

9.3 SOLID PROPELLANT GAS GENERATOR

The solid gas generator routine allows the use of any solid propellant for which the user has sufficient data. The routine accounts for heat transfer, burn rate variation, and condensibles in the combustion gas.

It is the responsibility of the user to justify the amount of heat transferred from the hot gas to its surroundings. The mechanism for including the results of a heat transfer analysis in the simulation is an exponential pressurant temperature decay curve. This differs from the polytropic expansion coefficient used in the cold gas routine, because the combustion products are not well modeled by a polytropic expansion coefficient. According to the polytropic expansion equation.

$$T = T_{GG} \left(\frac{P}{P_{GG}} \right)^{(\gamma_{poly}-1)/\gamma_{poly}}$$

the lowest obtainable temperature is:

$$T = T_{gg} (p/p_{gg}) \quad \text{For } \gamma_{poly} \rightarrow \infty$$

Since the combustion products temperature can drop below such a value, this is not a good model for the solid gas generator system.

The inputs which define the solid propellant and the pressurization task are shown below.

SOLID PROPELLANT GAS GENERATOR INPUTS

(Some Inputs are Computer Generated)

Default Values¹

540	T_{ref}	reference temp for c	(°R)
3932	c^*	solid grain characteristic velocity	(ft/sec)
0.00114 0.095	c	burn rate coeff @ T_{ref}	(in./sec)
0.64	n	burn rate exponent	(-)
0.0036	π_{PK}	temp sensitivity of P_C	(°R ⁻¹)
0.0013	σ	temp sensitivity of burn rate	(°R ⁻¹)
0.056	ρ_{sg}	solid grain density	(lb/in. ³)
395	T_{min}	min operating temp	(°R)
620	T_{max}	Max operating temp	(°R)
	P_{min}	gas generator min operating pressure @ T_{min}	(psia)
	P_{pT}	propellant tank pressure	(psia)
	V_{pT}	volume of propellant tank	(in. ³)
	t_b	burn time	(sec)
1.27	γ_{isen}	combustion products ratio of specific heats	(-)
19.0	M	combustion products molecular weight	(-)
2590	T_{GG}	combustion products temperature	(°R)
1.25	C_{des}	design complexity multiplier	(-)
1.5	b	multiplier on T_{min} to calculate T_{eq}	(-)
100	t_d	time at which temp decays by 0.75 x ($T_{isen} - T_{eq}$) °R	(sec)
0.2662	f_{H_2O}	molar fraction of water in combustion products	(-)
3.0	$(A_p/A_t)_{min}$	port to throat minimum area ratio	(-)

¹assuming TAL-8 solid propellant

The starting point for the solid gas generator model is the ideal gas equation.

$$W_{pbo} = \text{pressurant weight @ burnout} = \frac{P_{PT} V_{PT} M}{R T_{bo}}$$

To account for burning rate changes over the design temperature range, increase the pressurant requirement by the ratio (r_{max}/r_{min}) (maximum burn rate/minimum burn rate). Next, multiply by a design complexity factor (C_{des}) to account for delivered flowrate being greater than demand flowrate. For example, a "perfect" design gives $C_{des} = 1.0$, and off-design operation increases the value of C_{des} (default = 1.25). It also accounts for use of pressure control vent valves which need not close completely. Finally, multiply by the condensibles multiplier (C_{cond}) to allow for replacement of condensed species with uncondensed gas.

The following equation is the result of the above procedure.

$$W_{sg} = W_{pbo} C_{des} C_{cond} (r_{max}/r_{min}) = [\text{solid grain weight}]$$

$$V_{sg} = W_{sg} / \rho_{sg} = [\text{solid grain volume}]$$

In order to follow the above method, the values for T_{bo} , C_{cond} , r_{min} , and r_{max} must be determined. This is accomplished as shown in the following equations.

The gas generator is designed to deliver some minimum pressure (p_{min}) at a minimum operating temperature (T_{min}). The burn rate under these conditions is:

$$r_{min} = c p_{min}^n e^{\sigma(T_{min} - T_{ref})}$$

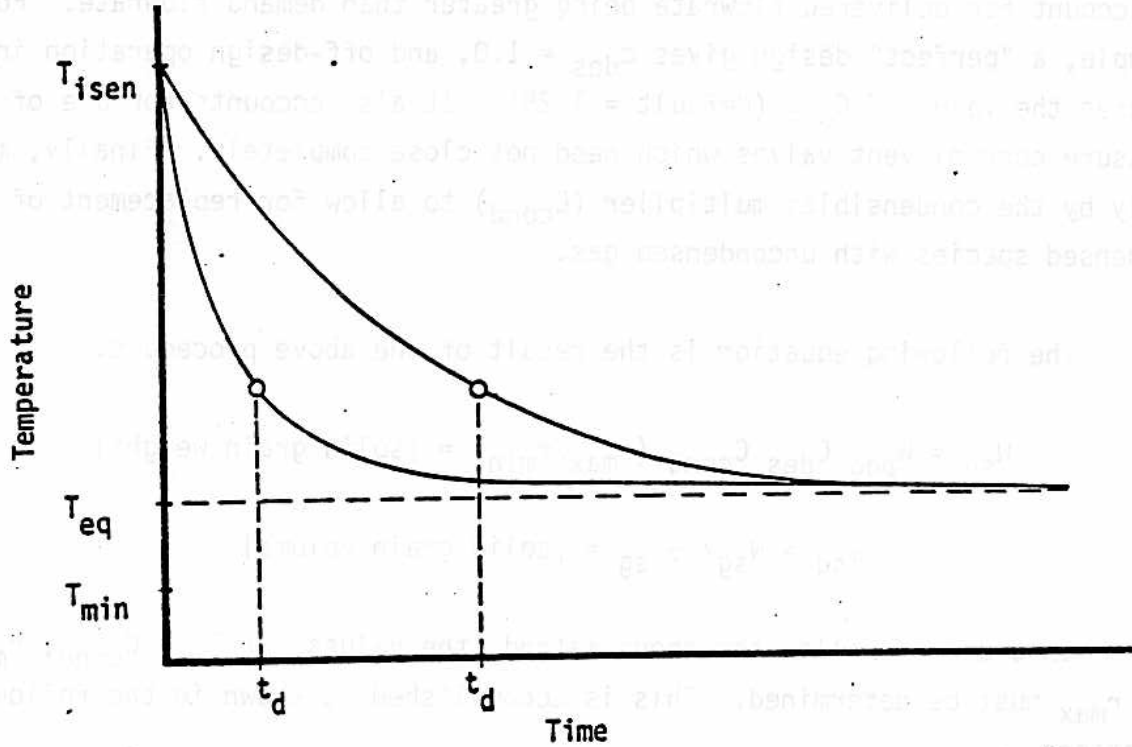
When designed to meet a minimum pressure at a minimum temperature, the maximum pressure (P_{max}) will be:

$$P_{max} = p_{min} e^{\pi PK (T_{max} - T_{min})}$$

The burn rate at that condition (r_{\max}) is then

$$r_{\max} = c p_{\max}^n e^{\sigma(T_{\max} - T_{\text{ref}})}$$

Having established the minimum and maximum burn rates, it remains to calculate the gas temperature at burn out (T_{bo}) and the condensibles multiplier (C_{cond}). The burn out temperature is calculated by assuming a temperature vs. time curve of the following form.



The temperature of the gas at time zero is equal to that of a simple isentropic expansion (ie no heat transfer).

$$T_{\text{isen}} = T_{\text{GG}} \left(\frac{p_{\text{PT}}}{p_{\text{min}}} \right)^{(\gamma_{\text{isen}} - 1) / \gamma_{\text{isen}}}$$

Assume an exponential decay of gas temperature to an equilibrium value. The user input the equilibrium temperature and the time (t_d), at which it reaches 75% of the distance to that value. (Notice above how the choice of t_d changes the character of the curve.)

Then: $T = T_{eq} + (T_{isen} - T_{eq})e^{-at}$

Where: $a = \frac{1.3863}{t_d} = \frac{-\ln(1 - 0.75)}{t_d}$

The program calculates T_{eq} from:

$$T_{eq} = b \times T_{min}$$

Where: (default) $b = 1.5$

Using the above definitions the temperature at burnout is calculated as:

$$T_{bo} = T_{eq} + (T_{isen} - T_{eq}) e^{-at_b} = \text{pressurant temp @ burnout}$$

The condensibles multiplier is calculated assuming water to be the major condensible species. The partial pressure of water vapor in the propellant tank is calculated as:

$$P_{vw} = \text{Water vapor partial pressure in combustion products in propellant tank}$$

$$= f_{H_2O} P_{PT}$$

$$f_{H_2O} = .2662$$

The amount of water vapor which can remain in the pressurant gas is the saturation pressure which corresponds to the gas temperature. At burnout, that gas temperature (T_{bo}) can be used to calculate the burnout saturation pressure of water vapor by using the following curve-fit of saturated steam P vs. T data.

$$P_{vbo} = [0.0078164 (T_{bo} - 444.1)]^{4.6674} \quad \text{For } T_{bo} \geq 660^\circ\text{R}$$

$$= [0.0042071 (T_{bo} - 323.6)]^{7.0321} \quad \text{For } T_{bo} < 660^\circ\text{R}$$

By comparing the actual partial pressure at water vapor (P_{vw}) with the maximum allowable saturation pressure (P_{vbo}) the value of the condensible multiplier (C_{cond}) can be determined.

$$\text{If } P_{vw} \leq P_{vbo} \text{ , then } C_{cond} = 1.0 \quad (\text{no condensation})$$

$$\text{If } P_{vw} > P_{vbo} \text{ , then } C_{cond} > 1.0 \quad (\text{condensation})$$

If condensation occurs, then C_{cond} can be calculated by first calculating the allowable mole fraction of water vapor in the combustion gas (f_{allow}).

$$f_{allow} = P_{vbo}/P_{pT} = \text{allowable mole fraction of condensibles in pressurant gas}$$

The total number of moles in the gas phase after condensation (n) can be calculated as:

$$n = P_{pT} V_{pT}/R T_{bo} = \text{ideal \# moles at burnout}$$

Finally the equation for C_{cond} is:

$$C_{cond} = \frac{n}{1 + f_{allow} - f_{H_2O}}$$

Where: f_{H_2O} is the actual mole fraction of water in the combustion gas and f_{H_2O} is greater than f_{allow} .