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ESTIMATES OF THE NUCLEAR DESIGN REQUIREMENT FOR THE PECHORA-KAMA CANAL PROJECT

Milo D. Nordyke

January 16, 1979

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ABSTRACT

The Soviet Union is considering the use of nuclear explosives to excavate a portion of the Pechora-Kama Canal to divert water from northward-flowing rivers into the Caspian Sea. The Soviets have provided a general description of the Canal project, but detailed analyses of the nuclear design, including yields and number of nuclear charges, have never been published. We present estimates for the nuclear design based on three different approaches. Because of the meager amount of data provided by Soviet scientists, we made a variety of assumptions, based on U.S. experience, regarding media properties and design parameters. The resulting estimates are strongly dependent upon these assumptions. We found that reasonable sets of assumptions can be found which lead to results in agreement with the published Soviet estimates for the total yield and total number of explosives. Our results also indicate that the nuclear canal can be constructed, under most assumptions, to meet all identified Soviet criteria using only nuclear explosives with yields less than or equal to 150 kt.

INTRODUCTION

Over the last 10 years, Soviet scientists have spoken often and published many papers describing their plans for using nuclear explosives to excavate a portion of the Pechora-Kama (Kolva) Canal. (For more details on the proposed Canal project, see Ref. 1.) However, they have provided little factual data on which to base an independent analysis of the explosive requirements for this project. The most commonly quoted statement is that of Kedrovskiy in 1970. He stated that the portion of the Canal to be excavated with nuclear explosives would be 65 km long, have a cross section of 5000 m^2, and require about 250 individual charges emplaced at depths ranging from 150-285 m. Further, these charges would be fired in groups of up to 20, with a total yield of 3 Mt per group. Privately,[3] the Soviets indicated the yield of individual explosives would be between 40-500 kt, with a total yield of 36 Mt. Reports[4] published later stated the required cross section would be reduced from 5000 to 3000 m^2. Recent private remarks[5] indicated the length considered for nuclear excavation has been reduced from 65 to 53 km and the required cross section may have been further reduced to 2000 m^2.

The most useful data available to analyze this project is the topographic cross section along the alignment shown in Fig. 1. Nuclear excavation is indicated for the left half (northern portion)* of the cross section shown in Fig. 1. The geological structure along the alignment is also crudely shown. The geology appears to consist of surficial, unconsolidated sediments 20-50 m thick (except for a 120 m deep trough about 36 km from the northern end) underlain by sandstone, siltstone, and argillite. Figure 1 also indicates both the planned water level for the Canal (about 130 m) and the line-of-emplacement of the nuclear charges. This water level probably also corresponds roughly to the existing water table in the area.[4] Figure 2 shows a typical lateral cross section for such a canal produced by a row of discrete charges. The useful portion of the cross section, indicated by crosshatching, is considerably smaller than the

*As indicated by comparison with data in Ref. 4.

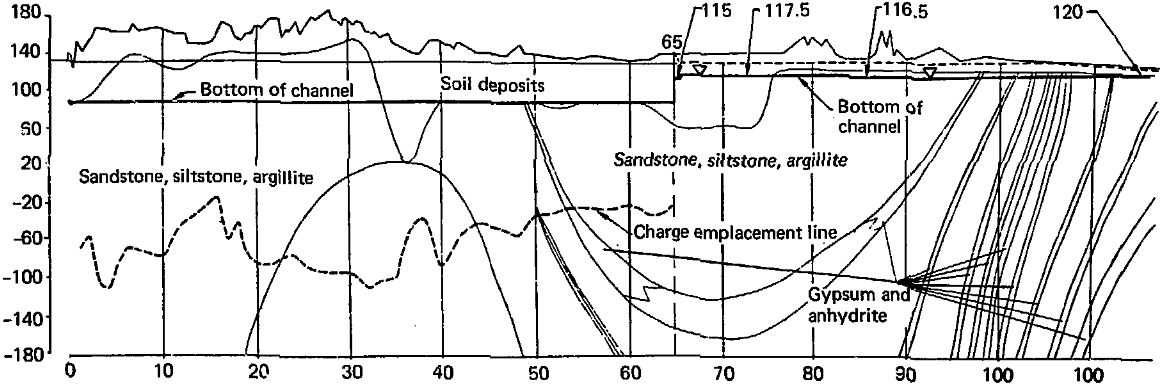

FIG. 1. Cross section along axis of Pechora-Kama Canal.

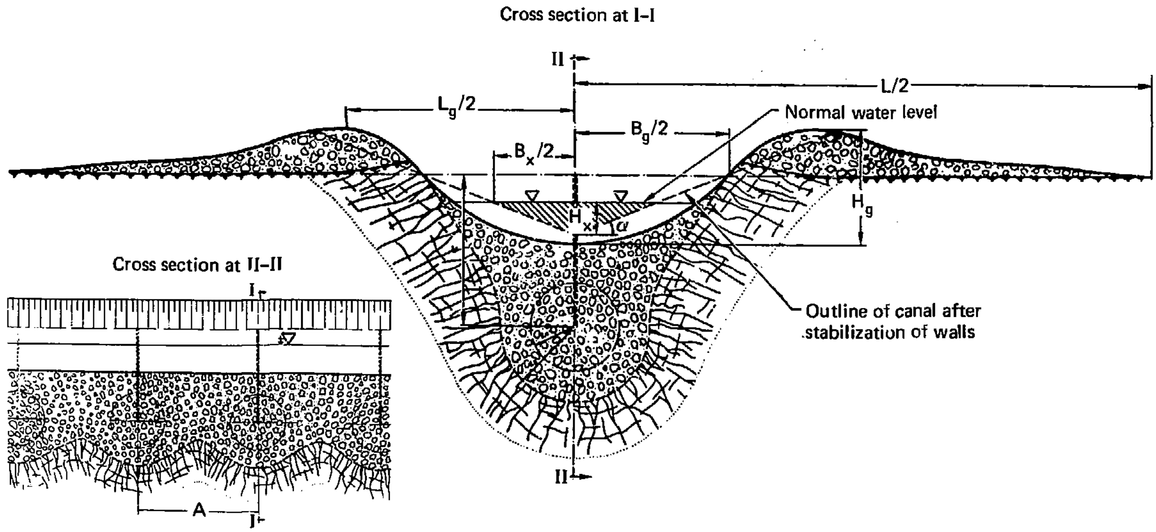

FIG. 2. Diagrams of a typical canal cross-section formed by cratering from Kedrovskiy.

available cross section produced by the explosion. Notations in Fig. 2 indicate the useful cross section is the residual area after allowance is made for stabilization of the crater slopes. (Both Figs. 1 and 2 are taken from Ref. 2.)

We can make estimates of the explosive requirements for construction of this Canal by a number of different methods, although the paucity of available data makes it impossible to make definitive statements. One method is to base the calculations on the line-of-emplacement curve in Fig. 1 by assuming a constant scaled depth-of-burial. A second method calculates the explosive requirements based solely on the topographic cross section[2] of Fig. 1 and U.S. knowledge of the cratering properties of comparable materials. A third method uses the design assumptions inherent in the canal cross section[3] of Fig. 2 and the topographic cross section along the canal alignment.[2] Estimates based on these three methods are described below.

ESTIMATE BASED ON SOVIET LINE-OF-EMPLACEMENT CURVE

We can estimate the number and yield of nuclear charges planned for this project from the charge emplacement line shown in Fig. 1. Postulating a family of explosives, W_i, ranging from 50-600 kt, we can calculate the corresponding required depths-of-burial, Z_i, assuming a constant scaled depth-of-burial, Z_s, of 43 $m/kt^{1/3.4}$ (as used for 1004, the Soviet 125-kt nuclear crater). (See Table 1.) We examined Fig. 1 to estimate the total number of kilometers, ΔL, of the route that had depths-of-burial between the ones shown in Table 1. These lengths are then used to estimate the number of charges of each yield required.

If we assume a spacing for the charges equal to the depth-of-burst (i.e., $S/Z = 1.0$), this calculation results in a total required number of charges of 287, somewhat in excess of the 250 cited by Kedrovskiy.[2] If we use a spacing equal to 1.3 times the depth-of-burial, a value generally recommended in the Soviet literature, we get a total of 223 charges, somewhat less than 250. (See the last column of Table 1.) While this agreement on the total number of charges is fairly good, the total yields for these two cases are 93 and 70 Mt, respectively, significantly greater than Kedrovskiy's 36 Mt. If we use a scaled depth-of-burst of 50 $m/kt^{1/3.4}$, the maximum individual yield is reduced to 400 kt, but the total number of charges remains almost unchanged. The total yields, however, are reduced to 56 and 44 Mt, respectively, much closer to Kedrovskiy's 36 Mt. This method only checks the internal consistency of the numbers Kedrovskiy provided and does not really address the question of what yields are really needed to carry out the desired task.

TABLE 1. Estimated explosives requirements for the Pechora-Kama Canal. These estimates are based on explosive depths-of-burial in Fig. 1 for $Z_s = 43 m/kt^{1/3.4}$.

W_i (kt)	Z_i (m)	ΔL ($Z_{i-1} < Z < Z_i$) (m)	Number of explosives (S/Z = 1.0)	Number of explosives (S/Z = 1.3)
50	136	2,600	19	15
100	167	5,400	32	25
200	204	19,000	93	72
400	250	20,000	80	62
600	285	18,000	63	49
		65,000	287	223
Total yields			93 Mt	70 Mt

ESTIMATE BASED ON U. S. CRATERING EXPERIENCE

An alternative approach is to calculate the explosive requirements on the basis of the topographic cross section shown in Fig. 1, assumptions regarding the desired canal cross section, and the cratering properties of the media. The latter are based on U. S. cratering experience. Although the results of this calculation are very sensitive to the assumptions, they do serve to indicate bounds for the problem.

A substantial amount of research by the Corps of Engineers[6] indicated that row craters have hyperbolic cross sections. Therefore, we can describe the cross section of a row crater in terms of its half-width, r, as a function of the distance from the bottom, d, by

$$(d + b)^2 - r^2 m^2 = b^2$$

or

$$r^2 = \frac{d^2 + 2bd}{m^2}$$

where m is the asymptotic slope of crater walls. Figure 3 illustrates these relationships. The parameter b is defined by the values of r and d at the level of the original ground surface, R and D, respectively, from

$$b = \frac{m^2R^2 - D^2}{2D} .$$

Since $R = R_s W^{1/3.4}$ and $D = D_s W^{1/3.4}$, where R_s and D_s are the scaled crater half-width and depth, we can write

$$b = b_s W^{1/3.4}$$

where

$$b_s = \frac{m^2R_s^2 - D_s^2}{2D_s} . \qquad (1)$$

If we wish to have a given area, A, with a depth, c, at the bottom of such a hyperbolic cross section, we can show that

$$A = \frac{b^2}{m} f(x) \qquad (2)$$

where

$$x = \frac{c}{b}$$

and

$$f(x) = (x + 1)(x^2 + 2x)^{1/2} - \ln[(x + 1) + (x^2 + 2x)^{1/2}] . \qquad (3)$$

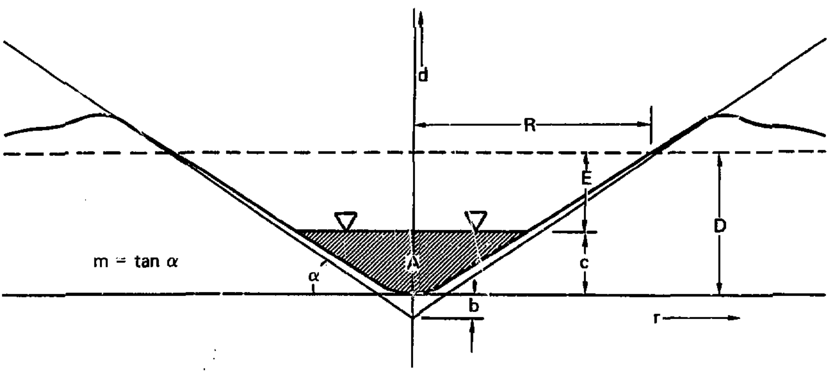

FIG. 3. Typical hyperbolic row crater cross section.

Figure 4 is a plot of f(x) for values of x between 0 and 10.

The elevation, E, through which a given yield, W, can construct a canal with a usable cross section, A, and a water depth, c, is thus given by

$$E = D - c = D - xb = W^{1/3.4}(D_s - xb_s) . \qquad (4)$$

Note that here E is the elevation above the water surface. (See Fig. 3.) Knowing A, we can calculate f(x) from Eq. (2) and determine x from Fig. 4. This then permits E to be determined as a function of W from Eq. (4).

We assume, conservatively, that the media along the Pechora-Kama Canal route will crater in a manner similar to U. S. experience in dry, hard rock. This leads to a choice of scaled parameters of

$$R_s = 41\ \mathrm{m/kt}^{1/3.4} ,$$

$$D_s = 24\ \mathrm{m/kt}^{1/3.4} ,$$

$$Z_s = 40\ \mathrm{m/kt}^{1/3.4} ,$$

and

$$m = 0.7 .$$

These values give

$$b_s = 5.16$$

which leads to the curves of E vs W for areas of 2000, 3000, 5000, and 10,000 m^2 shown in Fig. 5. The 10,000 m^2 cross section is included to provide a case with a safety factor of 2 for possible slumping and scalloping of the crater walls.

To obtain a quantitative estimate of the length of the Canal occurring at various elevations, the topographic cross section shown in Fig. 1 for the northern 65 km of the Canal route was smoothed and replotted at a 20:1 exaggerated vertical scale in Fig. 6. The total length of the route occurring in various 4-m intervals was then calculated and is presented in Table 2.

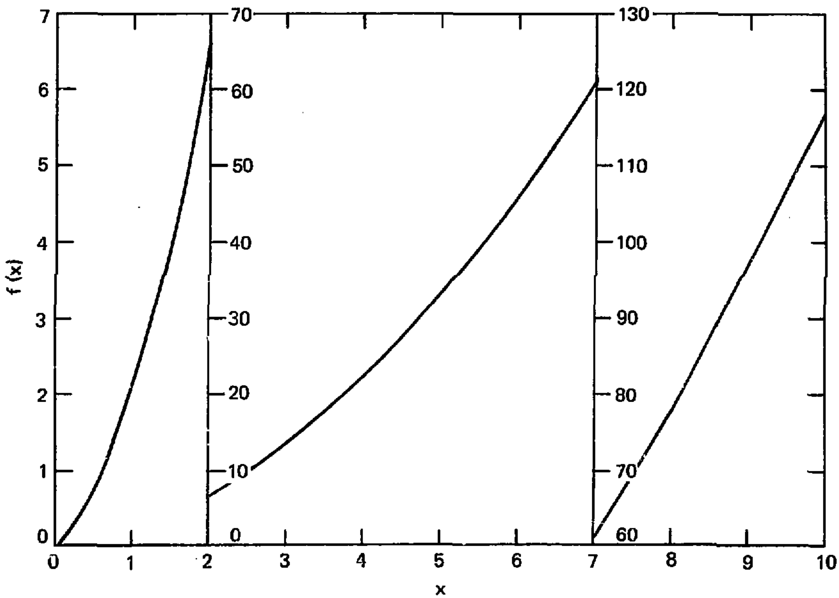

FIG. 4. Plot of f (x) vs x.

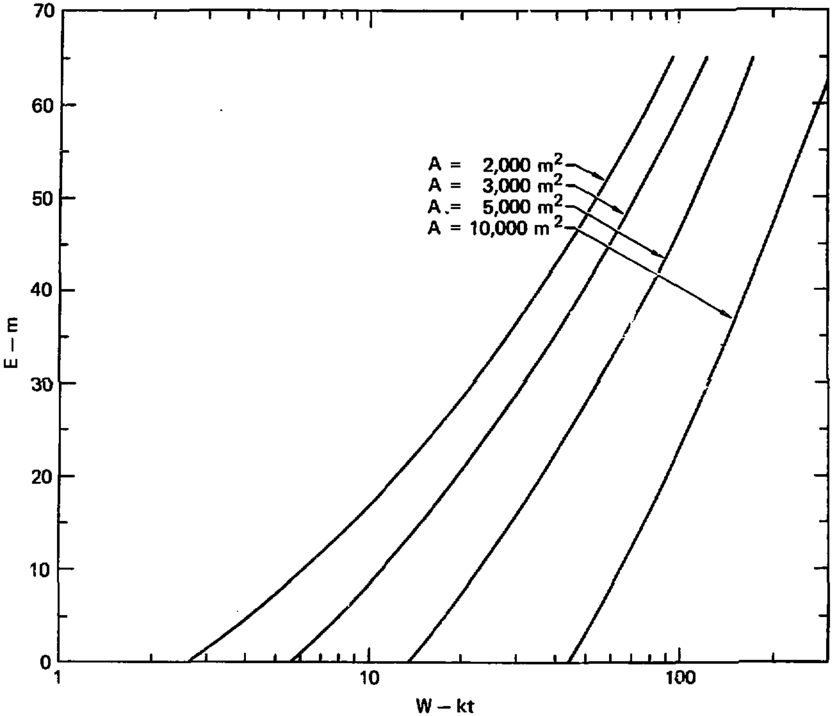

FIG. 5. Water surface elevation vs yield and cross-sectional area for dry, hard-rock cratering parameters.

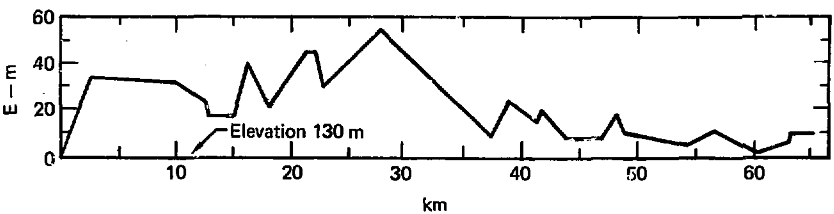

FIG. 6. Topographic surface from Fig. 1 with enhanced vertical scale.

TABLE 2. Aggregate length of constant elevation intervals for the Pechora-Kama Canal.

Elevation interval above 130 m (m)	Total length in elevation interval (km)
0–4	2.3
4–8	3.3
8–12	12.0
12–16	8.8
16–20	6.5
20–24	3.3
24–28	3.6
28–32	4.1
32–36	10.4
36–40	3.0
40–44	2.4
44–48	2.8
48–52	1.6
52–56	0.9
	65.0 km

The maximum elevation along the Pechora-Kama Canal alignment is about 56 m above the projected water level in the Canal (approximately 130 m above sea level). Reference to Fig. 5 shows that this elevation will require individual yields of 70, 90, 135, and 250 kt to excavate channels having areas of 2000, 3000, 5000, and 10,000 m^2, respectively, assuming no enhancement of crater dimensions as a result of close spacing of the charges. A spacing of S = 1.2Z to 1.3Z is generally believed to lead to row craters having no enhancement of width and depth as compared to single craters produced by the same yield and depth-of-burial. Closer spacing will increase R_s and D_s, thereby decreasing the yields required to excavate the indicated areas.

Application of the curves in Fig. 5 to the topographic data given in Table 2 requires the assumption of a family of yields. Experience has shown that the specific choices of explosive yields are not critical, although larger numbers in the family of explosives generally lead to a somewhat larger total number of explosives. A family of 15, 30, 60, 100, 150, and 300 kt explosives was assumed for this calculation. (See Table 3.) A spacing corresponding to 1.3Z or 52 $m/kt^{1/3.4}$ was assumed. The remainder of Table 3 presents the maximum elevation through which each yield can excavate a given area, the length of the route with elevations that can be excavated by that explosive, and the total number of explosives required. The larger numbers of explosives for areas of 2000 and 3000 m^2 reflect the use of large numbers of small yields to excavate the lower elevations. When only larger yields are used, as for A = 10,000 m^2, the total number of explosives decreases and is comparable with the number cited by Kedrovskiy. Only the 10,000 m^2 option, including a safety factor of 2 or 3, requires use of yields in excess of 150 kt.

Based on the descriptions of the geologic condition of the Pechora-Kama Canal provided by the Soviets, the cratering properties of the rock in this area appear more favorable than those we assumed for the above example. An alternative approach is to assume a crater dimension more representative of saturated, soft rock. For such conditions, the values

TABLE 3. Nuclear design estimates for the Pechora-Kama Canal. These are for dry, hard rock cratering parameters based on U.S. cratering experience. R_s = 41 $m/kt^{1/3.4}$, D_s = 24 $m/kt^{1/3.4}$, and Z_s = 40 $m/kt^{1/3.4}$.

W (kt)	Spacing (m)	A = 2000 m^2			A = 3000 m^2			A = 5000 m^2			A = 10,000 m^2		
		E (m)	L (km)	N	E (m)	L (km)	N	E (m)	L (km)	N	E (m)	L (km)	N
15	115	23	35.9	312	15	25.6	223	–	–	–	–	–	–
30	141	37	[illegible]	138	29	15.2	108	16	26.4	187	–	–	–
60	173	53	9.0	52	45	19.5	113	32	17.5	101	8	10.6	61
100	201	66	0.7	3	59	4.7	23	46	17.2	86	23	24.9	124
150	227	–	–	–	–	–	–	60	3.9	17	37	19.5	86
300	278	–	–	–	–	–	–	–	–	–	62	10.0	36
Total number of explosives required				505			467			391			307

from 1004, the Soviet 125-kt nuclear crater, appear to be reasonable. The values are

$$R_s = 49\,m/kt^{1/3.4} ,$$

$$D_s = 20\,m/kt^{1/3.4} ,$$

$$Z_s = 43\,m/kt^{1/3.4} ,$$

and

$$m = 0.7 .$$

These cratering parameters lead to the curves shown in Fig. 7 for elevation, E, as a function of the yield, W. Application of these curves to the profile data in Table 2 leads to the nuclear design estimates given in Table 4. A spacing of 1.3Z was also used for this case. The total number of explosives required for this case are somewhat less than the first case (Table 3), but still quite comparable. Again, only the 10,000 m^2 option requires the use of explosives larger than 150 kt.

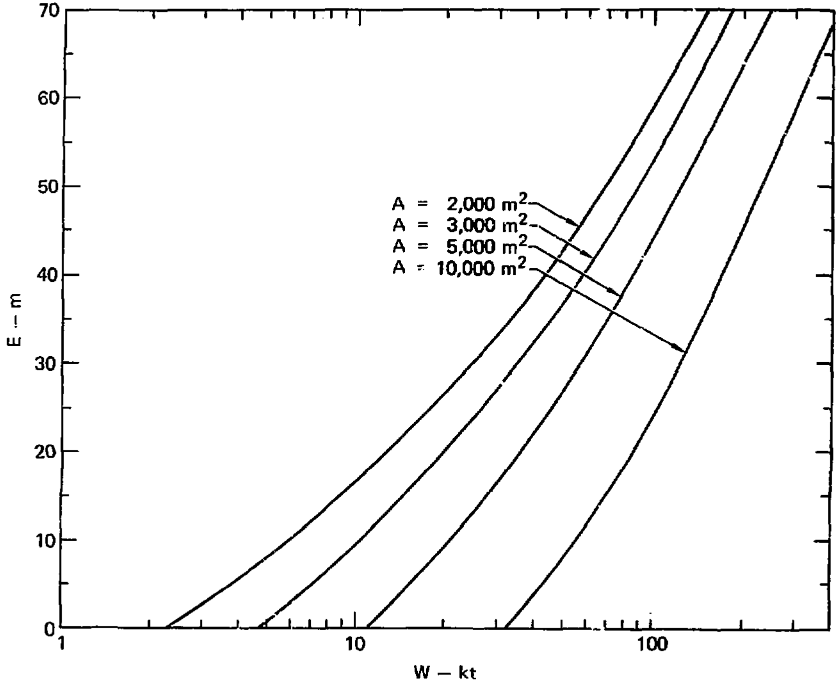

FIG. 7. Water surface elevation vs yield and cross-sectional area for saturated, soft-rock cratering parameters.

TABLE 4. Nuclear design estimates for the Pechora-Kama Canal. These are for saturated, soft rock parameters based on U.S. cratering experience.[a] $R_s = 49\ m/kt^{1/3.4}$, $D_s = 20\ m/kt^{1/3.4}$, and $Z_s = 43\ m/kt^{1/3.4}$.

W (kt)	Spacing (m)	A = 2000 m² E (m)	L (km)	N	A = 3000 m² E (m)	L (km)	N	A = 5000 m² E (m)	L (km)	N	A = 10,000 m² E (m)	L (km)	N
15	124	22	34.6	279	10	16.6	134	–	–	–	–	–	–
30	152	33	11.9	78	27	22.3	147	16	26.4	174	–	–	–
60	186	47	15.3	82	41	19.0	102	31	16.5	89	12	22.6	122
100	216	59	3.2	15	52	6.2	29	44	16.8	78	24	13.6	63
150	244	–	–	–	64	0.9	4	56	5.3	22	36	18.1	74
300	299	–	–	–	–	–	–	–	–	–	59	10.7	36
Total number of explosives required				454			416			363			295

[a]These cratering parameters are consistent with the Soviet 125-kt nuclear crater 1004.

ESTIMATE BASED ON KEDROVSKIY'S TYPICAL LATERAL CANAL CROSS SECTION

Using the notation from Fig. 2, we can see that the Soviets assumed slope failure could occur until the slope reached an angle of α as measured from the horizontal. It was also assumed that the final slope intersects the original crater wall precisely at the original ground surface where the row crater half-width is $R(-B_g/2$ in Fig. 2). Thus, the bottom of the triangle representing the useful cross section is at a depth below the original ground surface of $R \cdot \tan\alpha$. For a canal passing through terrain having an elevation, E, above the desired water surface in the canal, we can see the height of the useful triangular canal cross section (i.e., the depth of the water) is $H_x = R \tan\alpha - E$ and the width of the water bearing section, B_x, is

$$B_x = \frac{2H_x}{\tan\alpha} .$$

Therefore, the useful area, A, is given by

$$A = \frac{B_x H_x}{2} = \frac{H_x^2}{\tan\alpha} = \frac{(R\tan\alpha - E)^2}{\tan\alpha} .$$

Since $R = R_s W^{1/3.4}$, we can write

$$W = \frac{1}{R_s^{3.4}}\left[\left(\frac{A}{\tan\alpha}\right)^{1/2} + \frac{E}{\tan\alpha}\right]^{3.4} . \quad (5)$$

Thus, the yield, W, required to excavate a canal of useful cross section A through an elevation E can be calculated, assuming a value for the scaled crater radius and a final slope for the sides of the crater, α. Figure 8 presents the variation of elevation, E, as a function of yield as given by Eq. (5) for areas of 2000, 3000, and 5000 m², respectively, and for slope angles with tangents equal to 0.2, 0.3, and 0.4. These correspond to slope angles of 11, 17, and 22°. Slopes flatter than 20–25° are not expected in anything but the weakest materials. A value of 49 $m/kt^{1/3.4}$ for R_s was used for all calculations.

Using the plots of E vs W from Fig. 8 and the aggregate length intervals from Table 2, we can calculate the explosive requirements to excavate the Pechora-Kama Canal under this method. Results of these calculations are presented in Tables 5-7 for useful areas of 2000, 3000, and 5000 m², respectively. A spacing equal to 1.3 times the depth-of-burst of 43 $m/kt^{1/3.4}$ was used for all these calculations.

The results range quite widely, depending on the assumption for input numbers. The use of m = 0.4, a reasonable (or even conservative) value for

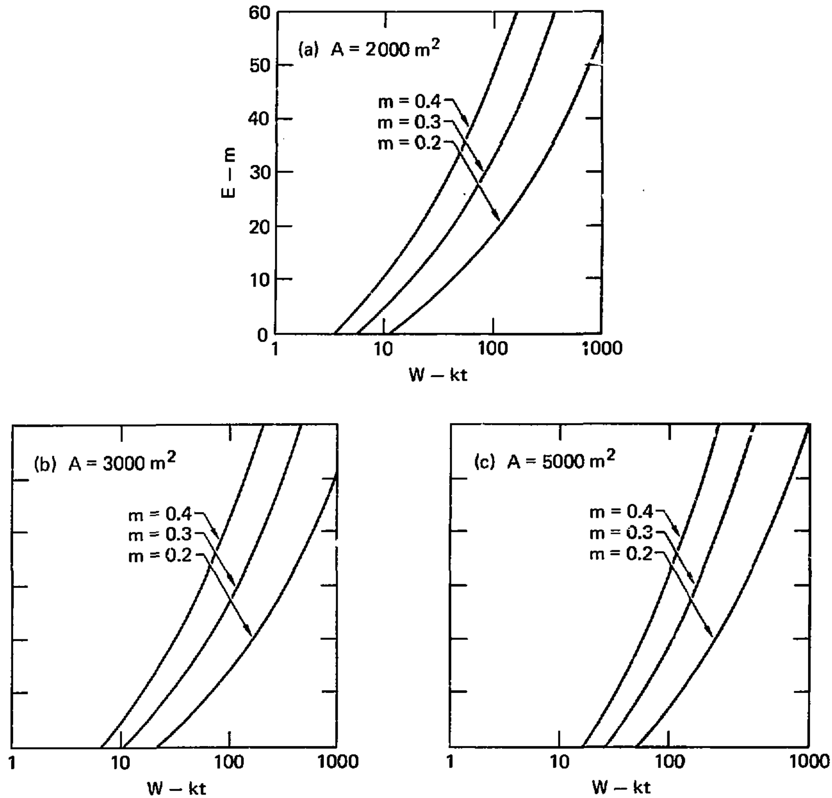

FIG. 8. Water surface elevation vs yield and slope angle α for cross-sectional areas of (a) 2000 m², (b) 3000 m², and (c) 5000 m².

most of the types of materials indicated in Fig. 1 and one which corresponds to the slope used in Fig. 2, gives results that are quite comparable with the values quoted by Kedrovskiy for the 5000 m² canal (i.e., 28.7 vs 36 Mt and 325 vs 250 explosive). Further, the results indicate that yields above 150 kt are only required for the 3000 and 5000 m² options, not for the 2000 m² one. However, the results from this method are very sensitive to the choice of final slope angle and any angle flatter than 30° will require an explosive larger than 150 kt for all current cross section options.

TABLE 5. Nuclear design estimates for the Pechora-Kama Canal. The estimates are based on Kedrovskiy's lateral canal cross section with final slopes of m = 0.4 and 0.2, and $R_s = 49\ m/kt^{1/3.4}$.

A = 2000 m^2							
W (kt)	Spacing (m)	m = 0.4			m = 0.2		
		E (m)	L (km)	N	E (m)	L (km)	N
15	124	16	26.4	213	2	1.2	10
30	152	26	11.5	76	6	5.3	35
60	186	38	17.9	96	13	17.1	92
100	216	48	6.7	31	18	6.0	28
150	244	58	2.5	10	23	6.3	26
300	299	-	-	-	33	10.6	35
600	366	-	-	-	45	13.9	38
1000	426	-	-	-	55	4.6	11
				426			275
Total yield (Mt)				15.8			56.6

TABLE 6. Nuclear design estimates for the Pechora-Kama Canal. The estimates are based on Kedrovskiy's lateral canal cross section with final slopes of m = 0.4 and 0.2, and $R_s = 49\ m/kt^{1/3.4}$.

A = 3000 m^2							
W (kt)	Spacing (m)	m = 0.4			m = 0.2		
		E (m)	L (km)	N	E (m)	L (km)	N
15	124	10	16.6	134	-	-	-
30	152	19	14.6	96	2	1.2	8
60	186	31	11.6	62	8	9.4	51
100	216	42	15.7	73	13	12.9	50
150	244	51	5.2	21	18	6.1	25
300	299	70	1.3	4	28	10.2	34
600	366	-	-	-	40	17.5	48
1000	426	-	-	-	50	6.0	14
1500	480	-	-	-	60	1.7	4
				390			244
Total yield (Mt)				20.3			72.0

TABLE 7. Nuclear design estimates for the Pechora-Kama Canal. The estimates are based on Kedrovskiy's lateral canal cross section with final slopes of m = 0.4 and 0.2, and $R_s = 49\ m/kt^{1/3.4}$.

A = 5000 m^2							
W (kt)	Spacing (m)	m = 0.4			m = 0.2		
		E (m)	L (km)	N	E (m)	L (km)	N
30	152	8	10.6	70	-	-	-
60	186	21	23.1	124	1	0.6	3
100	216	31	9.1	42	6	5.9	27
150	244	47	19.0	78	14	18.0	74
300	299	60	3.2	11	21	9.2	31
600	366	-	-	-	32	10.2	28
1000	426	-	-	-	43	15.2	36
1500	480	-	-	-	52	5.0	10
2000	522	-	-	-	60	0.9	2
				325			211
Total yield (Mt)				28.7			95.1

CONCLUSIONS

Estimates of the nuclear explosive requirements for the Pechora-Kama Canal, based on the crude profile and geologic section provided by the Soviets, indicate that the nuclear canal can be constructed to meet all identified criteria entirely with nuclear explosives with yields less than or equal to 150 kt. The total numbers of explosives estimated in this report are, in general, larger than those provided in 1970-71 by Kedrovskiy. This larger number indicates that either 1) a much larger canal was contemplated, 2) a very large safety factor was included to provide for scalloping or slumping, or 3) the use of explosives larger than the minimum required for the given elevation and cross section were planned. The last course of action appears the most probable since it is both the minimum cost and minimum radioactivity release design.

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