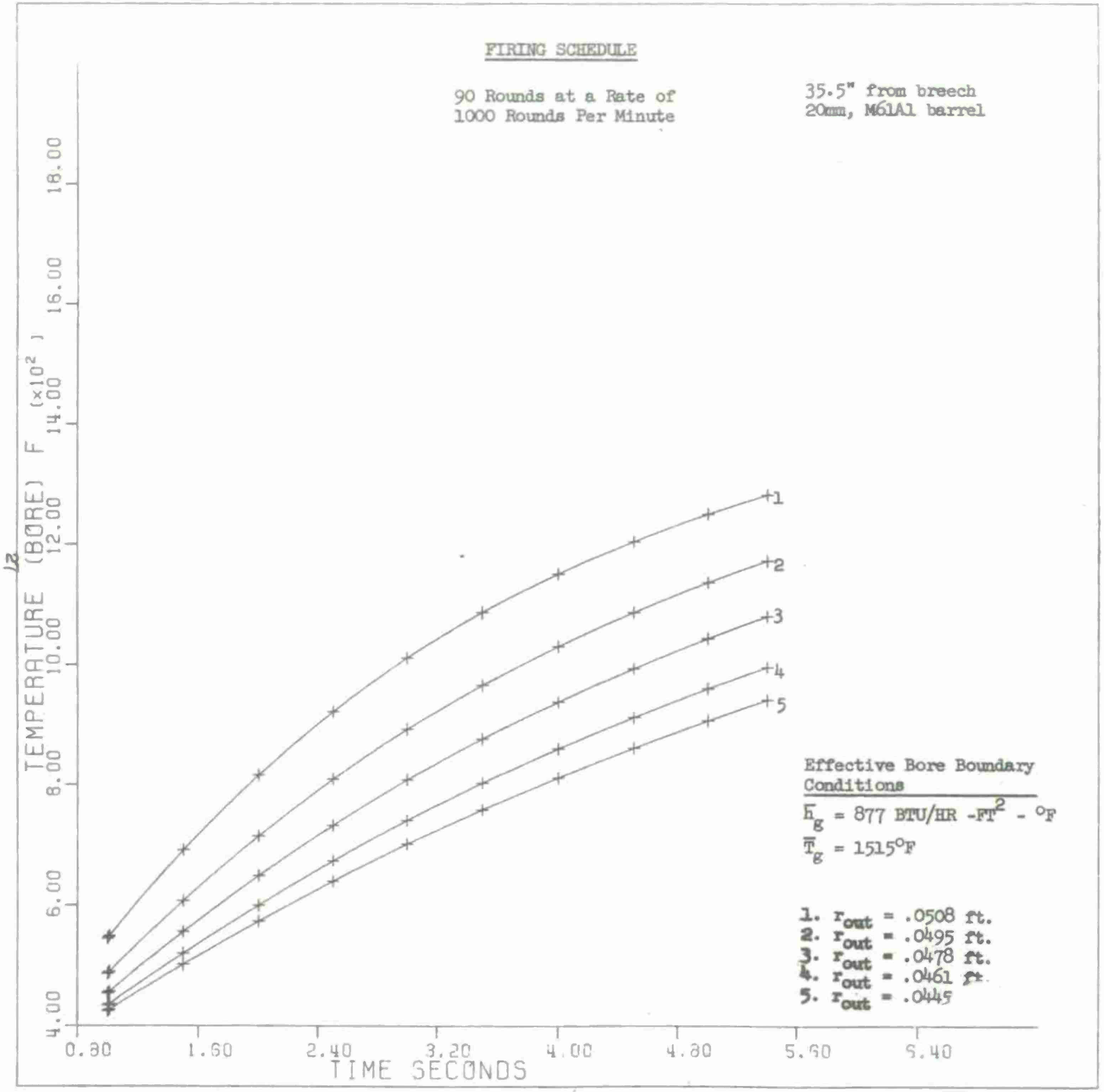
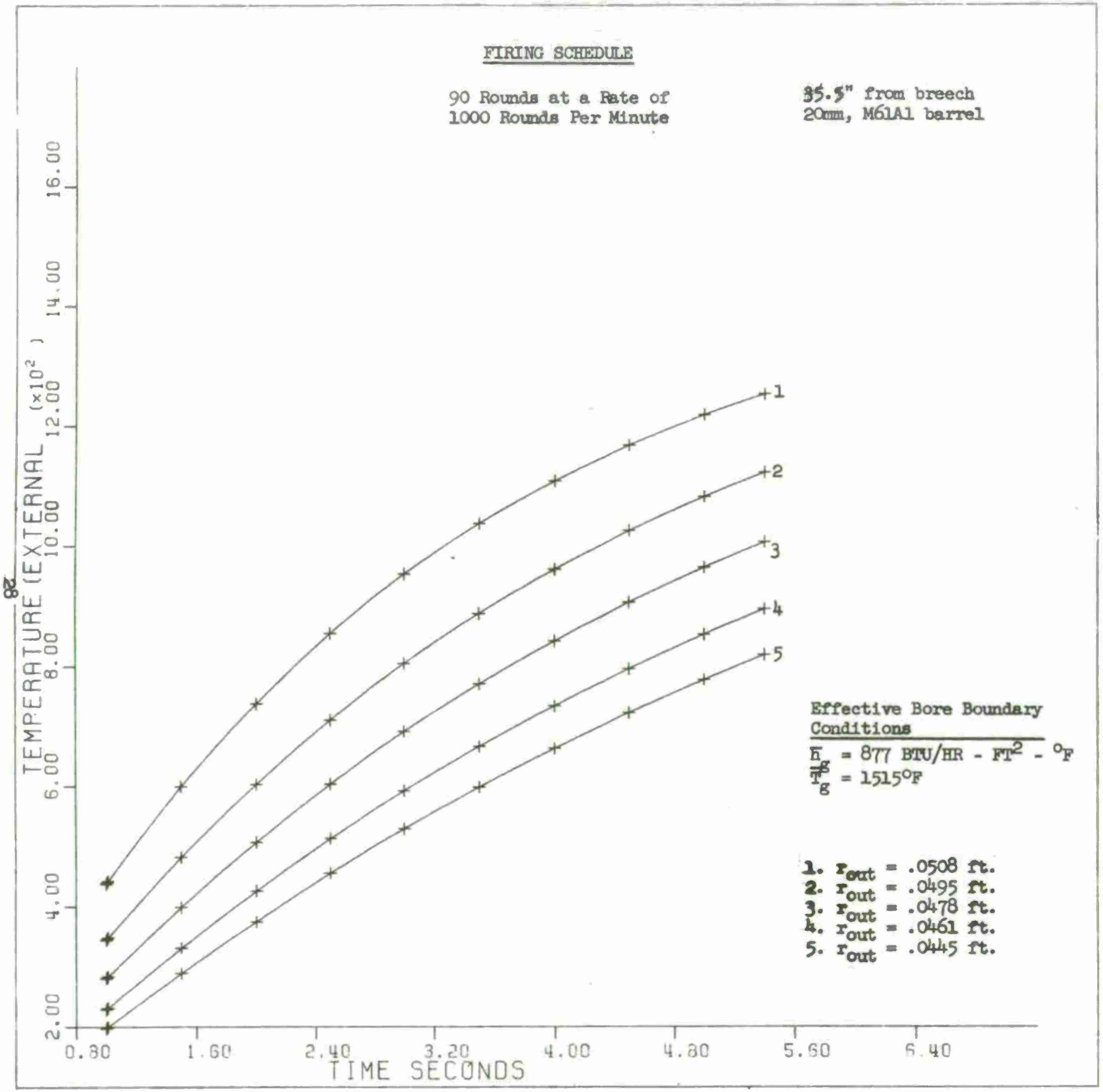

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
35.5" from breech
20mm, M61A1 barrel
TEMPERATURE (BORE) F (x10²)
TIME SECONDS
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
1
2
3
4
5
Effective Bore Boundary Conditions
$\overline{h}_g$ = 877 BTU/HR -FT^2 - ^{o}F
$\overline{T}_g$ = 1515^{o}F
1. r_{out} = .0508 ft.
2. r_{out} = .0495 ft.
3. r_{out} = .0478 ft.
4. r_{out} = .0461 ft
5. r_{out} = .0445

FIGURE 19



FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
35.5" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
h̄g = 877 BTU/HR - FT² - °F
T̄g = 1515°F
1. rout = .0508 ft.
2. rout = .0495 ft.
3. rout = .0478 ft.
4. rout = .0461 ft.
5. rout = .0445 ft.
TEMPERATURE (EXTERNAL (×10²)
TIME SECONDS
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5

FIGURE 20

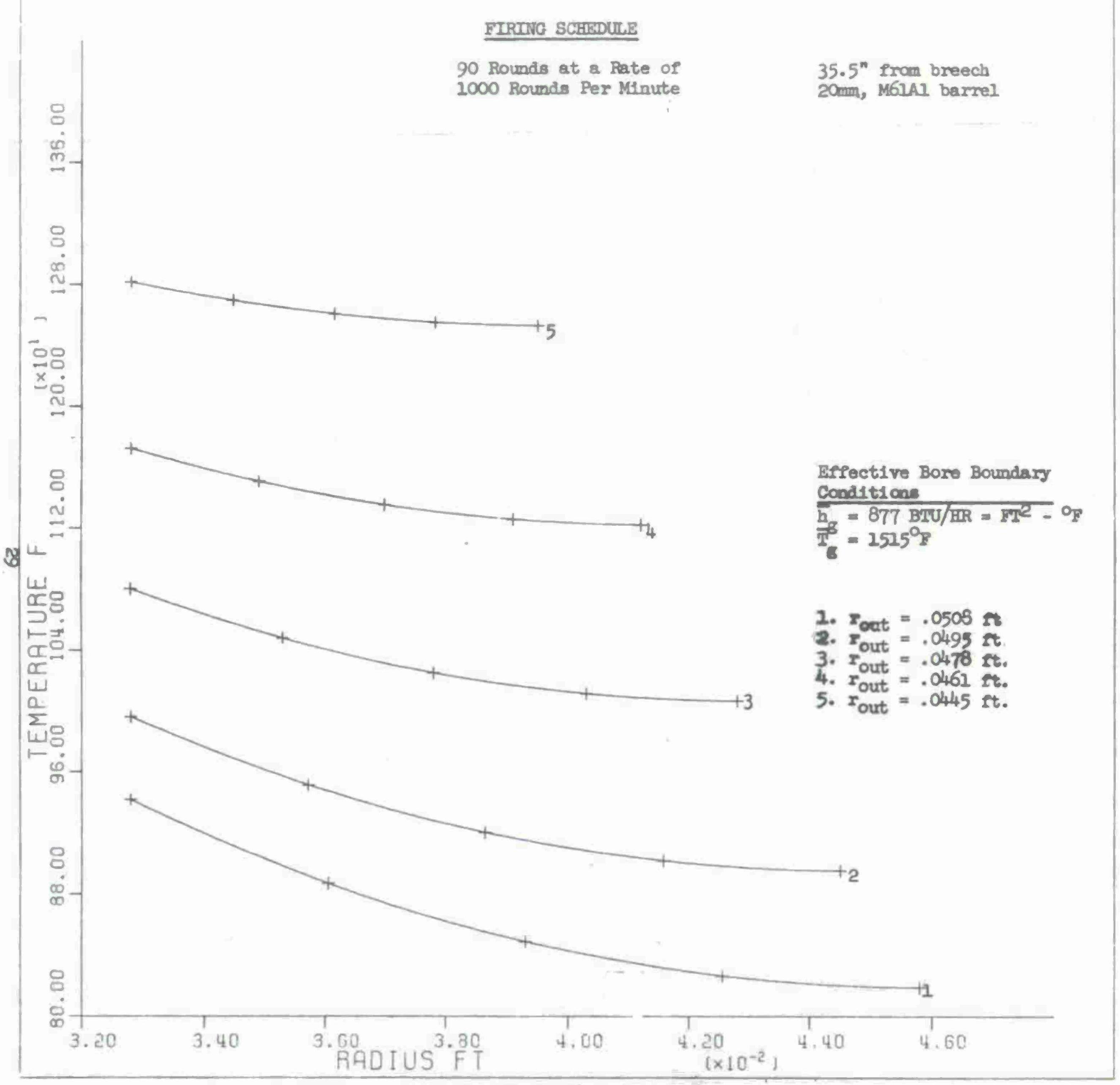

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
35.5" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
h_g = 877 BTU/HR - FT² - °F
T_g = 1515°F
1. r_out = .0508 ft
2. r_out = .0495 ft
3. r_out = .0478 ft.
4. r_out = .0461 ft.
5. r_out = .0445 ft.
TEMPERATURE F
(×10¹)
80.00
88.00
96.00
104.00
112.00
120.00
128.00
136.00
RADIUS FT
(×10⁻²)
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
1
2
3
4
5

FIGURE 21

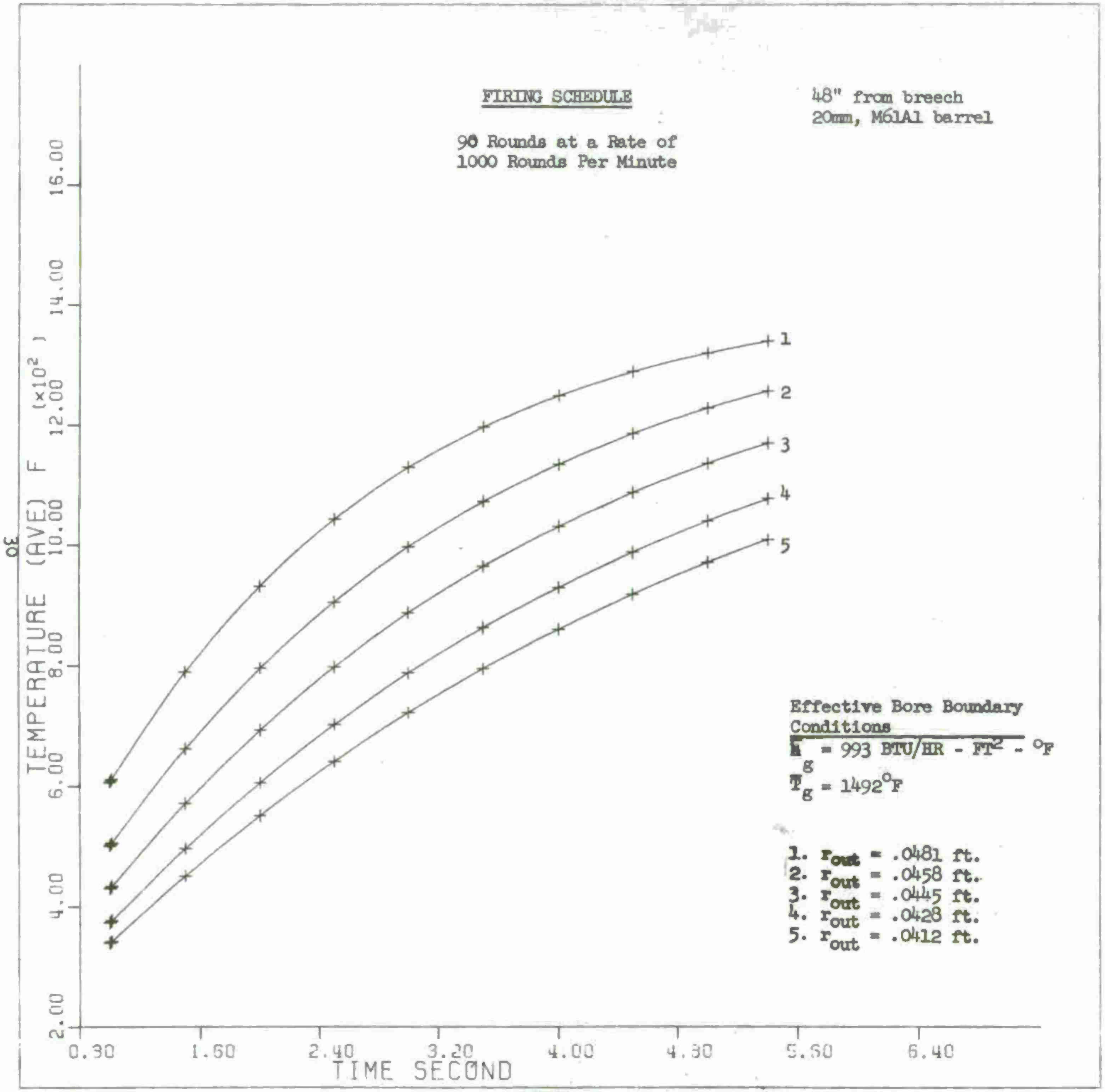

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
48" from breech
20mm, M61A1 barrel
TEMPERATURE (AVE) F (×10²)
TIME SECOND
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
1
2
3
4
5
Effective Bore Boundary Conditions
$\bar{h}_g$ = 993 BTU/HR - FT² - °F
$\bar{T}_g$ = 1492°F
1. r_{out} = .0481 ft.
2. r_{out} = .0458 ft.
3. r_{out} = .0445 ft.
4. r_{out} = .0428 ft.
5. r_{out} = .0412 ft.

FIGURE 22

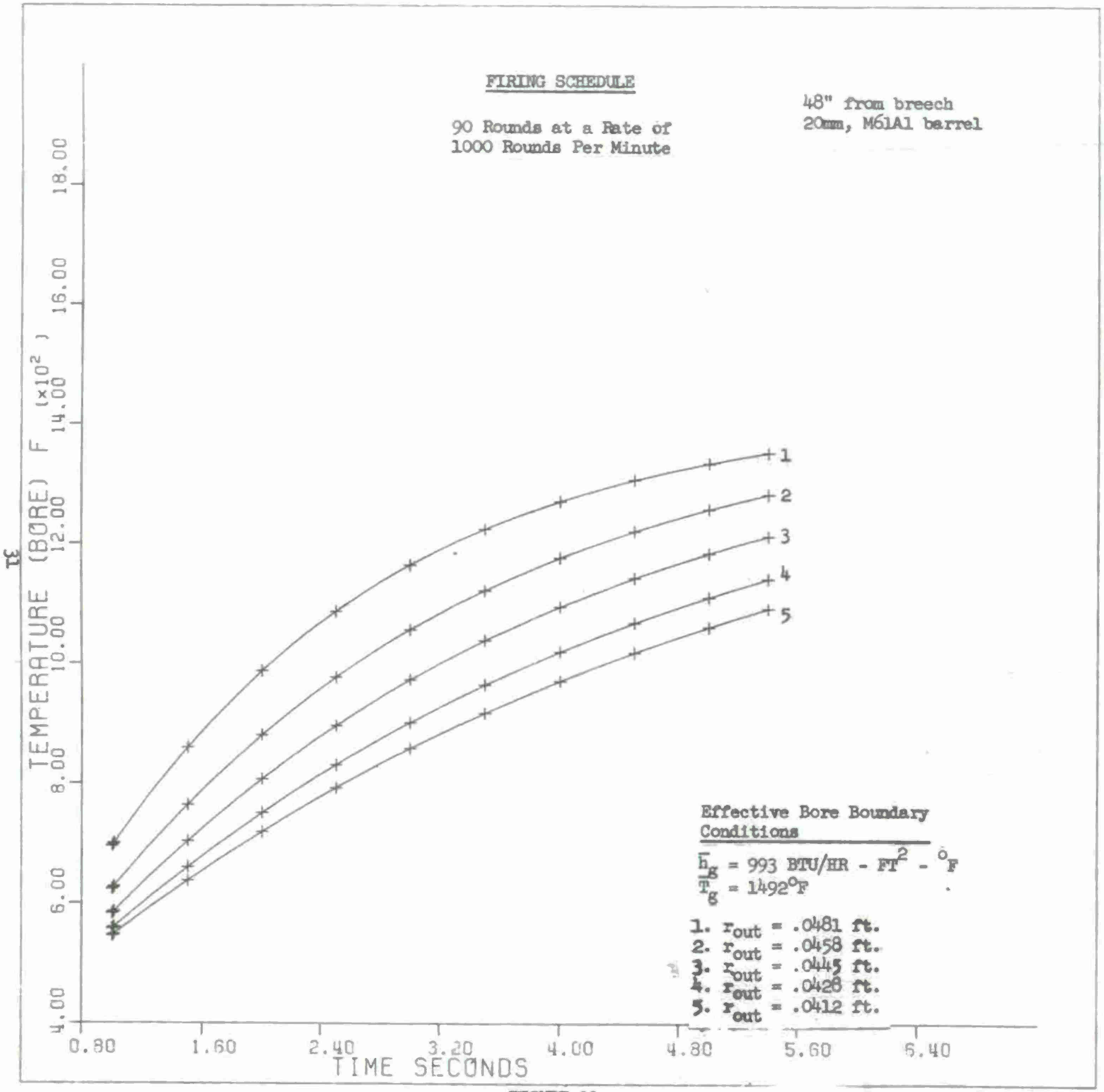

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
48" from breech
20mm, M61A1 barrel
TEMPERATURE (BORE) F (×10²)
TIME SECONDS
Effective Bore Boundary Conditions
$\bar{h}_g$ = 993 BTU/HR - FT² - °F
$\bar{T}_g$ = 1492°F
1. r_{out} = .0481 ft.
2. r_{out} = .0458 ft.
3. r_{out} = .0445 ft.
4. r_{out} = .0428 ft.
5. r_{out} = .0412 ft.

FIGURE 23

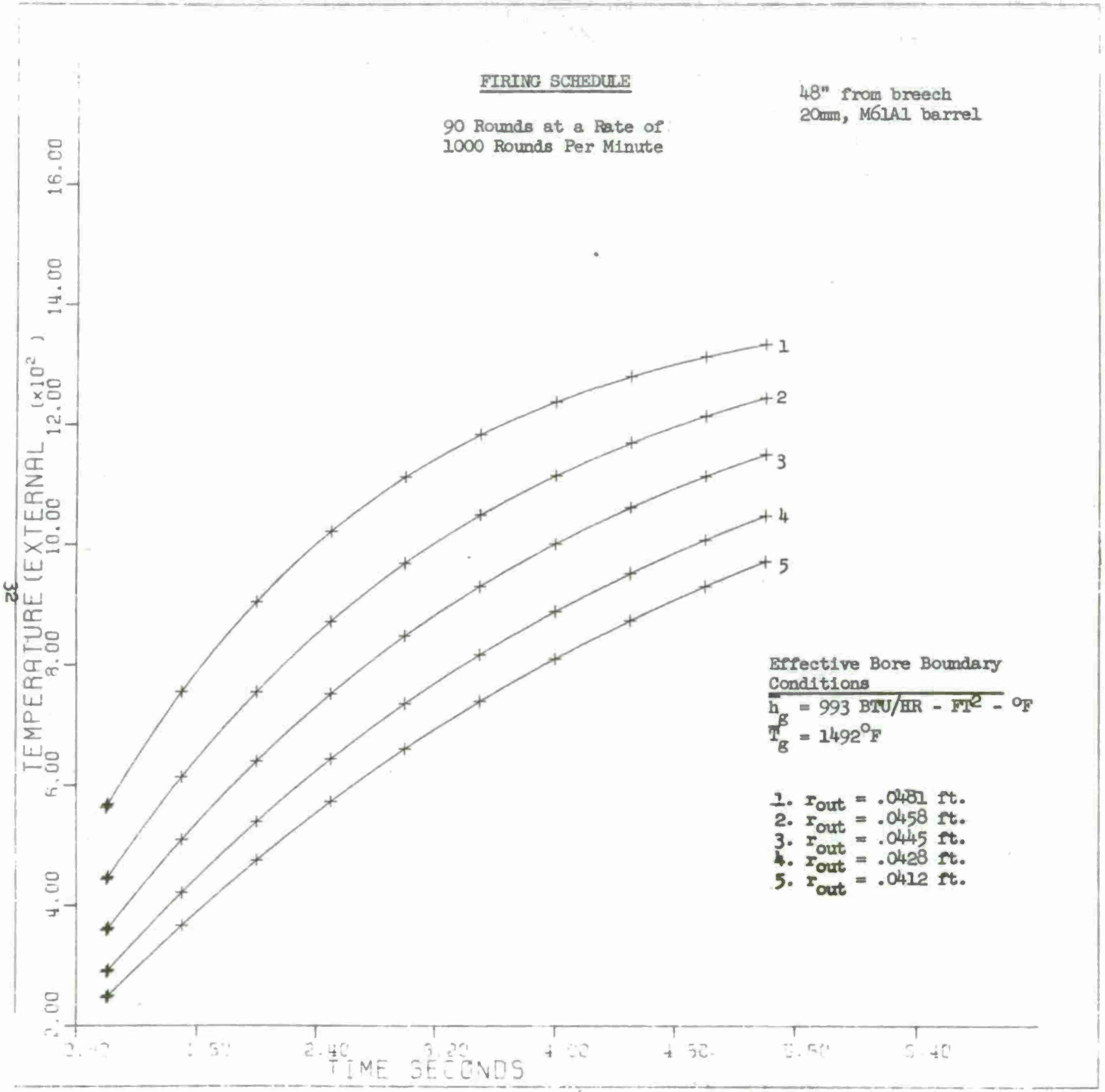

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
48" from breech
20mm, M61A1 barrel
TEMPERATURE (EXTERNAL (x10^2)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
TIME SECONDS
1
2
3
4
5
Effective Bore Boundary Conditions
h_g = 993 BTU/HR - FT^2 - ^{o}F
T_g = 1492^{o}F
1. r_{out} = .0481 ft.
2. r_{out} = .0458 ft.
3. r_{out} = .0445 ft.
4. r_{out} = .0428 ft.
5. r_{out} = .0412 ft.

FIGURE 24

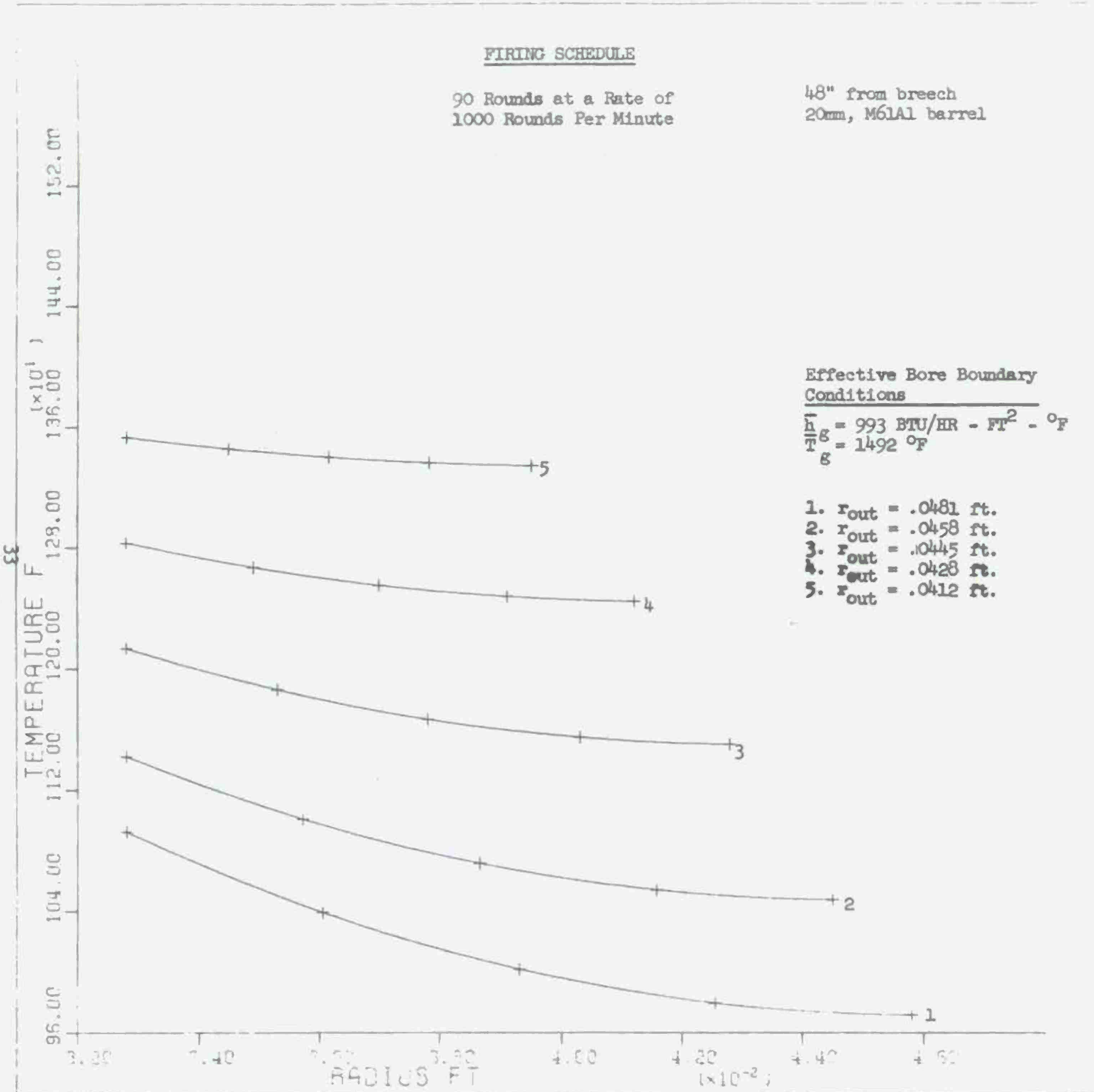

FIRING SCHEDULE
90 Rounds at a Rate of
1000 Rounds Per Minute
48" from breech
20mm, M61A1 barrel
Effective Bore Boundary Conditions
$\bar{h}_g$ = 993 BTU/HR - FT^2 - °F
$\bar{T}_g$ = 1492 °F
1. r_{out} = .0481 ft.
2. r_{out} = .0458 ft.
3. r_{out} = .0445 ft.
4. r_{out} = .0428 ft.
5. r_{out} = .0412 ft.
TEMPERATURE F
(×10^1)
96.00
104.00
112.00
120.00
128.00
136.00
144.00
152.00
RADIUS FT
4.00
4.20
(×10^{-2})
1
2
3
4
5

FIGURE 25

M61 BARREL THERMOCOUPLE STATIONS

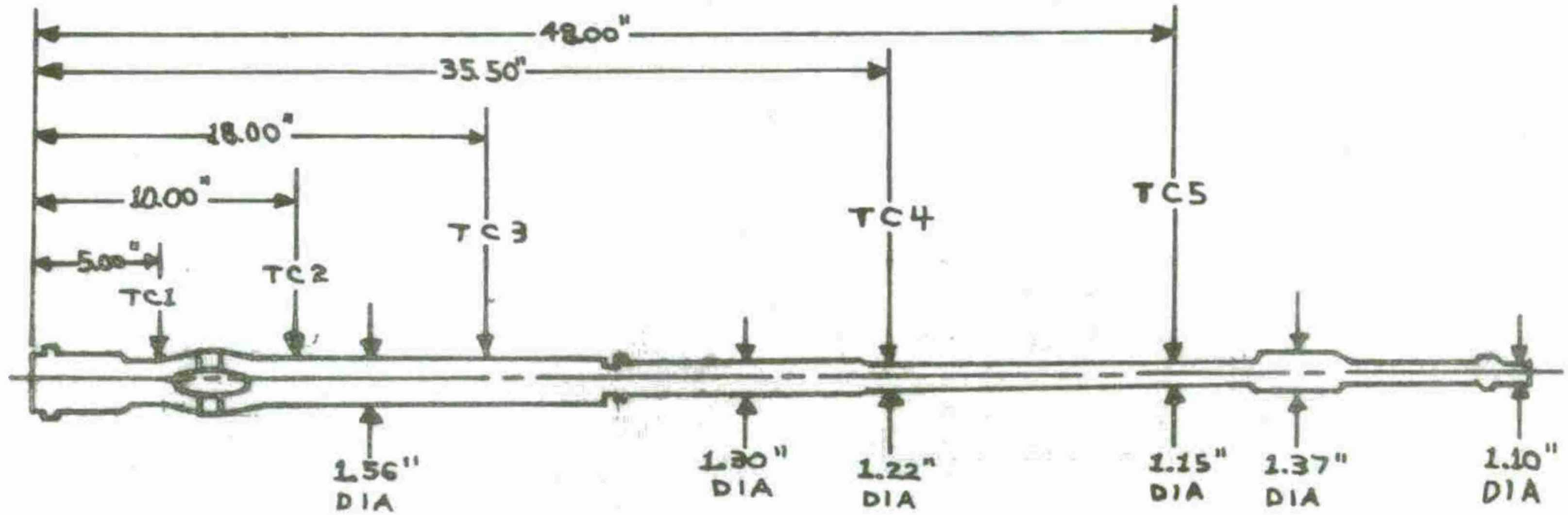


FIGURE 26

YIELD STRENGTH CR-MO-VA

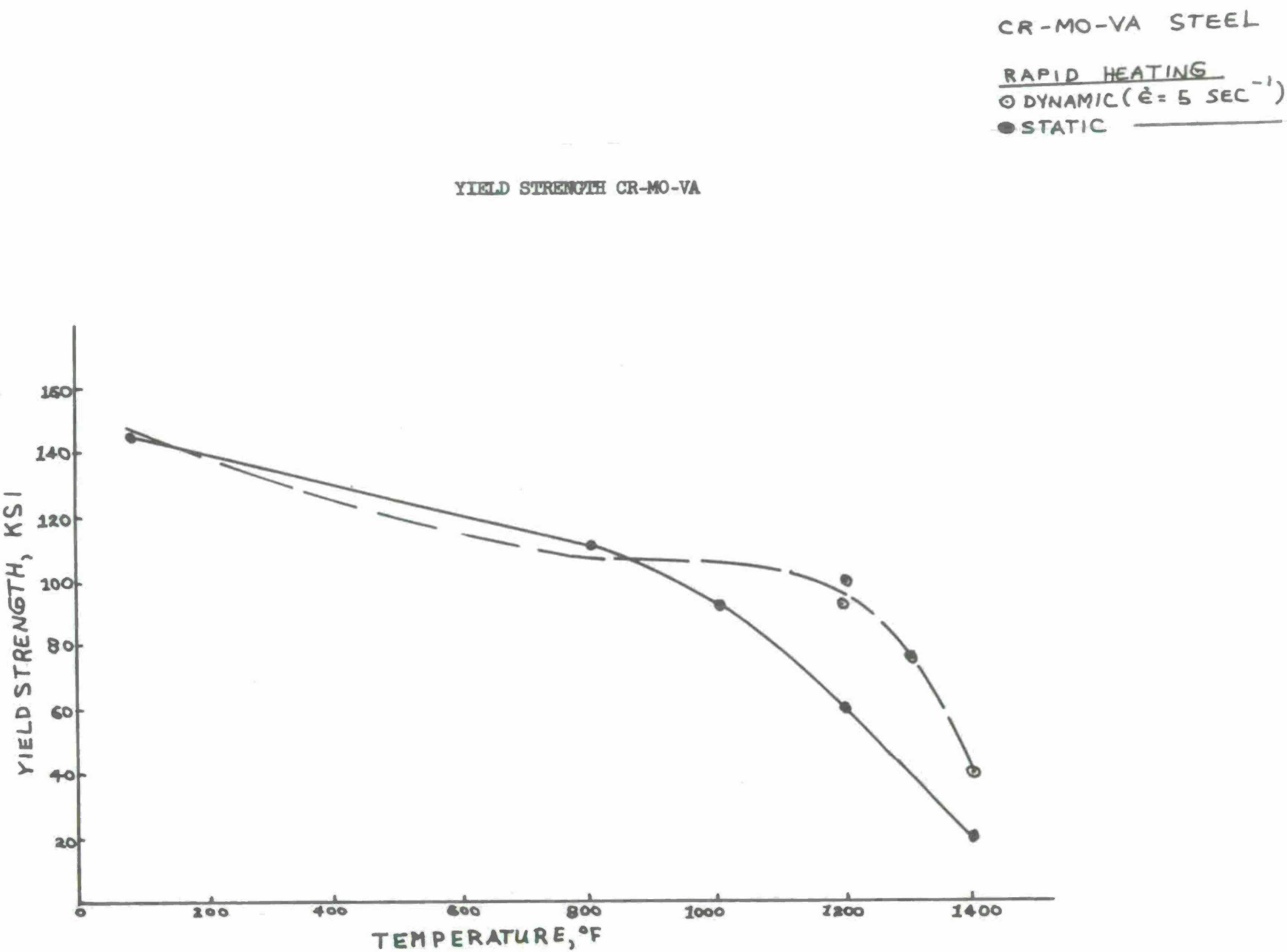


FIGURE 27

PROPOSED 20mm LIGHTWEIGHT BARREL

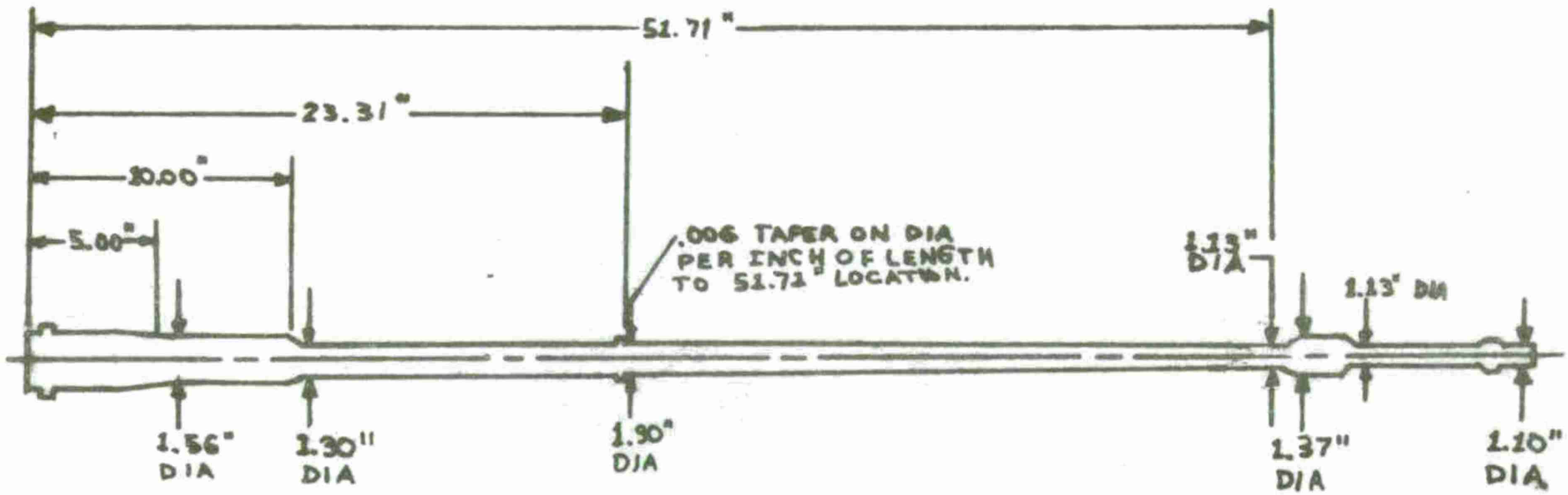


FIGURE 28

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Prepared by: Philip D. Benzkofer

Technical Report No. R-TR-76-022
36 pages, Incl Figures & Tables

A thermal analysis of the M61A1 VULCAN gun barrel was performed. This analysis included the calculation of bore boundary conditions by methods previously developed by the Research Directorate and the application of these boundary conditions to an outer barrel profile analysis. Pressure stress analyses were also performed. The final results are proposed outer barrel profiles for particular performance requirements.

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1. M61A1 Vulcan Barrel
2. Thermal Analysis
3. Bore Boundary Conditions
4. Experimental Data
5. Wall Ratios

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1. M61A1 Vulcan Barrel
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5. Wall Ratios