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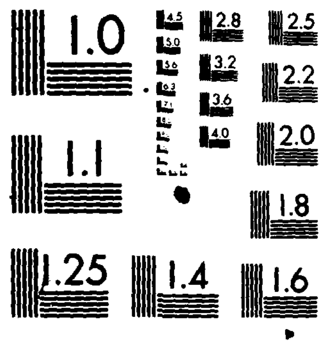

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OPTIMAL DESIGN OF MULTIPLE TUBE
GRAIN AND THEIR ARRANGEMENT

by

Zhao Baihua

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FTD-ID(RS)T-0523-82

EDITED TRANSLATION

FTD-ID(RS)T-0523-82 29 June 1982

MICROFICHE NR: FTD-82-C-000838

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English pages: 20

Source: Acta Armamentarii, Nr. 4, 1981, pp. 9-22

Country of origin: China
Translated by: LEO KANNER ASSOCIATES
F33657-81-D-0264
Requester: FTD/TQTA

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OPTIMAL DESIGN OF MULTIPLE TUBE GRAIN AND THEIR ARRANGEMENT*

Zhao Baihua

ABSTRACT

This paper presents four arrangement methods of multiple tube grain in the combustion chamber and the theorectic calculating formulae for the grain number n and relative exterior diameter $\bar{D}$. Several formulae for computing grain number n in the "hexagonal crowded arrangement" have been corrected. Results of the computer calculations have been optimized. Finally, a group of grain design curves have been given to meet the requirements of various web coefficient $\bar{e}$. These curves have practical significance to the grain design of some missiles, rocket launchers and rocket boosters.

* Received on September 12, 1980.

SYMBOLS

D, d, L, e	exterior diameter, interior diameter, length and thickness of grain;
n	grain number;
i	number of circle arranged;
I	total impulse;
I_{sp}	specific impulse;
W_p	weight of grain;
γ_p	specific weight of propellant;
D_i	interior diameter of combustion chamber;
$\bar{D}=\frac{D}{D_i}$	relative exterior diameter of grain;
$\bar{d}=\frac{d}{D_i}$	relative interior diameter of grain;
$\bar{e}_i=\frac{e_i}{D_i}$	web coefficient;
$\varkappa$	inlet parameter;
$\varkappa_i$	interior inlet parameter;
$\varkappa_e$	exterior inlet parameter;
$\lambda=\frac{\varkappa_i}{\varkappa_e}$	ratio of interior inlet parameter to exterior inlet parameter;
η	packing coefficient

FOREWORD

Certain missiles, rocket launchers and rocket boosters usually require instant completion of combustion of multiple tube grain in order to achieve high initial velocity. However the grain number n in currently available charts and tables is less than 40, and is limited to only one arrangement - hexagonal crowded arrangement. Furthermore there are some doubts as to some of the theoretic formulae in computing the value of n in such hexagonal crowded arrangement. Thus it is rather difficult in quickly arriving at a set of design when the grain number is more than 50.

This paper performs research on the arrangement methods of multiple tube grain in combustion chamber, suggests four feasible arrangements, and derives formulae in computing n and $\bar{D}$ in several arrangements, thus correcting several formulae used in computing n in hexagonal crowded arrangement. Based on the control formulae of n and $\bar{D}$ in various arrangements and the control formulae that relate design parameters and geometric parameters, computer programs are written and large quantity of calculation results are obtained. Finally through selection a set of design curves having a range of n from 3 through 200 and meeting the requirements of various $\bar{e}_1$ are compiled. Optimal design can be quickly arrived at by using the methods and design curves presented in this paper.

METHODS OF ARRANGEMENT

There are primarily four arrangement methods of multiple tube grain in an engine, namely hexagonal arrangement, fixed peripheral arrangement, revised arrangement and even arrangement. The following is a brief discussion.

1. Hexagonal Arrangement (represented by ⊙)

Hexagonal arrangement, otherwise known as hexagonal crowded arrangement, is an arrangement in which one tube is first placed in the center of a combustion chamber and then other tubes are placed hexagonally outward. Only one 1/6 sector is being studied here in Fig. 1 as the six sectors are symetrically identical.

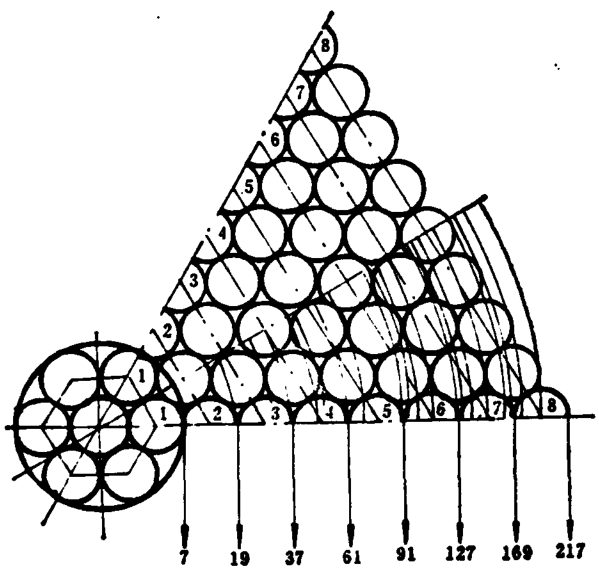

Fig. 1. Diagram of hexagonal arrangement.

By progression analysis, when the number of circles arranged i is positive integer, the computing formula for n is

$$n=\{1+3i(1+i)\}_i$$

Analysis indicates that n in hexagonal arrangement depends on both the value of i and the odd/even quality of i. Based on the concept of sets, the computing formula for n in hexagonal arrangement can be represented in series as

$$n_{\triangle}(i)=\{a_i,\ \{a_i+6k\}_{k\in m_i}\}_1^i \qquad (1)$$

$$a_i=1+3i(1+i)$$

Combining $m_i=\begin{cases}\{k \mid k=2m-1\leqslant i\} & \text{when i is odd number}\\ \{k \mid k=2m\leqslant i\} & \text{when i is even number}\end{cases}$

m is natural number 1, 2, 3, 4, 5, 6, 7 ......

All values of n in hexagonal arrangement can be accurately computed by using Formula (1), and the results agree with the analysis from Fig. 1, as given in Table 1 where Δn is the differential in grain number.

Table 1.

i	1		2		3			4			5				6				7				
$n_{\triangle}$	7	13	19	31	37	43	55	61	73	85	91	97	109	121	127	139	151	163	169	175	187	199	211
Δn	1×6		2×6		1×6, 3×6			2×6, 4×6			1×6, 3×6, 5×6				2×6, 4×6, 6×6				1×6, 3×6, 5×6, 7×6				

When i is a positive integer, the relative exterior diameter $\overline{D}$ can be computed by using the following formula

$$\overline{D}=\frac{1}{2i+1}$$

Other values of $\overline{D}$ can be obtained by geometric relation.

I came across several formulae in computing n in hexagonal arrangement:

$$n = 1 + 3(m + m^2) \qquad (2)$$

$$n = 1 + 3[(m-1) + (m-3) + (m-5) + (m-7) + \cdots] \qquad (3)$$

$$n = 1 + 6m \qquad (4)$$

where m is natural number. There are some doubts about these formulae. Formula (2) is presented in [3] in the bibliography. The n values computed from this formula are by majority medium packing density, and all values of n of optimal high packing density are dropped. Similarly Formula (3) drops a good part of optimal n values; some nonexistent n values are present. Formula (4) simply treats hexagonal arrangement as a variation of arithmetical progression of multiple of six, and it is obviously an error. Formula (1) suggested in this paper can correctly compute all n values in hexagonal arrangement.

2. Fixed Peripheral Arrangement (represented by Δ)

Fixed peripheral arrangement, otherwise known as fixed-peripheral-constant-diameter-inward arrangement, is an arrangement in which integral number of grain are first placed on the most outer ring inside a combustion chamber, and then other tubes of equal diameter are placed in circles, inwardly toward the center. Analysis reveals that, for the same values of n, in some cases the fixed peripheral arrangement results in higher packing density than the hexagonal arrangement. For instance:

$$\eta_{n=13\Delta} > \eta_{n=13\odot}, \quad \eta_{n=19\Delta} > \eta_{n=19\odot},$$

Let us assume $n_1 (\geq 10)$ being the grain number on the most outer ring, the number of eccentric circles being i, m being a natural number, we can obtain the following formula for n based on the geometric relation in Fig. 2.

$$
\left.\begin{aligned}
n_3(i) &= n_0 + \sum_{i=1}^{n} \frac{\pi}{\arcsin \dfrac{\bar{D}}{1-(2i-1)\bar{D}}}\Bigg|_{zh} \\
\bar{D} &= \frac{\sin\dfrac{\pi}{n_1}}{1+\sin\dfrac{\pi}{n_1}}
\end{aligned}\right\} \qquad (5)
$$

When $n_2=1\sim5$, $n_0=0$; when $n_2=6\sim9$, $n_0=1$; when $n_2>9$, then $n_0=0$; n_2 being the most inner circle and zh being the sum based on positive integers. Formula (5) can be used to compute the grain number on each eccentric circle as well as the total grain number in the fixed peripheral arrangement.

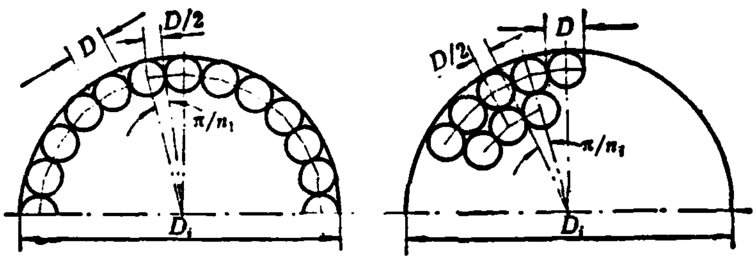

Fig. 2. Diagram of fixed peripheral arrangement.

3. Revised Arrangement (represented by X)

Revised arrangement is an arrangement in which integral number of grains are first placed in the most inner circle inside a combustion chamber (but this is not hexagonal arrangement), and then other tubes of equal diameter are placed in circles, toward the side of the chamber. It is an arrangement derived from revising the fixed peripheral arrangement and can in some cases achieve higher packing density than the fixed peripheral arrangement.

Let us assume $n_2(\geqslant 3)$ being the grain number on the most inner circle, the number of eccentric circles being i, we can arrive at the following formula for $n_x(i)$ based on the geometric relation in Fig. 3.

$$
\left.\begin{aligned}
n_x(i) &= n_0 + \sum \frac{\pi}{\arcsin \dfrac{\overline{D}_{in_2}}{1-\overline{D}_{in_2}}}\Bigg|_{zh} \\
\overline{D}_{in_2} &= \frac{\sin \dfrac{\pi}{n_2}}{1+(2i-1)\sin\dfrac{\pi}{n_2}}
\end{aligned}\right\} \qquad (6)
$$

When $n_2=3,4,5$, $n_o=0$; when $n_2=6,7,8,9$, $n_o=1$; zh is the sum based on positive integers. $\overline{D}_{in_2}$ is the relative exterior diameter of the ith circle when the grain number on the most inner circle is n_2.

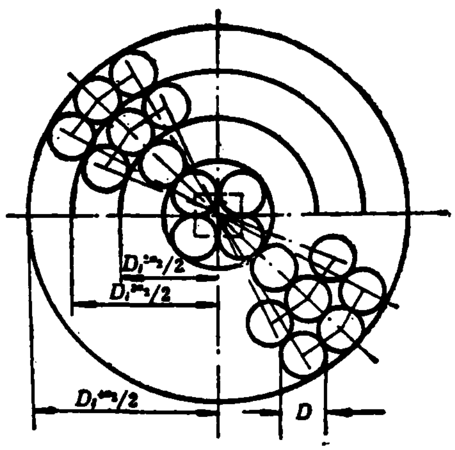

Fig. 3. Diagram of revised arrangement.

Formula (6) can be used to compute the grain number on each eccentric circle as well as the total grain number $n_x(i)$ in the revised arrangement.

4. Even Arrangement

Experiments indicate that for the above arrangements, even when $\lambda=\frac{\varkappa_{.j}}{\varkappa_{.e}}=1$, relatively high dispersion of internal ballistic performance will still exist, causing dispersion of initial velocity in rockets and missiles. Such phenomenon in crowded arrangement is caused by fracture of grain tubes due to partial flow velocity differential and pressure differential created in the interior and exterior inlet. In order to solve the problem in dispersion of internal ballistic performance and grain tube stability, such even arrangement is presented.

In $\bar{D}_p=\phi\bar{D}_{th}$ (7)

$\bar{D}_{th}$ is the theoretic value of the relative exterior diameter of the grain, $\bar{D}_p$ is the practical value of the relative exterior diameter of the grain for revision coefficient ϕ for consideration. As far as consideration limiting case for crowded arrangement is concerned, $\phi=0.98$ is usually adopted; however for even arrangement, $\phi=0.95$, 0.90, 0.85 are employed. Table 2 lists the value of n and the computed results of its $\bar{D}$ for several arrangements.

Table 2. $\bar{D}_{th}=f_1$ (n, arrangement)

n	arr.	$\bar{D}_{th}$	n	arr.	$\bar{D}_{th}$	n	arr.	$\bar{D}_{th}$	n	arr.	$\bar{D}_{th}$
3	×	0.4641	38	△	0.1413	85	△	0.0946	141	×	0.0735
4	×	0.4142	40	×	0.1369	85	⊙	0.0984	144	△	0.0728
5	×	0.3702	41	△	0.1353	87	×	0.0934	149	×	0.0714
6	×	0.3333	43	×	0.1261	90	△	0.0919	151	△	0.0711
7	⊙	0.3333	43	⊙	0.1297	91	⊙	0.0909	151	⊙	0.0741
8	△	0.3026	44	△	0.1297	93	×	0.0909	153	×	0.0707
9	△	0.2768	47	×	0.1250	95	△	0.0893	158	△	0.0695
10	△	0.2549	48	△	0.1246	97	⊙	0.0878	161	×	0.0694
11	△	0.2470	50	×	0.1226	98	×	0.0885	163	⊙	0.0709
12	△	0.2470	52	△	0.1199	101	△	0.0868	165	△	0.0680
13	⊙	0.2239	53	×	0.1187	102	×	0.0861	169	⊙	0.0673
13	△	0.2361	55	⊙	0.1218	106	△	0.0845	173	△	0.0666
14	△	0.2280	56	△	0.1155	109	⊙	0.0863	180	×	0.0653
15	△	0.2198	57	×	0.1149	112	△	0.0823	181	△	0.0652
17	△	0.2056	60	△	0.1114	117	×	0.0806	186	×	0.0641
19	⊙	0.2000	61	⊙	0.1111	119	△	0.0802	187	⊙	0.0667
19	△	0.2056	62	×	0.1099	121	⊙	0.0824	188	△	0.0639
20	△	0.1931	65	△	0.1076	123	×	0.0787	193	×	0.0628
22	△	0.1820	66	×	0.1074	125	△	0.0782	195	△	0.0626
24	△	0.1721	70	△	0.1040	127	⊙	0.0769	196	×	0.0625
27	△	0.1632	73	⊙	0.1029	130	×	0.0769	199	⊙	0.0648
31	△	0.1552	74	△	0.1007	132	△	0.0763	204	△	0.0614
31	⊙	0.1589	78	×	0.0985	136	×	0.0752	211	⊙	0.0621
34	△	0.1480	80	△	0.0976	138	△	0.0745	215	×	0.0599
37	⊙	0.1429	82	×	0.0960	139	⊙	0.0760	223	⊙	0.0602

Two sets of control formulae are combined as follows in order to facilitate computer programming.

$n=f_1(\bar{D}$, arrangement, i) control formulae

$$n_{\odot}(i)=\{a_i,\ \{a_i+6k\}_{k=m_i}\}_i,\quad \bar{D}=\frac{1}{2i+1}$$

(The other formulae are omitted here)

$$n_\Delta(i) = n_0 + \sum_{i=1}^{m} \frac{\pi}{\arcsin \frac{\overline{D}}{1-(2i-1)\overline{D}}}\Bigg|_{zh}, \quad \overline{D} = \frac{\sin\frac{\pi}{n_1}}{1+\sin\frac{\pi}{n_1}}$$

$$n_x(i) = n_0 + \sum \frac{\pi}{\arcsin \frac{\overline{D}_{in_2}}{1-\overline{D}_{in_2}}}\Bigg|_{zh}, \quad \overline{D} = \frac{\sin\frac{\pi}{n_2}}{1+(2i-1)\sin\frac{\pi}{n_2}}$$

Design parameter=f_2 (geometric parameter) control formulae

$$\bar{d} = \frac{1-n\bar{D}}{n\bar{D}\lambda} = \bar{d}\ (n, \lambda, \text{arrangement})$$

$$\eta = n(\overline{D}^2 - \bar{d}^2) = \eta(n, \lambda, \text{arrangement})$$

$$\frac{W_p}{\gamma_p D_i^3 \varkappa} = \frac{\pi}{16}(\overline{D}-\bar{d})[1 - n(\overline{D}^2 - \bar{d}^2)] = \Omega(n, \lambda, \text{arrangement})$$

$$\bar{e}_1 = \frac{\overline{D}-\bar{d}}{2} = \bar{e}_1(n, \lambda, \text{arrangement})$$

$\overline{D}_p = \phi\overline{D}_{th}$ (n, arrangement), ϕ=0.98, 0.95, 0.90, 0.85

Computation results are compiled in the table that follows.

For n ranging from 3 to 200, there are 21 values of $n_{\odot}(i)$ in hexagonal arrangement; 44 values of $n_{\times}(i)$ in fixed peripheral arrangement and 30 in revised arrangement. To facilitate applications and optimal design, five categories are listed to the size of their packing coefficient η (ϕ + 0.98, λ + 1). The classification and screening results are shown in Table 3.

Table 3.

η category	arr.	n values (from left to right on decreasing η)
η_{I} (>0.70)	⊙	199, 187, 151, 85, 121, 163, 55, 109, 139
	△	19
η_{II} (0.64~0.68)	⊙	31, 7, 73
	△	173, 181, 132, 188, 138
	×	161, 136, 130, 93, 98, 180, 196
η_{III} (0.60~0.64)	⊙	169, 19, 61, 91, 127, 97
	△	119, 125, 195, 158, 144, 165, 80, 101, 90, 38, 112, 95, 70, 106, 65, 41, 74, 52, 58, 31, 20, 48, 34
	×	153, 186, 123, 141, 66, 193, 17, 149, 87, 78, 102, 82, 57, 50, 40, 62, 53, 60
η_{IV} (0.5~0.60)	⊙	43
	△	8, 44, 22, 15, 13, 27, 24
	×	47, 6, 3
η_{V} (<0.5)	△	9, 10
	×	4, 5, 43

The relations of η_{I}, η_{II} with respect to n, arrangement and λ are obtained through selection and are illustrated in Fig. 4 and Fig. 5.

Analysis through categorized selection reveals that within the range of η_{I} there are 9 arrangements in hexagonal arrangement; i. e., $n_{\odot}$=199, 187, 151, 85, 121, 163, 55, 109, 139 whereas in fixed peripheral arrangement, there is only one, namely $n_{\triangle}$=19. Within the range of η_{II} there are 3 arrangements in hexagonal arrangement; i. e., $n_{\odot}$ =31, 7, 73 and five arrangements in fixed peripheral arrangement; i. e., $n_{\triangle}$=173, 181, 132, 188, 138 as opposed to seven arrangements in revised arrangement; i. e., $n_{\times}$=161, 136, 130, 93, 98, 180, 196.

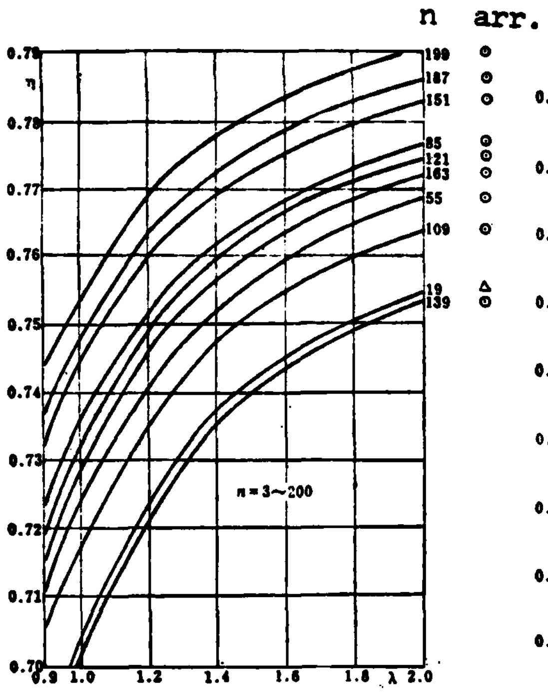

Fig. 4. $\eta_I = \eta_I(n, \text{arrangement}, \lambda)$

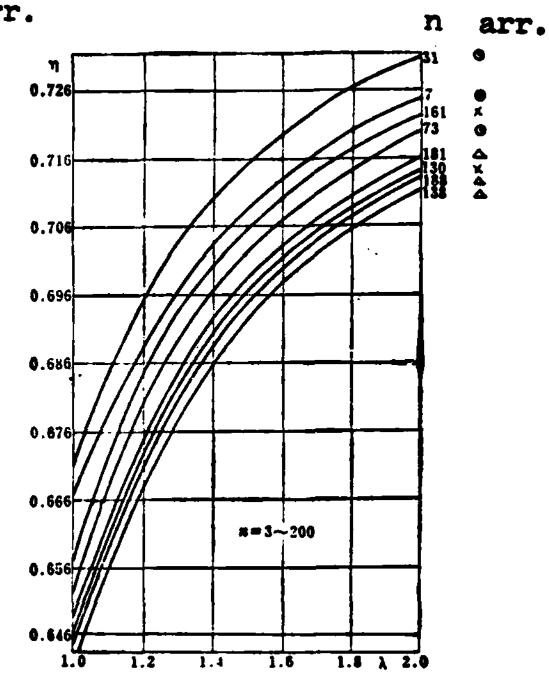

Fig. 5. $\eta_{II} = \eta_{II}(n, \text{arrangement}, \lambda)$

In order to satisfy the need in various applications, values of n are divided into four groups and are further selected by category. Results are given in Table 4.

Table 4.

n range	η	n values (from left to right on η)
Group 1 3~50	η_I	19△
	η_{II}	31⊙, 7⊙
	η_{III}	19⊙, 38△, 37⊙, 41△, 50×, 40×, 31△, 20△, 48△, 34△
Group 2 51~100	η_I	85⊙, 55⊙
	η_{II}	73⊙, 93×, 98×
	η_{III}	80△, 66×, 90△, 87×, 95△, 70△, 78×, 82×, 61⊙, 63[illegible], 57×, 91⊙, 74△, 62×, 97⊙, [illegible]△, 56△, 53×
Group 3 101~150	η_I	121⊙, 109⊙, 139⊙
	η_{II}	136×, 130×, 132△, 138△
	η_{III}	11[illegible]⊙, 125△, 144△, 123×, 141×, 101△, 117×, 1[illegible]×, 112△, 106△, 102×, 127⊙
Group 4 151~200	η_I	199⊙, 187⊙, 151⊙, 163⊙
	η_{II}	161×, 173△, 181△, 180×, 196×
	η_{III}	169⊙, 153×, 186×, 193△, 158△, 16[illegible], 193×

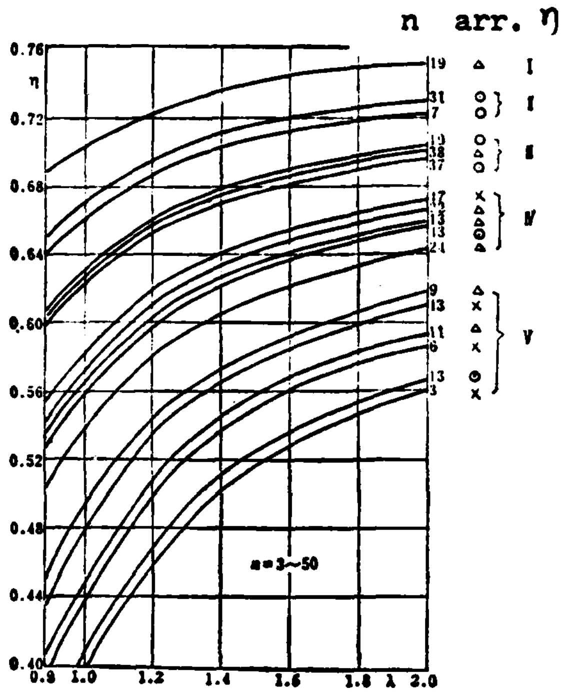

Fig. 6. $\eta=\eta$(n, arrangement, λ)

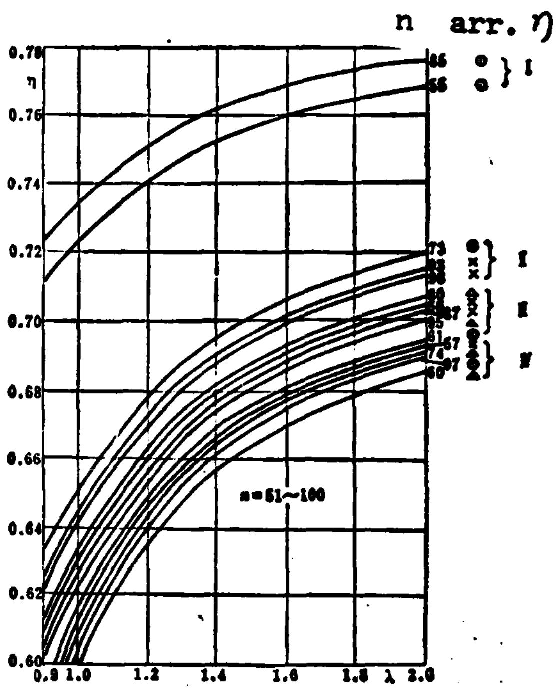

Fig. 7. $\eta=\eta$(n, arrangement, λ)

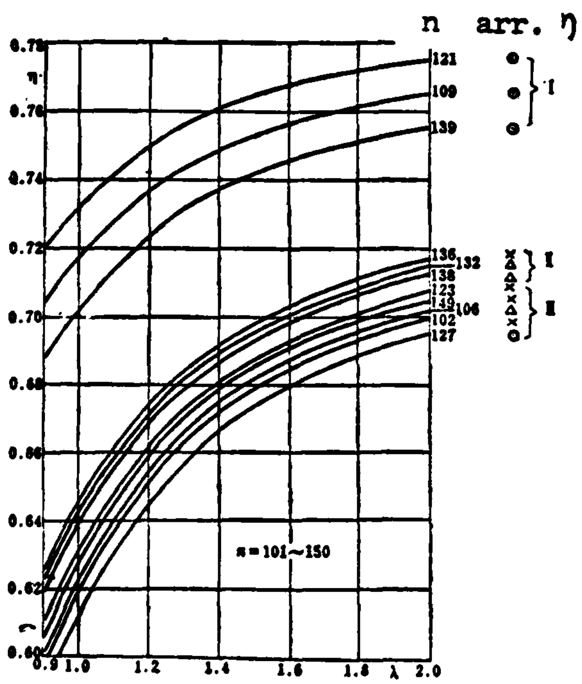

Fig. 8. $\eta=\eta$(n, arrangement, λ)

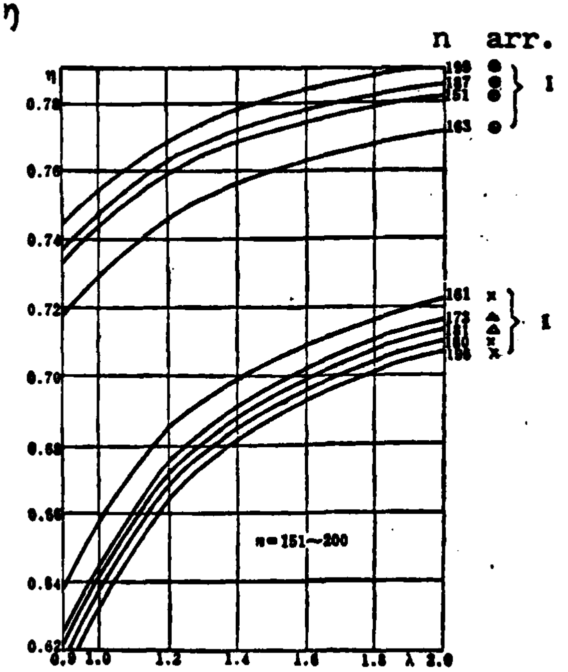

Fig. 9. $\eta=\eta$(n, arrangement, λ)

The relationship of packing coefficient η with respect to n, arrangement and λ in each group are given from Fig. 6 through Fig. 9. As far as η_I is concerned, there is one in group 1, i. e., 19△; two in group 2, i. e., 85⊙, 55⊙; three in group 3, i. e., 121⊙, 109⊙, 139⊙, and four in group 4 i. e., 199⊙, 187⊙, 151⊙, and 163⊙. As far as η_{II} is concerned, there are two in group 1, i. e., 31⊙, 7⊙; three in group 2, i. e., 73⊙, 93X, 98X; four in group 3, i. e., 136X, 130X, 132△, 138△, and five in group 4, i. e., 161X, 173△, 181△, 180X and 196X.

Due to different arrangement, for equal values of grain number n, their values in η are different and in some cases the difference is quite big. For example, at n=19 when hexagonal arrangement is changed to fixed peripheral arrangement, its value in η can raise from η_{II} to η_I. At n=85, η_{II} can also be raised to η_I if fixed peripheral arrangement is changed to hexagonal arrangement. Therefore we can say that an optimal arrangement exists when values of n are equal. Optimal design for n=13, 19, 31, 43, 85, 151 is listed in Table 5.

Table 5. Optimal arrangement for same values of n.

value of n	arr.	η	optimal arrangement
13	⊙	0.4023	$\eta_{13\triangle} > \eta_{13\odot}$ Take n=13△
	△	0.5631	
19	⊙	0.6300	$\eta_{19\triangle} > \eta_{19\odot}$ Take n=19△
	△	0.7036	
31	⊙	0.6697	$\eta_{31\odot} > \eta_{31\triangle}$ Take n=31⊙
	△	0.6056	
43	⊙	0.5605	$\eta_{43\odot} > \eta_{43\times}$ Take n=43⊙
	×	0.4772	
85	⊙	0.7349	$\eta_{85\odot} > \eta_{85\triangle}$ Take n=85⊙
	△	0.6312	
151	⊙	0.7442	$\eta_{151\odot} > \eta_{151\triangle}$ Take n=151⊙
	△	0.6359	

The above analysis shows how to achieve optimal design of multiple tube grain and their arrangement according to the principle of maximum packing density. Certain launchers and uncontrolled rocket boosters demand extreme short working time and the requirement is very stringent. In other words, there is a definite requirement on the value of $\bar{e}_1$. The following analysis will present optimal design of multiple tube grain and their arrangement in the cases that the values of $\bar{e}_1$ is to be satisfied.

When $\bar{e}_1 \geqslant 0.1$, we can select corresponding grain type to fulfill the requirement of $\bar{e}_1$ of various ranges. For $\bar{e}_1 < 0.1$, available grain types are multiperforated grain, laminated grain, coiled grain and multiple tube grain, the first being an area augmenting grain. Generally multiple tube grain is used in order to achieve near constant area behavior. Analysis shows that for a given $\bar{e}_1$ there are multiple values of n and its arrangement that can meet the requirement. Results are shown in Fig. 10 when optimal selection is performed based on maximum packing coefficient. Analysis on Fig. 10 reveals the following:

$\bar{e}_1 = 0.02 \sim 0.044$ is the region of high packing density web coefficient $\bar{e}_1$. In such $\bar{e}_1$ region values of n and its arrangement in ranges of η_{I} or η_{II} can be selected which will satisfy $\bar{e}_1$ provided that pressure is controlled properly. $\bar{e}_1 = 0.044 \sim 0.07$ is the region of medium packing density web coefficient $\bar{e}_1$. In such region the majority of n values selected on $\bar{e}_1$ fall on η_{III} range, except for a few cases of n and its arrangement based on η_{I}. $\bar{e}_1 = 0.07 \sim 0.11$ is the region of low packing density web coefficient $\bar{e}_1$. In such region with the two exceptions of $\bar{e}_1$ [$\bar{e}_1 = 0.708(\eta_{I})$ and $\bar{e}_1 = 0.661(\eta_{II})$] a great majority of n values selected on $\bar{e}_1$ and its arrangement are low, falling on η_{II} range or η_{V} range. For a required $\bar{e}_1$ whose corresponding n and η from its arrangement are on the low side, $\bar{e}_1$ value can be modified through the selection of a propellant of constant combustion rate or through the selection of pressure, thus boosting its corresponding n and η on its arrangement.

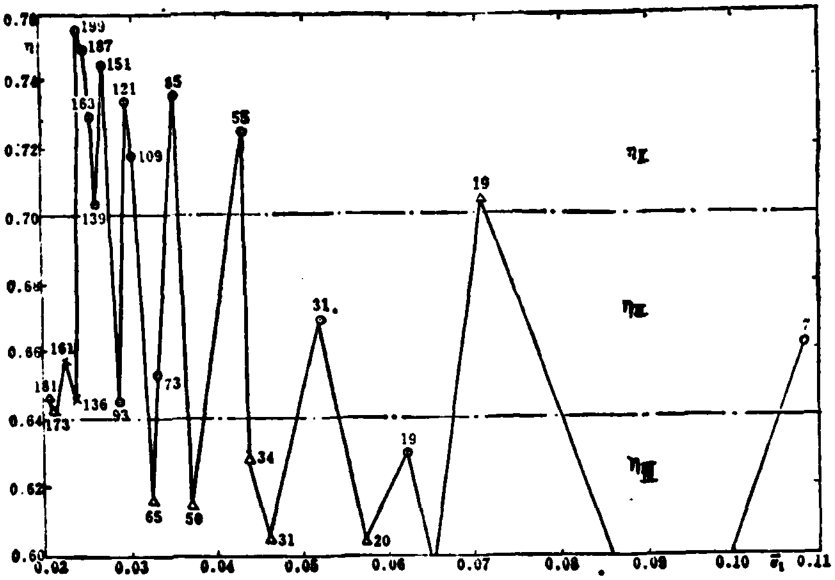

Fig. 10. Relation of $\eta = f(\bar{e}_1)$ when $\lambda = 1$.

Thus we are able to select an optimal n and its arrangement to meet the requirement of grain packing design.

This paper constructs the following three sets of multiple tube grain design curves based on computation results with respect to n and its arrangement.

$\bar{d} = \bar{d}$(n, arrangement, λ, Φ) design curve;

$\bar{e}_1 = \bar{e}_1$(n, arrangement, λ, Φ) design curve;

$\frac{W_p}{\gamma_p D_j^3 x} = \Omega$(n, arrangement, λ, Φ) design curve.

These sets of design curves are presented in Fig. 11 through Fig. 16. By employing these sets of multiple tube grain design curves an optimal design of multiple tube grain and its arrangement satisfying $\bar{e}_1$ requirement can be quickly obtained.

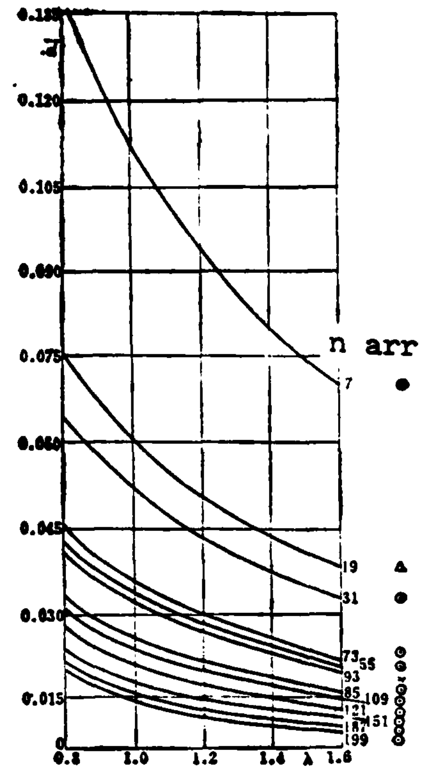

Fig. 11. ϕ=0.98

$\bar{d}=\bar{d}$(n, arrangement, λ) design curve

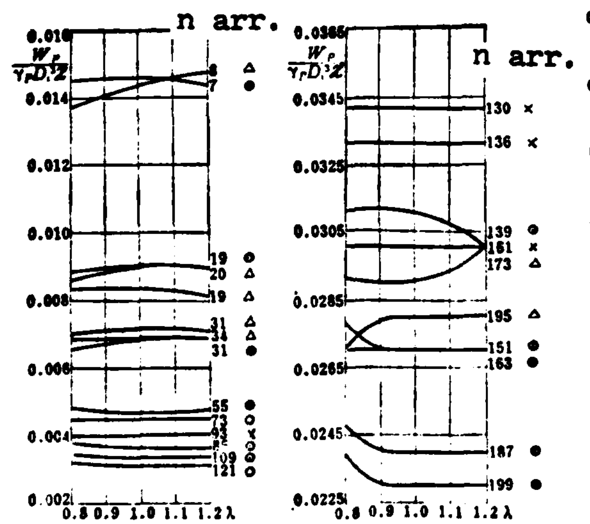

Fig. 13. ϕ=0.98

$\frac{W_P}{\gamma_P D_j^3 x}=\Omega$(n, arrangement, λ)

design curve

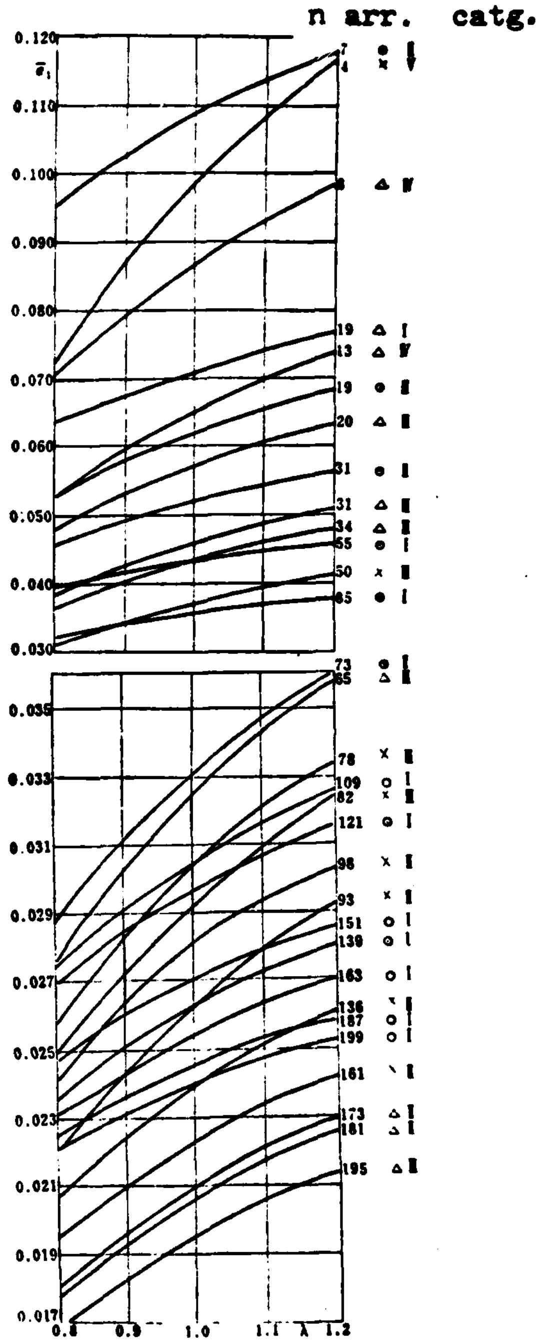

Fig. 12. ϕ=0.98

$\bar{e}_1=\bar{e}_1$(n, arrangement, λ)

design curve

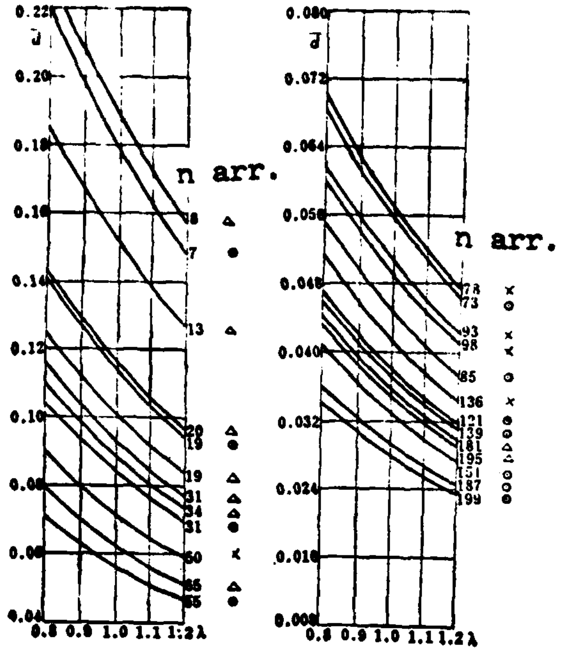

Fig. 14. ϕ=0.90

$\bar{d}=\bar{d}$(n, arrangement, λ) design curve

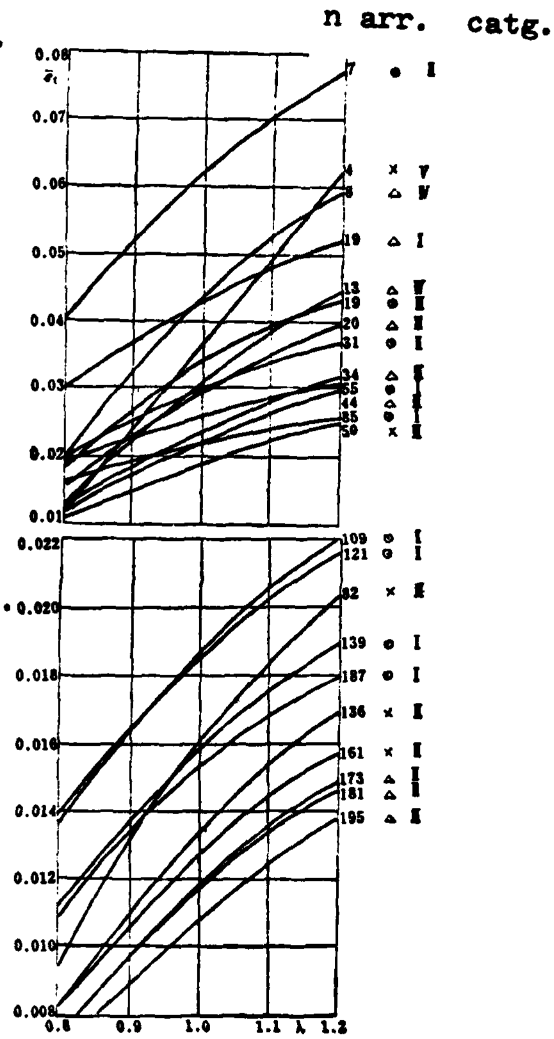

Fig. 15. ϕ=0.90

$\bar{e}_1=\bar{e}_1$(n, arrangement, λ)

design curve

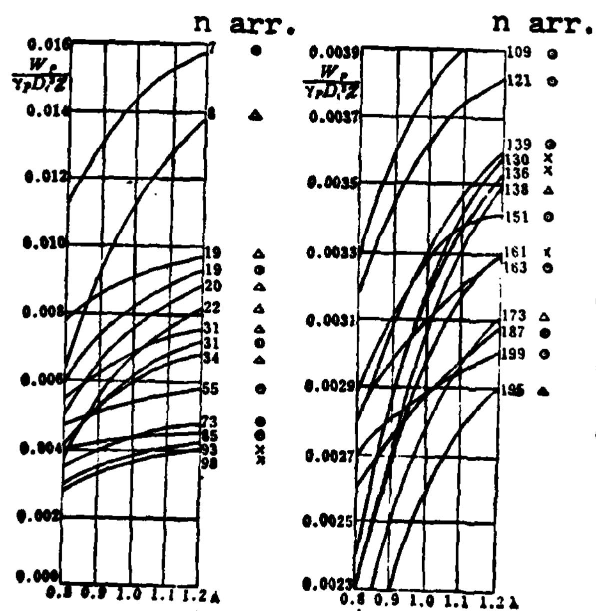

Fig. 16. ϕ=0.90

$\frac{W_p}{\gamma_p D_1^3 z}=\Omega$(n, arrangement, λ)

design curve

APPLICATION EXAMPLE

Suppose that a certain engine has an interior diameter (D_i) of 90 mm and a total impulse ($I_{+20°C}$) of 190 kg-sec is to be guaranteed for initial velocity. Try to design an optimal tube grain and its arrangement for a combustion time $t_b \leq 0.018$ sec at +20°C.

[Solution] Select a solid propellant whose specific impulse, specific weight and combustion rate are as follows:

I_{sp}=242 second, γ_p=1.704 g/cm^3, $r_{+20°C}=6.15p^{0.36}$

Pressure at +20°C in combustion chamber $p_{+20°C}$=300kg/cm^2

Then the grain thickness is

$$e_1=2ap^n t_b=2\times6.15\times300^{0.36}\times0.018=1.73(\text{mm})$$

The required web coefficient is

$$\bar{e}_1=e_1/D_1=1.73/90=0.0192$$

The required grain weight is

$$W_p=\frac{I}{I_{sp}}=\frac{190}{242}=0.785(\text{kg})$$

$\bar{e}_1$ for consideration is very small, and for the purpose of minimizing performance dispersion and stabilizing multiple grain, even arrangement for multiple tube grain is chosen. Select ϕ=0.90, for $\bar{e}_1$=0.0192, from Fig. 15, at ϕ=0.90, the following ten propositions are obtained as listed in Table 6 through the design curve $\bar{e}_i=\bar{e}_1$(n, arrangement, λ).

Table 6.

n	55⊙	65△	73⊙	78×	82×	85⊙	93⊙	98×	109⊙	121⊙
λ	0.80	1.06	1.025	1.11	1.14	0.89	1.15	1.175	1.035	1.05
η category	I	II	II	II	II	I	II	II	I	I

First look at the four propositions belonging to η_I, i. e., n=55⊙, 85⊙, 109⊙ and 121⊙. From Fig. 4 it can be seen that $\eta_{n=85} > \eta_{n=121} > \eta_{n=55} > \eta_{n=109}$. Looking up Fig. 16 for those four cases belonging to η_I, ϕ=0.90, $W_p/\gamma_p D_i^3 k=\Omega$(n, arrangement, λ), four values of n and λ, Ω, $\varkappa$ corresponding to its arrangement are obtained, as indicated in Table 7.

Table 7.

n	55⊙	85⊙	109⊙	121⊙
λ	0.80	0.89	1.035	1.05
Ω	0.0047	0.0040	0.00385	0.0037
$\varkappa$	135	158	164	172

Since such propellant has a threshold $\varkappa^*=150$ and the pressure for consideration are relatively high ($300kg/cm^2$), the allowed $\varkappa^*$ has to be raised accordingly, and thus the proposition of n=85 hexagonal arrangement is selected.

At n=85⊙ and λ=0.89, from Fig.14 we get $\bar{d}$=0.050. From Table 2 we get $\bar{D}=\phi\bar{D}_{th}$=0.9X0.0984=0.08856, Finally we obtain the optimal design that meets the requirement of armament technology as:

$$\frac{D}{d}\text{-LXn} = \frac{7.97}{4.50} - 136 \text{ X } 85 \quad \text{(hexagonal arrangement)}$$

After rounding we get

$$\frac{D}{d}\text{-LXn (arrangement)} = \frac{8.0}{4.6} - 137 \text{ X } 85 \quad \text{(hexagonal arrangement).}$$

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† Translator's note: Phonetic translation from Chinese back to the original language.