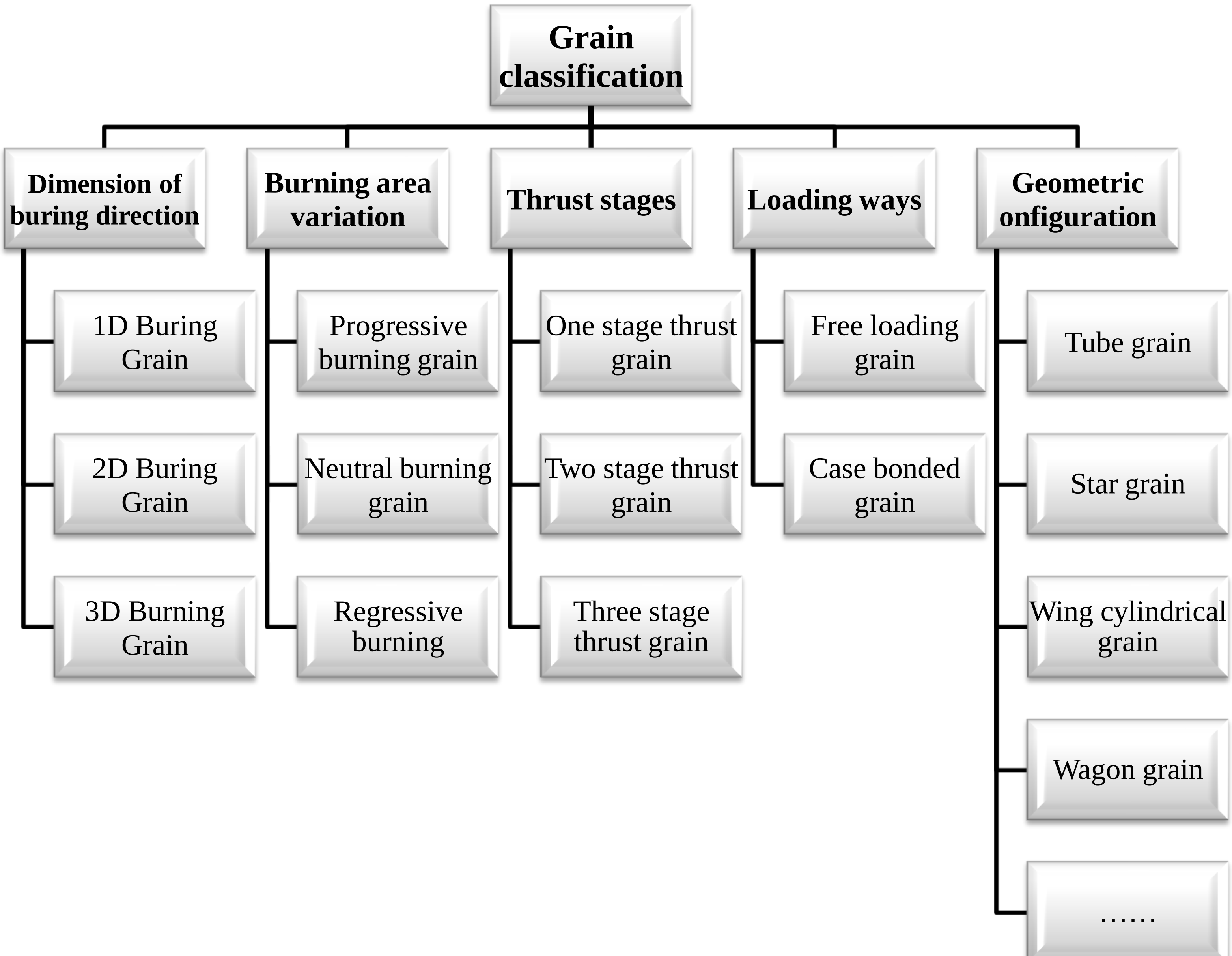
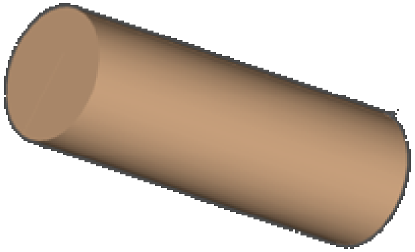
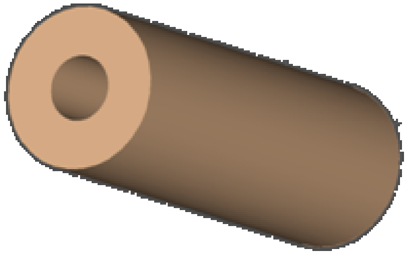
Solid Rocket Motor

Part 6 Propellant Grain Design

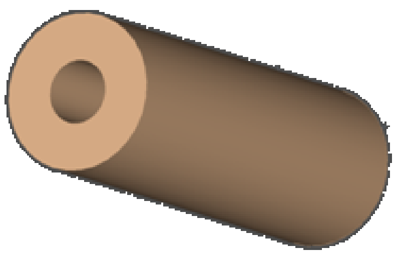
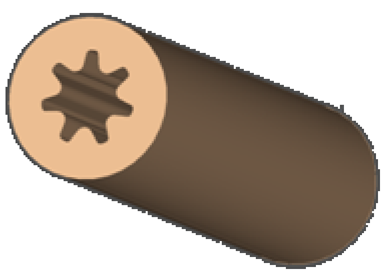
Propellant Grain Selection



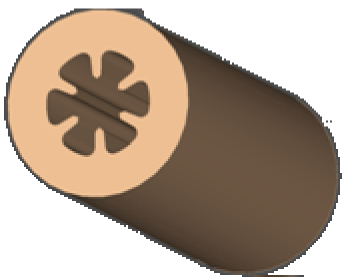
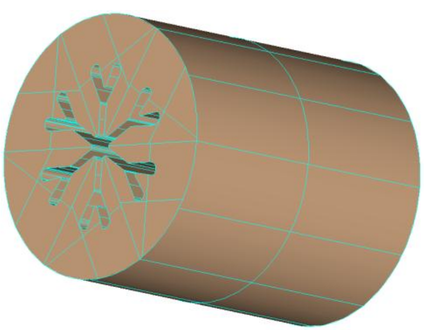
Grain configuration Selection

Grain	sketch	characteristics	Volume loading fraction	Web fraction	Typical application
End burning grain		➢ Large maximum web ➢ Long working time ➢ Small thrust ➢ Small burning area ➢ Big changes of the center of gravity	0.90~0.95	>1.0	sustaining motor Gas generator
Internal burning grain		➢ Simple structure ➢ Residual propellant free ➢ Without stress concentration ➢ Progressive burning ➢ Process maturity ➢ Convenient use	0.85~0.95	0.5~0.9	Catapult launch device Booster

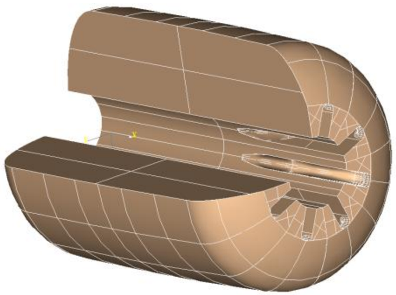
Grain configuration Selection

Grain	sketch	characteristics	Volume loading fraction	Web fraction	Typical application
Internal/ external burning tube grain		➢ Simple structure ➢ Residual propellant free ➢ Without stress concentration ➢ Neutral burning grain ➢ Process maturity ➢ Short working time ➢ Have broken grain	0.75~ 0.8	0.3~0.5	Rockets Booster motors
Star grain		➢ Large loading fraction ➢ Good structural integrity ➢ large adjustable range of burning area ➢ Residual propellant	0.75~ 0.85	0.3~ 0.6	Widely used in missile and launch vehicle motors

Grain configuration Selection

Grain	sketch	characteristics	Volume loading fraction	Web fraction	Typical application
Wagon grain		➢ Thin web ➢ Small loading fraction ➢ Multi stage thrust ➢ Stress concentration	0.65~ 0.70	0.2~ 0.3	Booster Igniter motor Small motors
Dendrite grain		➢ Thin web ➢ Small loading fraction ➢ Multi stage thrust ➢ Stress concentration	0.65~ 0.70	0.2~ 0.3	Booster Igniter motor Small motors

Grain configuration Selection

Grain	sketch	characteristics	Volume loading fraction	Web fractio n	Typical applicat ion
Finocyl grain		➢ Case bonding ➢ Large loading fraction ➢ Good structural integrity ➢ large adjustable range of burning area ➢ Residual propellant free	0.75~ 0.85	0.4~ 0.7	Large motors
Star tube grain		➢ Case bonding ➢ large adjustable range of burning area ➢ Residual propellant free ➢ Two stage thrust realizability ➢ Good structural integrity	0.75~ 0.85	0.4~ 0.7	Two stage thrust motors

Overview

Grain → A general term of solid propellant with certain configuration in combustion chamber

The geometric structure change of grain during burning →

Gas generation rate and its variation law

Time dependent relation of Pc and F

(Internal ballistic curve)

Grain design is a kind of art which is the ingenious coordination of many constraints.

The design level of propellant grain affects the performance of solid rocket motors。

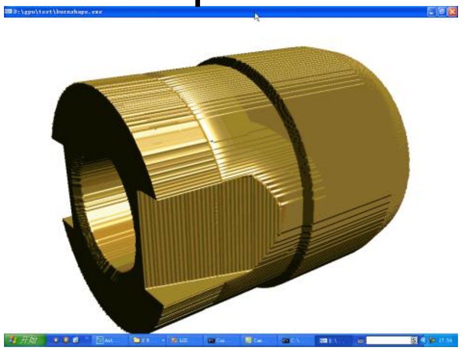
Overview

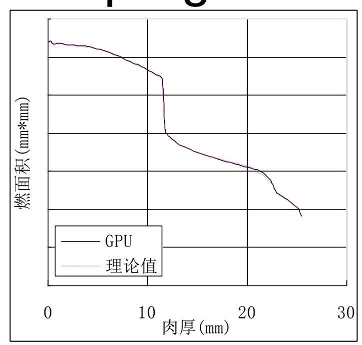
■ General principles of grain design

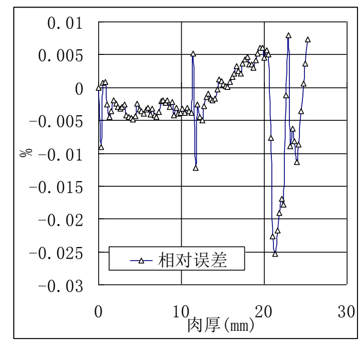
- Meet the requirements of the total impulse (C^*, ρ_p).

$$I_t = V_p \rho_p C^* C_F$$

- Energy release of the grain in burning process should be in accordance with the requirements of the thrust program.

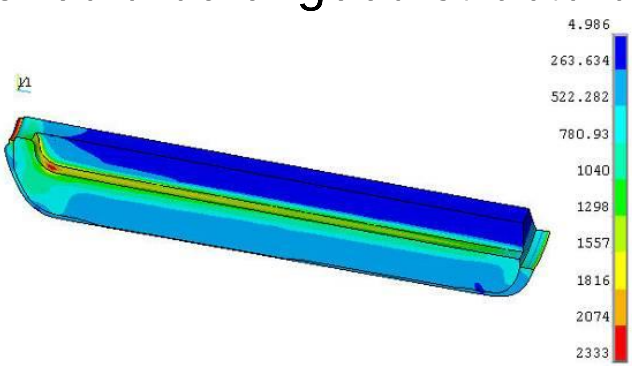




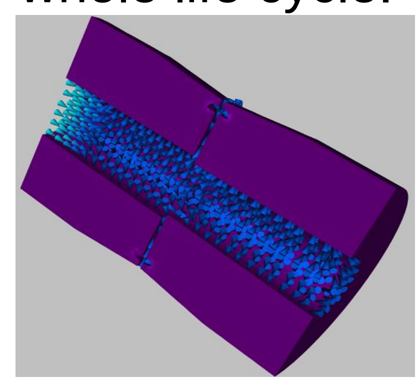


- The grain should be of good structural integrity in the whole life cycle.

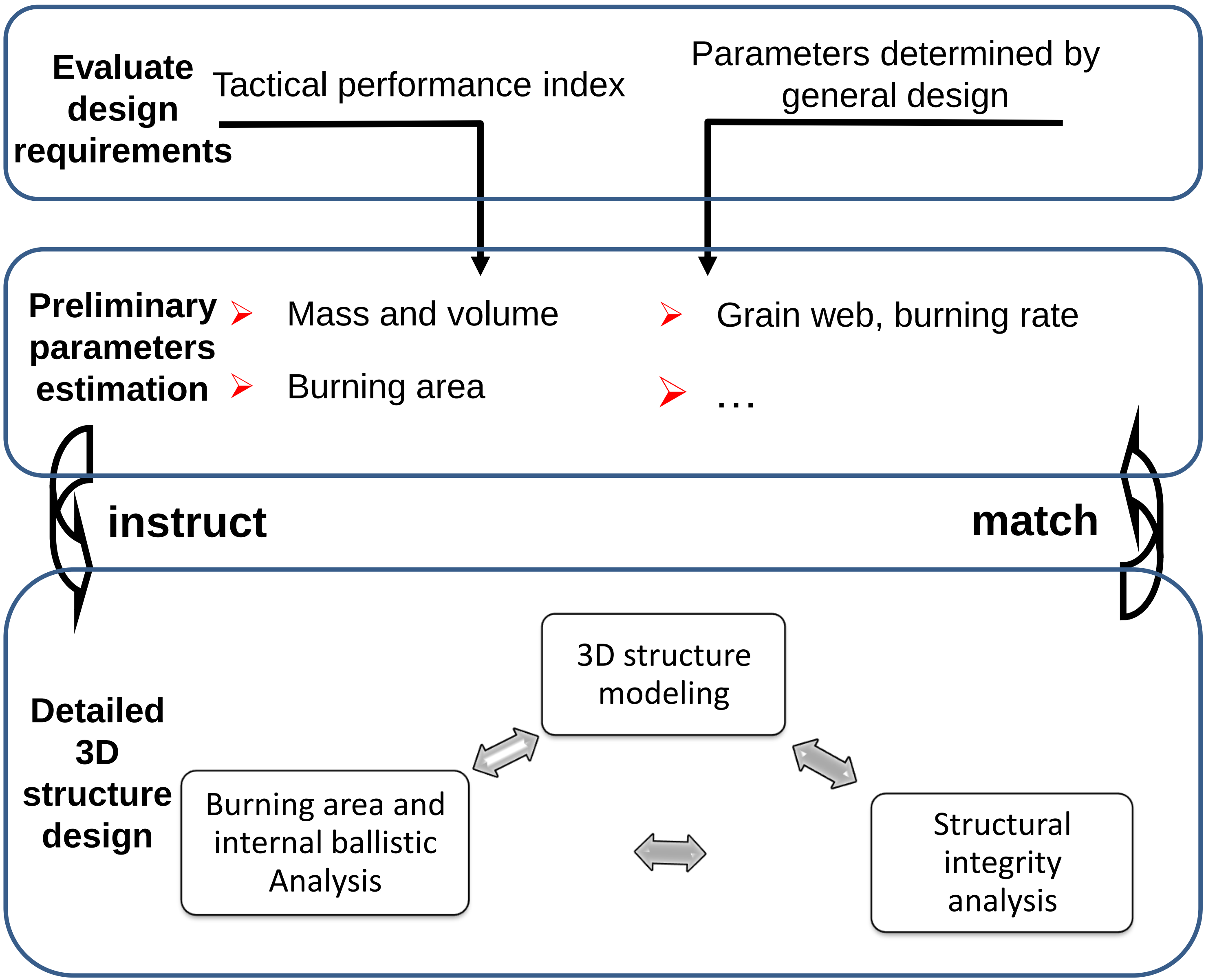
Stress distribution of grain in manufacturing process. (Curing and cooling)



Structure failure simulation of the grain of the Space Shuttle Challenger booster.



Evaluate design requirements

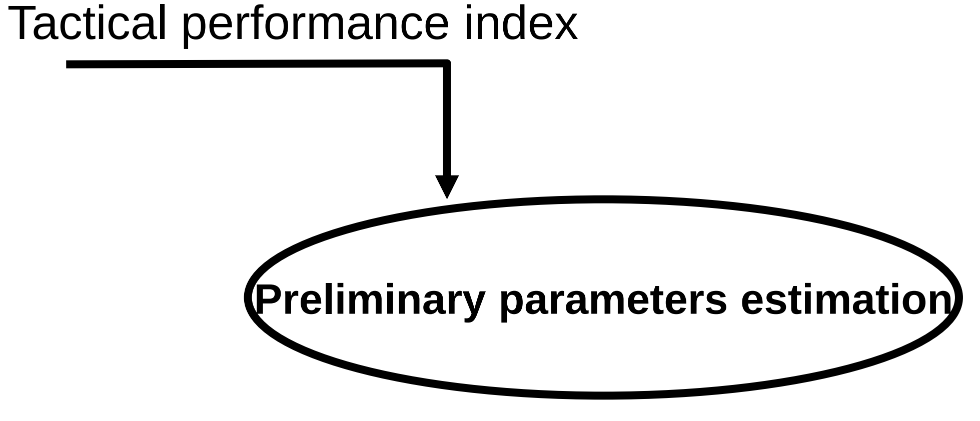


■ **Grain Design Process**

Evaluate design requirements

■ **Parameters related to the grain design in tactical performance index**

- Total impulse It (Impulse requirements of general design)
- Thrust scheme (Thrust stage? The magnitude of each stage thrust?…)
- Working time t (Working time of first stage t_1, Working time of second stage t_2, …)
- Flight environment (Operational height, Operational temperature, …)



Evaluate design requirements

■Parameters related to the grain design in general design

- Structure of the motors
- Propellant (Composite propellant？ Double based propellant？)
- Semidiameter of rocket R_m (In general, R_m Subtract 5-10mm (Insulation thickness) is the semidiameter of the propellant grain R_p)
- Pressure of the combustion chamber (P_c)
- Nozzle expansion ratio (ε_A) and Thrust coefficient (C_F)

Parameters determined by general design

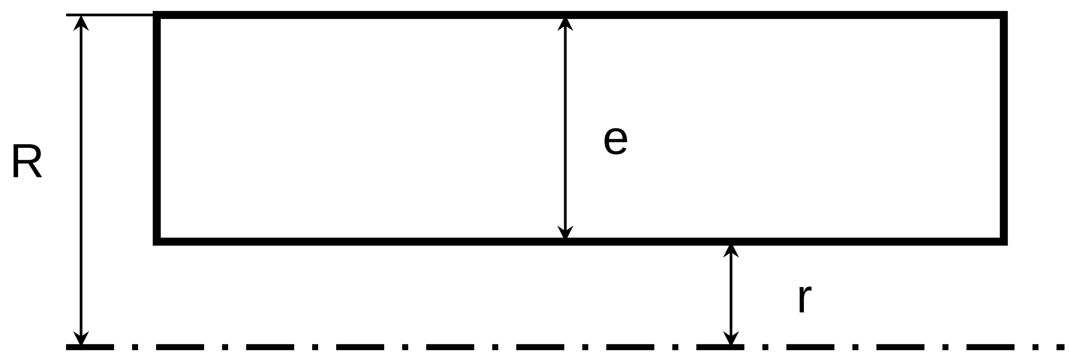
Preliminary parameters estimation

Several important parameters of grain

- For the requirements of total impulse： Estimate the weight (mp) and volume (Vp)

$$I_t = m_p C^* C_F C_F \qquad V_p = m_p / \rho_p$$

- For the requirements of working time： Estimate the max web (e) and burning rate (r)



- For the requirements of thrust scheme： Estimate the burning area (A_b) and the throat area of nozzle (A_t)

$$A_t = \frac{F}{C_F P_c} \qquad A_b = \frac{F}{C_F \cdot C^* \cdot \rho \cdot r}$$

Several important parameters of grain

■ （1） **Estimate the weight of grain (m_p)**

$$m_p = \frac{f \cdot I_t}{C^* \cdot C_F}$$

■ （1） **Estimate the volume of grain (V_p)**

$$V_p = m_p / \rho_p$$

Several important parameters of grain

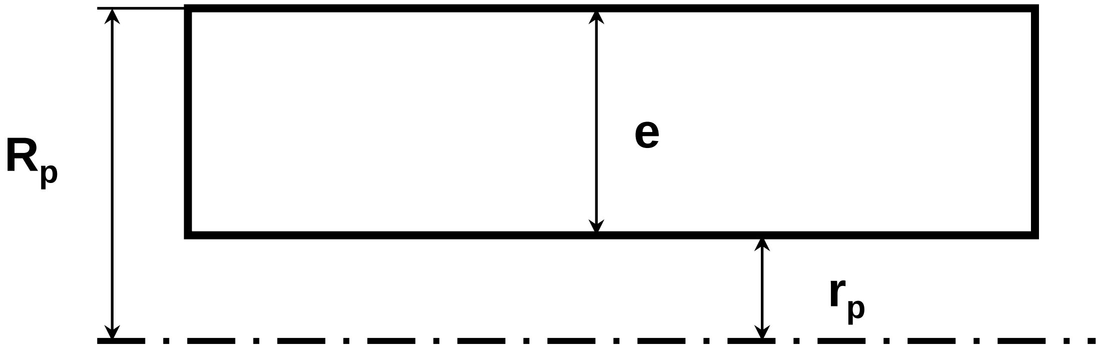
■ （2） Estimate the max web (e) and the burning rate (r)

- Web fractiom ($\bar{e}$)

$$\bar{e} = e / R_p$$

- Web fraction is a parameter response to loading density.

- The range of the web fraction: **0.4<** $\bar{e}$ **<0.8**



Several important parameters of grain

■ （2） Estimate the max web (e) and the burning rate (r)

- The maximum web (e) can be determined by the selected web fraction.

Internal burning grain： $$e = \bar{e} \cdot R_p$$

Internal/external burning grain： $$e = \bar{e} \cdot R_p / 2$$

- Burning rate of propellant under working pressure (r)

$$r = e / t$$

Several important parameters of grain

■ （2） Estimate the max web (e) and the burning rate (r)

- Volume loading fraction of grain (η_v)

$$\eta_\upsilon = \frac{V_p}{V_c}$$

- Volume loading fraction of grain is a more general parameter response to loading density.

Side burning grain: $$\eta_\upsilon \approx \frac{R^2-(R-e)^2}{R^2} = 2\bar{e} - \bar{e}^2$$

- The range of the volume loading fraction: **0.6<** η_v **<0.95**

Several important parameters of grain

■ （2） Estimate the max web (e) and the burning rate (r)

- Volume of the combustion chamber V_c

$$V_c = \frac{V_p}{\eta_\upsilon}$$

- Length of the propellant grain L_p

Side burning grain:

$$L_p = L_c = (\frac{V_p}{\eta_\upsilon}) / \pi R_p{}^2$$

End burning grain:

$$L_p = L_c * \eta_v$$

$e=L_p$ **$r=L_p/t$**

Several important parameters of grain

■（2） Estimate the max web (e) and the burning rate (r)

- Aspect ratio of grain (L_p/D_p) ——an important check parameter for grain design
- With the decrease of L_p/D_p, the effect of end area on burning area increase. To get a neutral burning grain, L_p/D_p has a great influence on the grain configuration selection;
- The high aspect ratio ($L_p/D_p>8$) will cause severe erosion burning, and will increase the trend of unstable combustion;
- In the case of a certain diameter of grain, Increasing the loading fraction excessively to reduce the aspect ratio will cause more serious structural damage 。

Several important parameters of grain

- **（3）Determination of the burning area of grain (A_b)**

$$A_b = \frac{F}{C_F \cdot C^* \cdot \rho \cdot r}$$

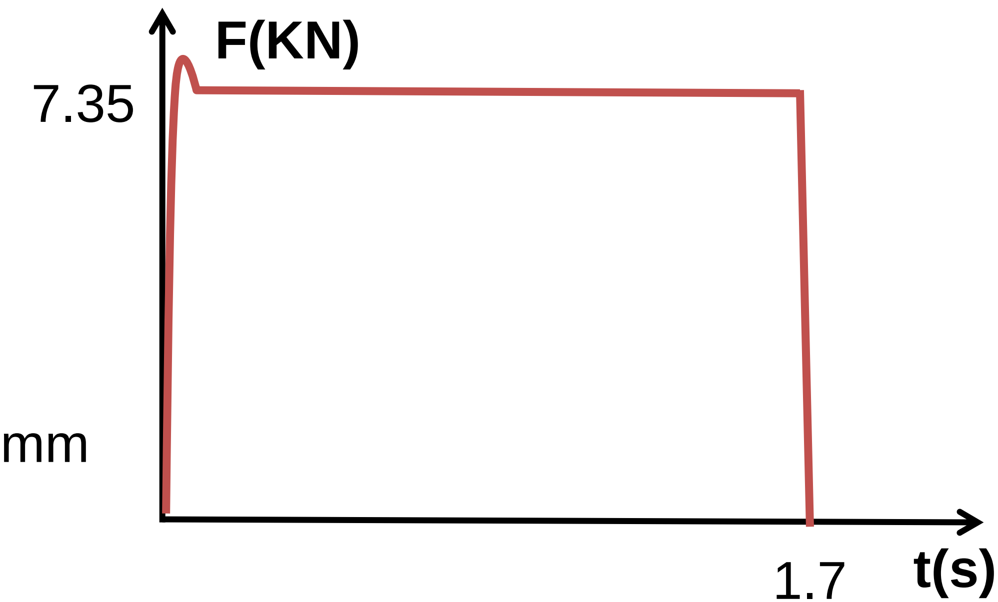
- **（3） Determination of the throat area of nozzle (A_t)**

$$A_t = \frac{F}{C_F P_c}$$

Determination of the general parameters of several typical grain

- **The parameters determined by the tactical performance and general design of a UAV booster**

  - Total impulse I_t: 12.5KN.s
  - Working time t: 1.7s
  - Thrust F: 7.35KN
  - Semidiameter of grain R_p: 56mm
  - Thrust coefficient C_F: 1.6
  - Pressure of the combustion chamber P_c: 10MPa



Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of UAV booster grain

- Propellant selection： double based propellant
  - $C^* = 1380 m/s$
  - $\rho =$ **1570kg/m³**
  - n = **0.3**
- Structure configuration selection of grain: Internal/external burning tube grain

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of UAV booster grain

- Estimate the weight of grain

$$m_p = \frac{f \cdot I_t}{C^* \cdot C_F} = \frac{1.03 \cdot 12500}{1380 \cdot 1.6} = 5.83kg$$

- Estimate the volume of grain

$$V_p = m_p / \rho_p = 5.83/1570 = 3.71 \times 10^6 mm^3$$

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of UAV booster grain

- Determine the web of grain

set $\bar{e} = 0.6$ ⇨ e=56*0.6=33.6mm

- Estimate and Determine the burning rate of grain

$$\bar{r} = (e/2)/t_b = 33.6/2/1.7 = 9.88mm/s$$

Finding the closest burning rate according to the propellant catalog:r=10mm/s

e=r*t*2=10*1.7*2= 34mm ⇨ $\bar{e} = e/R_p = 0.607$

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of UAV booster grain

- Loading fraction

$$\eta_\upsilon = \frac{V_p}{V_c} \approx \frac{R^2 - (R-e)^2}{R^2} = 2\bar{e} - \bar{e}^2 = 2 \cdot 0.607 - 0.607^2 = 0.846$$

- Volume of the combustion chamber

$$V_c = \frac{V_p}{\eta_\upsilon} = \frac{3.71 \times 10^6}{0.846} = 4.39 \times 10^6 mm^3$$

- Approximate length of the grain

$$L_p = (\frac{V_p}{\eta_\upsilon}) / \pi R_p{}^2 = \frac{3.71 \times 10^6}{0.846} / (3.14 \times 56^2) = 445mm$$

- Approximate aspect ratio of the grain

$$L_p / D_p = 445/112 = 3.97$$

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of UAV booster grain

- Throat area of the nozzle

$$A_t = \frac{F}{C_F P} = \frac{7350}{1.6 \cdot 10^7} = 4.59 \times 10^{-4} m^2 = 459 mm^2$$

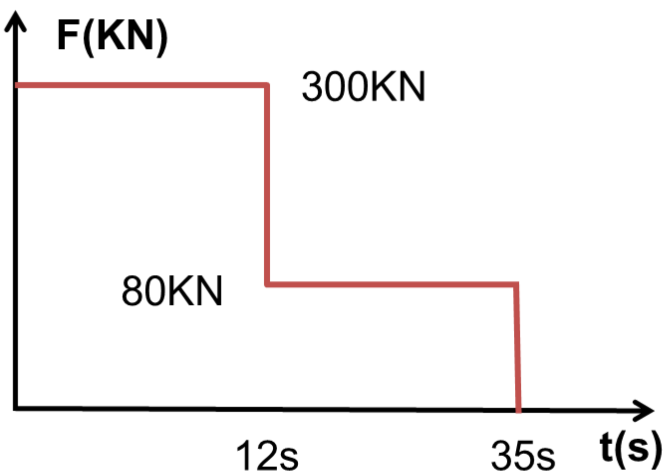
- Average burning area of the grain

$$A_b = \frac{F}{C_F \cdot C^* \cdot \rho \cdot r} = \frac{7350}{1.6 \cdot 1380 \cdot 1570 \cdot 0.01} = 0.212 m^2 = 212000 mm^2$$

Determination of the general parameters of several typical grain

■ The parameters determined by tactical performance and general design of a two stage motor

- Total impulse I_t: 1st stage 3600KN.s 2nd stage 1840KN.s
- working tiem t: 1st stage 12s, 2nd stage 23s
- Thrust F: 1st stage 300KN， 2nd stage 80KN
- Semidiameter of grain R_p: 365mm



- Thrust coefficient C_F: 1st stage 1.55, 2nd stage 1.35
- Pressure of the combustion chamber P_c: 1st stage 9Mpa, 2nd stage 2.8Mpa

Determination of the general parameters of several typical grain

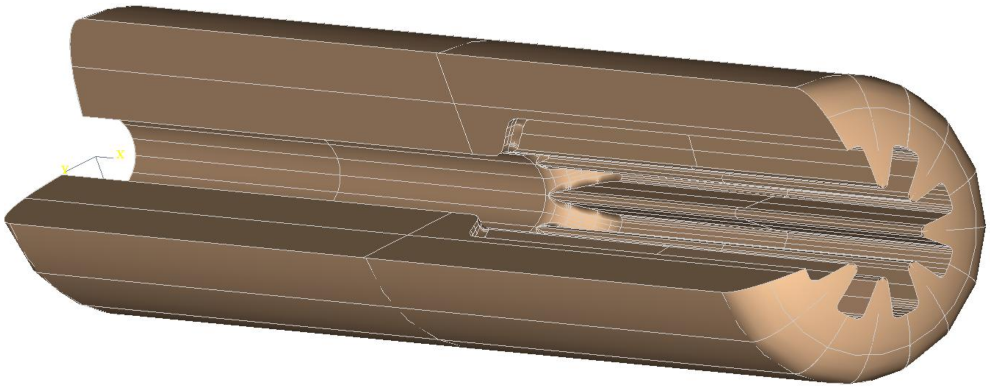
■ Preliminary parameters estimation of a two stage motor grain

➢ Propellant selection： composite propellant

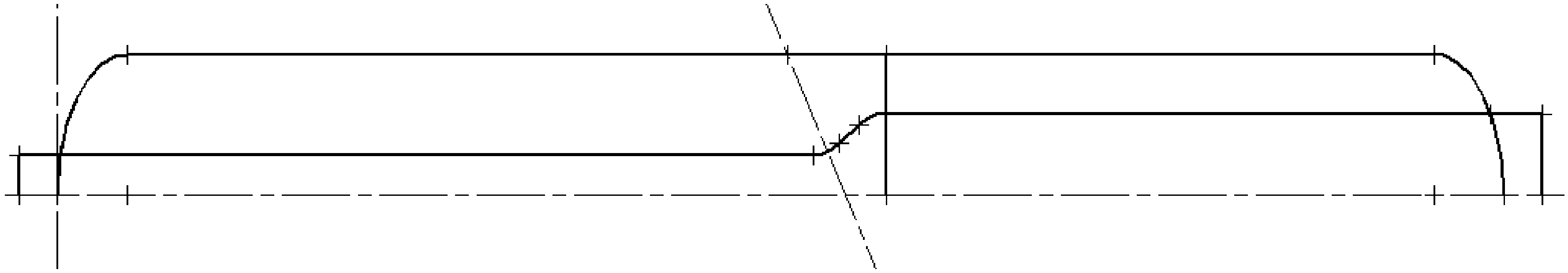
◆ $C^* = 1630 m/s$

◆ $\rho = \mathbf{1780 kg/m^3}$

◆ $n = \mathbf{0.4}$



➢ Structure configuration selection of grain: star-tube grain



Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of a two stage motor grain

- Estimate the weight of grain

$$m_p = \frac{f \cdot I_{t1}}{C^* \cdot C_{F1}} + \frac{f \cdot I_{t2}}{C^* \cdot C_{F2}} = ?$$

- Estimate the volume of grain

$$V_p = m_p / \rho_p = ?$$

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of a two stage motor grain

- Determine the web of grain

set $\bar{e} = 0.7$ ⇨ e=365*0.7=255.5mm

- Estimate and Determine the burning rate of grain

$$r_{9Mpa} \cdot t_1 + r_{2.8Mpa} \cdot t_2 = e$$

$$r = aP_c^{\ n}$$ ⇨ $$r_{2.8Mpa} = r_{9Mpa} \left(\frac{2.8}{9} \right)^{n=0.4}$$

Determination of the general parameters of several typical grain

■ Preliminary parameters estimation of a two stage motor grain

- Throat area of the nozzle

$$A_t = \frac{F}{C_F P_c} = ?$$

- Average burning area of the grain

$$\overline{A}_{b1} = \frac{F_1}{C_{F1} \cdot C_1^* \cdot \rho_p \cdot r_{9Mpa}} = \frac{A_t \cdot P_{c1}}{C_1^* \cdot \rho_p \cdot r_{9Mpa}} = ?$$

$$\overline{A}_{b2} = \frac{F_2}{C_{F2} \cdot C^* \cdot \rho \cdot r_{2.8Mpa}} = \frac{A_t P_{c2}}{C^* \cdot \rho \cdot r_{2.8Mpa}} = ?$$

Propellant selection

■ **Select propellant in accordance with the requirements of total impulse (I_t)**

➢ On energy characteristics： Under the premise of the overall design requirements, the propellant should have the high characteristic velocity(C*) and high density (ρ_p);

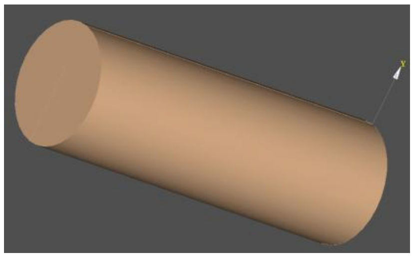
➢ On ballistic characteristics： The adjustable range of propellant burning rate (r) meets the requirements of grain design; Low pressure index (n), low temperature sensitivity coefficient of burning rate (a_T) ;

➢ On other characteristics： certain mechanical strength, good storage performance, appropriate price， …

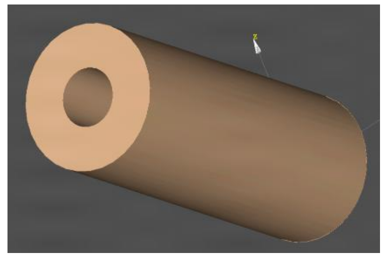
➢ If the propellant existed can meet the design requirements, then choose the propellant in the list of propellant manufacturer; else, a new propellant is needed.

Selection and design of grain configuration

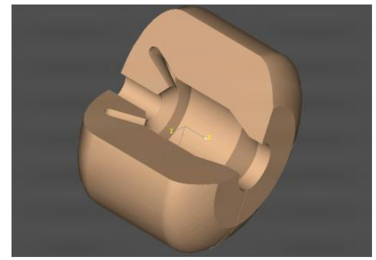
■ 3D grain configuration



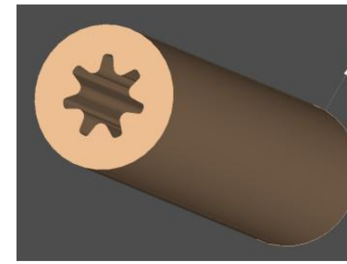
End burning



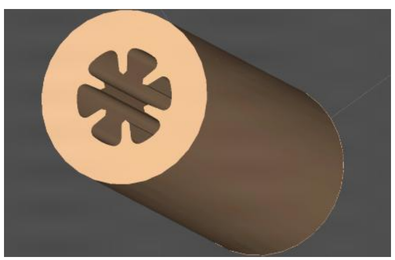
Tube



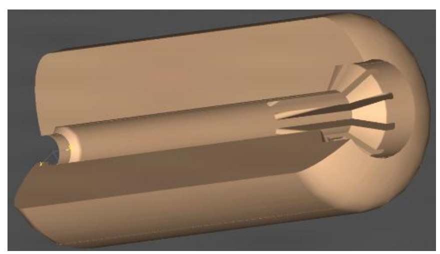
Rotary



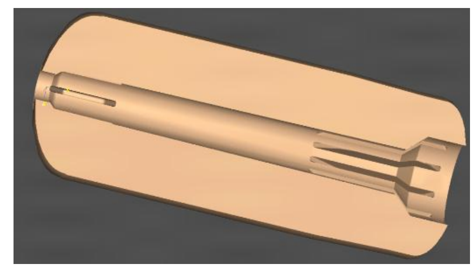
Star



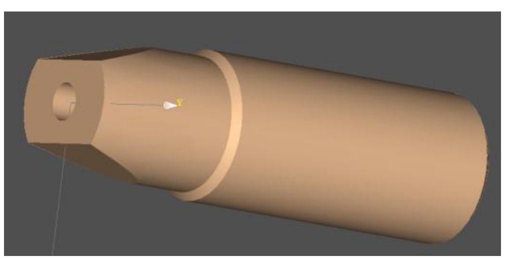
Wagon



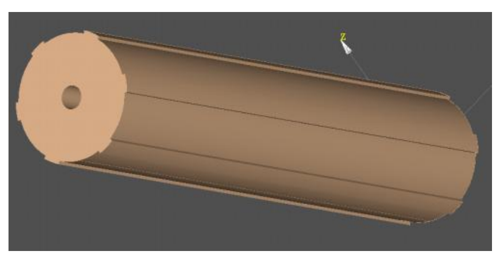
Finocyl



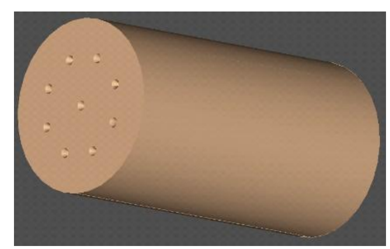
Front and rear finocyl



3D irregular



Gear



End embedded metal wire

Structure analysis of grain

■ Combustion geometry analysis

- analytic method； ➢ Solid modeling method；
- graphing method；➢ General coordinate method；
- various voxels discretization method ；

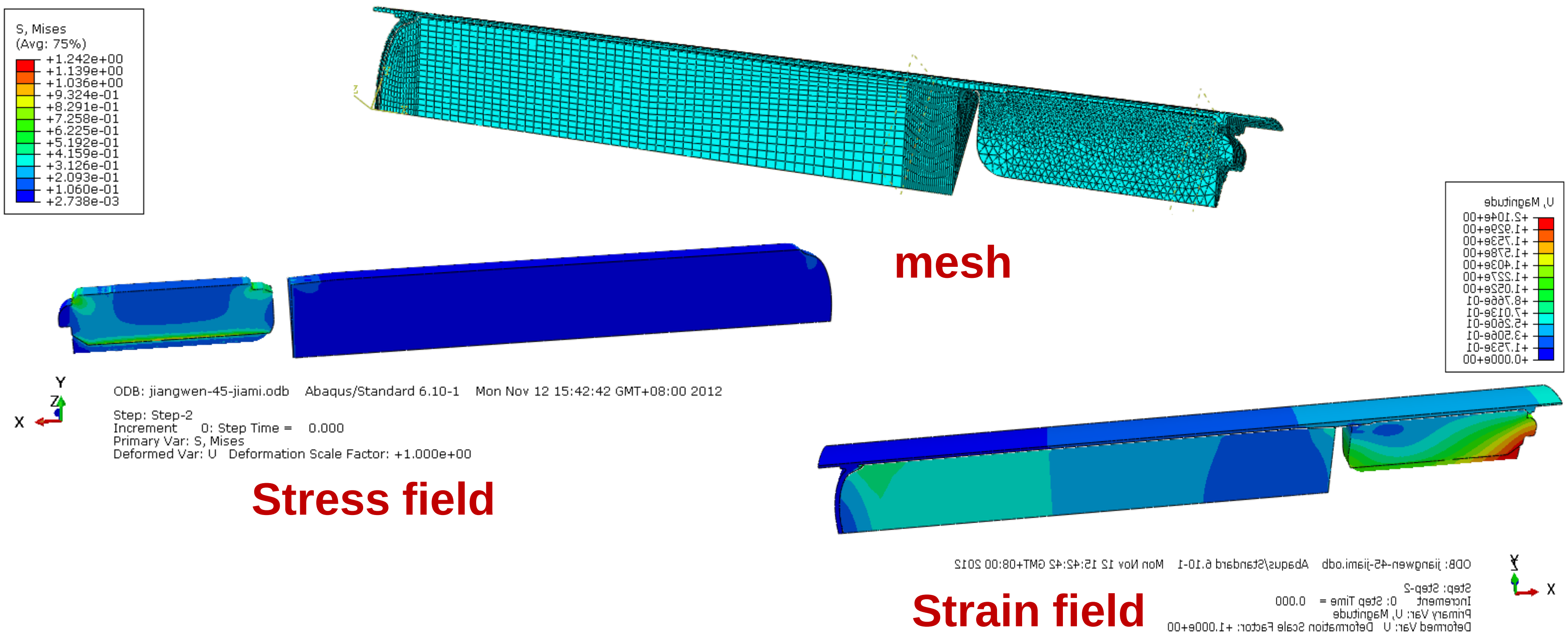
■ Interner ballistic calculation (P-t curve and F-t curve)

- 0-D Interner ballistic: formula of equilibrium pressure and thrust coefficient
- 1-D Interner ballistic: large aspect ratio (L/D>8), the more serious erosive burning grain
- 2,3-D Interner ballistic: complex internal structure and flow

Structure design of strain

■Structural integrity analysis

- Analyze the change of stress and strain of grain in the whole life cycle, including manufacturing (curing and cooling), storage, transportation, ignition and so on. Ensure the integrity of grain structure according to the criterion of structural failure.



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