SOLID PROPELLANT ROCKET MOTOR DESIGN

Reaction Research Society Solid Propellant Course

By George Garboden and Brian Wherley

George Garboden

- Rockets 2nd Class Pyrotechnic Operator – 2029-05
- 1st Rocket Experience – compressed air powered go-kart….1973
- Became involved with H_2O_2 race cars in 1975
- Currently produce aerospace and military hardware.

Design of 2.5 inch rocket . . .

Use AP/HTPB propellant

Use existing launch rack

Aluminum case - ease of fabrication

Bulkhead ignition

Graphite nozzle

PVC liners

Bates grain

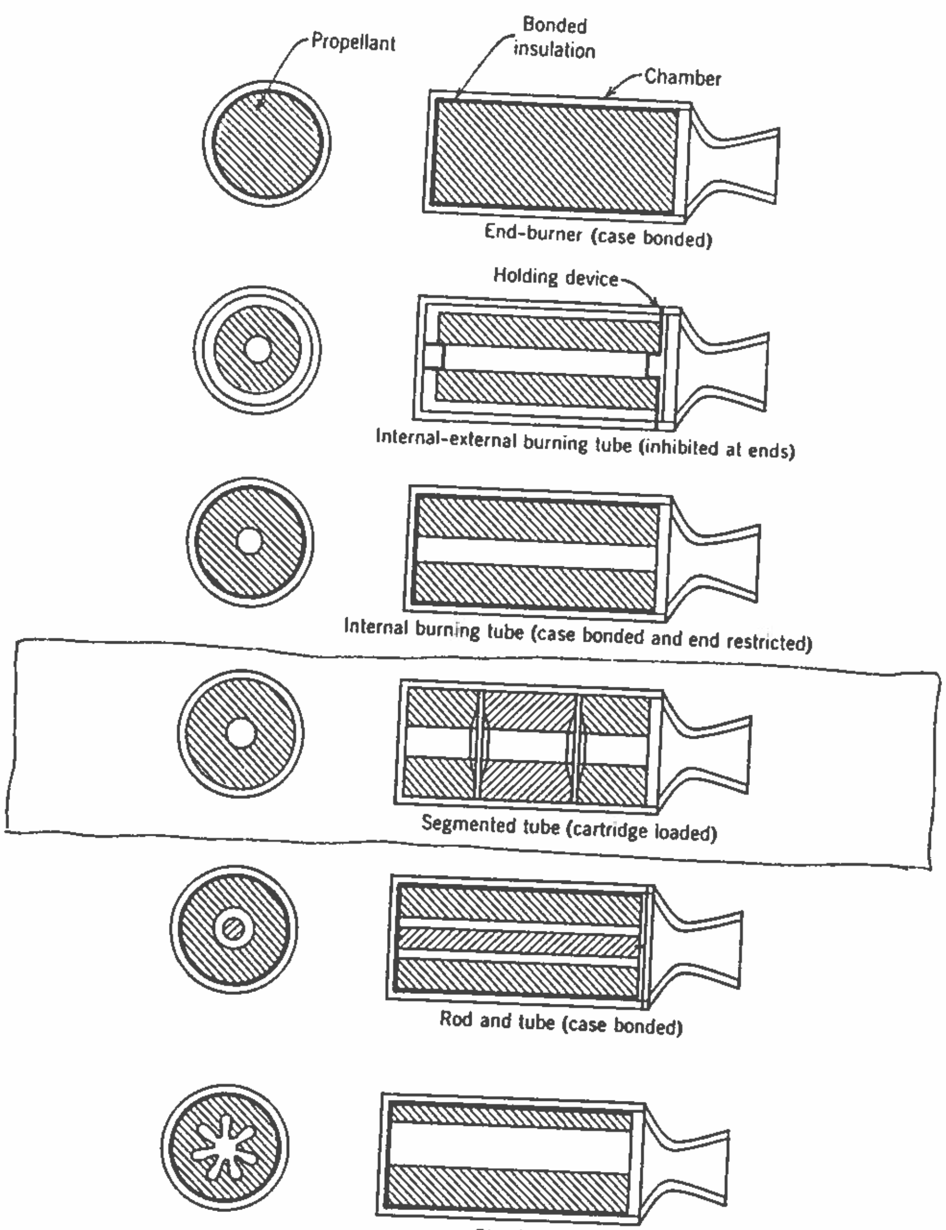


Fig. 10-8. Simplified diagrams of several grain configurations.

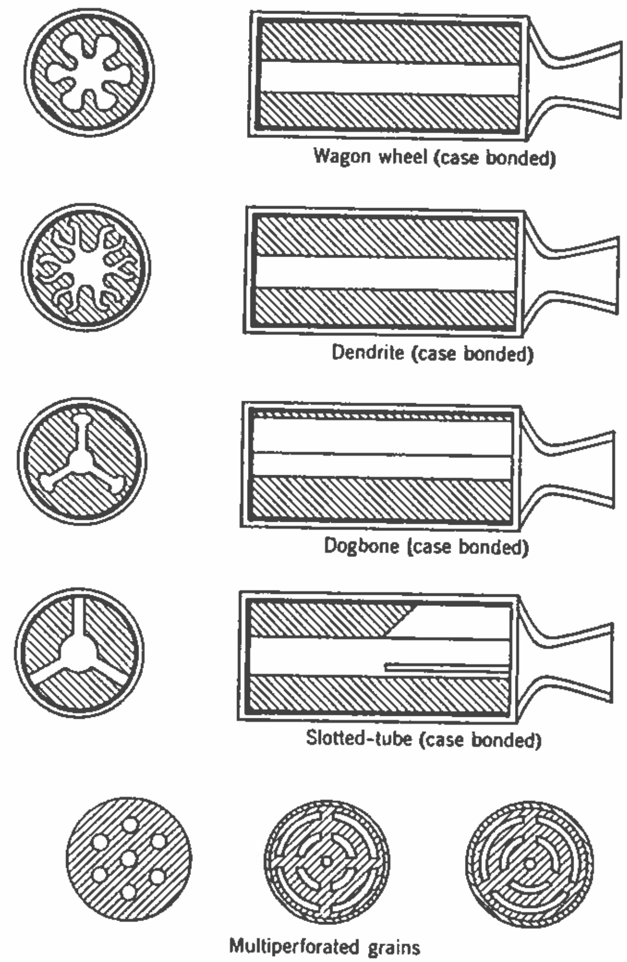
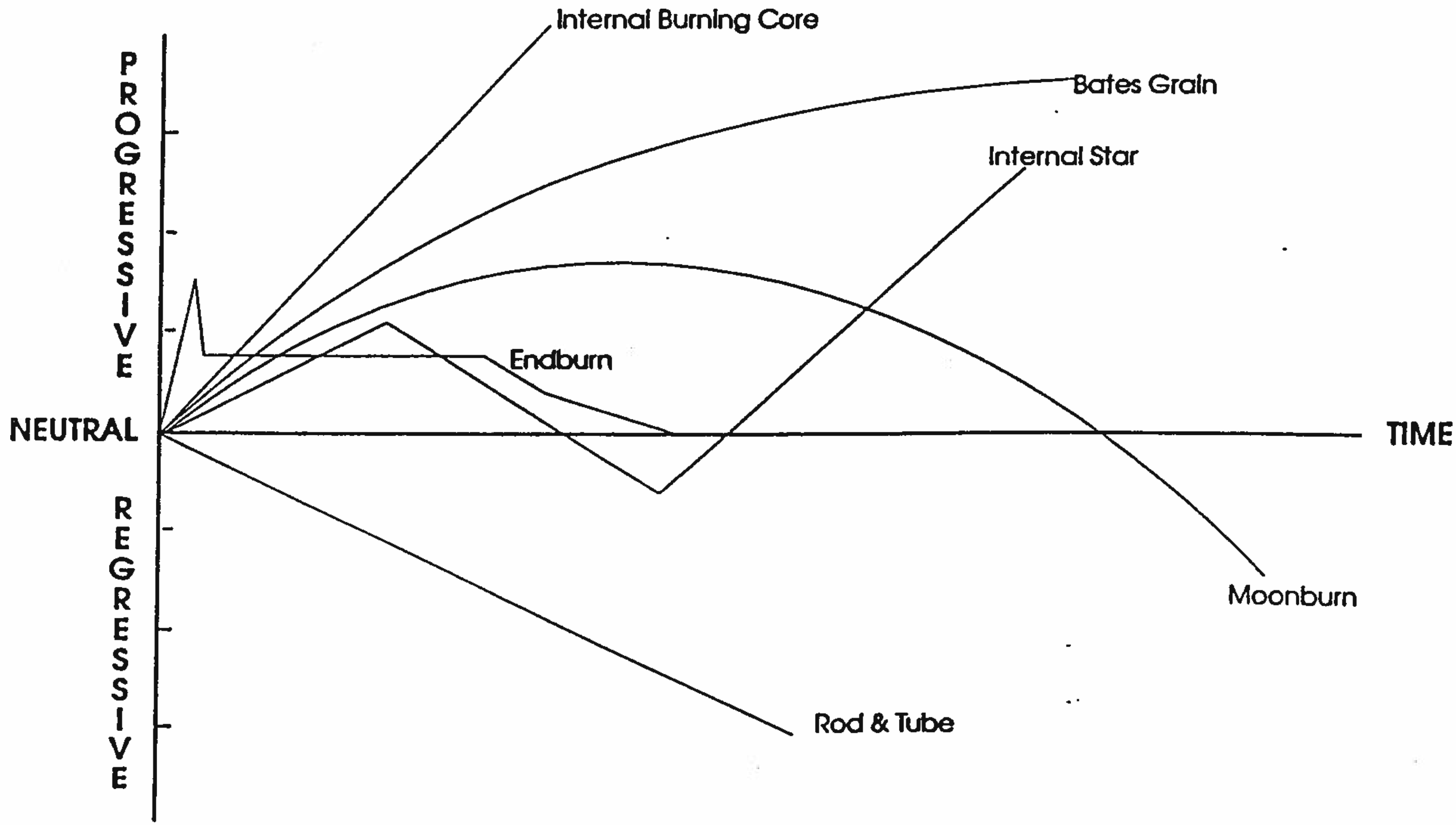


Fig. 10-8. (*continued*).

basic configurations listed in these tables can be extended by alterations such as (*a*) coning the ends of a cylindrical perforation to obtain neutrality, (*b*) adding small star points to slotted tube grains to increase the volumetric loading, (*c*) adding a conocyl to a high-web-fraction star for neutrality, and (*d*) slotting a high-web-fraction progressive star to obtain neutrality.

The *end burning grain* (burning like a cigarette) is unique; it burns solely in the axial direction and maximizes the amount of propellant that can be placed in a given cylindrical motor case. Historically, this configuration was used in assist-takeoff rockets manufactured by the thousands in the

GRAIN GEOMETRY BURNING CHARACTERISTICS



Sizing Propellant Segments

Software Tools
- PEP Code
- KN1

Rough estimate of dimensions of segments

Use KN1 program to determine values

Use results to bring values within limits

Use formulas to determine performance

Compare results to actual data if available

Return to KN1 program as needed

Nozzle

WEB-BURN AREA TABLE

Segment dia.. 2.060
Throat diameter.. .702
Throat/Port .493

Segment length.. 20
Number of ends.. 10
Volume 50.925

Grain
Port dia.. 1
Web increments.. 10
Weight 2.801

sample #	WX	Ab	NAb	Kn
0	0.0000	88.3072	1.0000	262.3789
1	0.0530	91.3726	1.0347	271.4867
2	0.1060	93.9085	1.0634	279.0213
3	0.1590	95.9148	1.0861	284.9827
4	0.2120	97.3917	1.1029	289.3709
5	0.2650	98.3391	1.1136	292.1858
6	0.3180	98.7571	1.1183	293.4276
7	0.3710	98.6455	1.1171	293.0961
8	0.4240	98.0045	1.1098	291.1914
9	0.4770	96.8339	1.0966	287.7136
10	0.5300	0.0000	0.0000	0.0000

Calculate ingredients ... (Y/N) ... ?

Burn All The End Surfaces

1803 GRAMS TOTAL MIXTURE

1390.11	grams	AP	(.771)	77.1%
120.80	grams	AL	(.067)	6.7%
180.30	grams	HTPB	(.100)	10%
79.33	grams	DOA	(.044)	4.4%
12.62	grams	HX878	(.007)	.7%
19.83	grams	PAPI	(.011)	1.1%
2.	drops	SAG		

... restart program (Y/N) ... ?

.054

5.4%

Density

Void at 15%

```
5 CLEAR:CLS
10 DIM AB(25), NAB(25),KN(25)
12 LOCATE 2,28:PRINT "WEB-BURN AREA TABLE"
15 NW=10
20 LOCATE 4,5:INPUT "Segment dia.. ",DG
25 LOCATE 4,30:INPUT "Segment length.. ",GL
30 LOCATE 4,55:INPUT "Port dia.. ",DP
35 LOCATE 5,5:INPUT "Throat diameter.. ",TD
40 LOCATE 5,30:INPUT "Number of ends.. ",N
45 LOCATE 5,55:PRINT "Web increments.. 10"
46 RT=(TD/DP)^2
47 LOCATE 6,5:PRINT"Throat/Port    "
48 LOCATE 6,20:PRINT USING ".###";RT
50 AA=(((DG/2)^2!)*3.14)-(((DP/2)^2!)*3.14)
55 AB=AA*GL
56 PW=AB*.055
60 LOCATE 6,30:PRINT "Volume    "
61 LOCATE 6,55:PRINT "Weight    "
62 LOCATE 6,41:PRINT USING "####.###";AB
63 LOCATE 6,63:PRINT USING "####.###";PW
65 ABREF=(DP*3.14*GL)+(2*AA)
66 AT=((TD/2)^2)*3.1416
68 LOCATE 10,1:PRINT "  sample #        WX              Ab              NAb
   Kn "
69 PRINT "-----------------------------------------------------------------------"
70 I=0
80 P=3.1416
90 W=(DG-DP)/(2!*NW)
100 FOR I=0 TO NW
110 C=DP+2!*I*W
111 WX=I*W
120 D=P*C*(GL-N*I*W)
125 IF(C>=(DG-.01)) OR ((N*I*W)>=(GL-.01)) THEN AB(I)=0:GOTO 150
130 E=P*N*((DG^2!)-C^2!)/4!
140 AB(I)=D+E
150 NAB(I)=AB(I)/AB(0)
155 KN(I)=(AB(I)/AT)*1.15
160 PRINT "     ";:PRINT I,:PRINT USING "####.####      ";WX,AB(I),NAB(I),KN(I)
170 NEXT I
180 LOCATE 24,8:PRINT "Calculate ingredients ... (Y/N) ... ?"
190 A$=INKEY$:IF A$="" THEN 190
191 IF A$="Y" OR A$="y" THEN 200
192 LOCATE 25,8:PRINT "Restart program ... (Y/N) ... ?"
193 B$=INKEY$:IF B$="" THEN 192
194 IF B$="Y" OR B$="y" THEN 5
195 GOTO 998
200 CLS
202 GR=INT((((((DG/2)^2)*3.14)*GL)*25)*1.0825)
204 CLS
206 LOCATE 6,24:PRINT GR "GRAMS TOTAL MIXTURE "
210 AP=GR*.771
211 AL=GR*.067
212 HTPB=GR*.1
213 DOA=GR*.044
214 HX=GR*.007
215 PAPI=GR*.011
216 SAG=CINT(GR/1000)
217 IF SAG<1 THEN SAG=1
220 LOCATE 10,24:PRINT USING "#####.##  grams AP   (.771) ";AP
222 LOCATE 11,24:PRINT USING "#####.##  grams AL   (.067) ";AL
```

```
C:\PEP\EXE>type input.dat
0003.out
HTPB-AP
    5    0     1
1.
298.
.3            0.0           0.0
0000000000
  846  137  063  742  368
0500.          12.00         10.7          77.1          6.7          1.1          4.4
550.           14.00         10.0          77.0

C:\PEP\EXE>type setup.pep
HD
c:\pep\exe\pepcoded.daf
c:\pep\exe\notused
c:\pep\exe\jannaf.daf
propep.out

C:\PEP\EXE>
```

The above files are important for running the PEP program.

R45M-AP Run using June 1988 Version of PEP,
Case 1 of 1 13 Mar 1997 at 4:47:15.94 pm

CODE		WEIGHT	D-H	DENS	COMPOSITION			
846	R45M	10.700	-30	0.04330	667C	999H	50	
137	AMMONIUM PERCHLORATE (AP)	77.100	-602	0.07040	1CL	4H	1N	40
63	ALUMINUM (PURE CRYSTALINE)	6.700	0	0.09760	1AL			
742	PAPI	1.100	-202	0.04480	224C	155H	270	27N
368	DIOCTYL ADIPATE	4.400	-733	0.03320	42H	22C	40	

THE PROPELLANT DENSITY IS 0.06377 LB/CU-IN OR 1.7653 GM/CC
THE TOTAL PROPELLANT WEIGHT IS 100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

4.344916 H	1.113011 C	0.664309 N	2.686243 O
0.248332 AL	0.656187 CL		

*****************************CHAMBER RESULTS FOLLOW ******************************

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
2943.	4838.	34.01	500.00	-50.18	245.29	1.2067	3.987	8.530

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL= 10.183 11.254
NUMBER MOLS GAS AND CONDENSED= 3.9874 0.1226

1.01871 H2O	0.94668 CO	0.80935 H2	0.63064 HCl
0.33158 N2	0.16621 CO2	0.12255 Al2O3*	0.04073 H
0.02162 Cl	0.01665 HO	0.00105 NO	0.00090 AlOCl
8.93E-04 AlCl	6.15E-04 AlCl2	5.10E-04 O	4.43E-04 AlHO2
2.58E-04 O2	2.32E-04 AlCl3	1.07E-04 AlHO	5.33E-05 Cl2
2.65E-05 CHO	2.64E-05 NH3	1.94E-05 COCl	1.73E-05 HOCl
1.72E-05 AlO	9.30E-06 OCl	5.74E-06 CNH	4.61E-06 NH2
3.72E-06 CH2O	3.51E-06 Al	2.10E-06 HO2	1.88E-06 N
1.27E-06 NHO	1.19E-06 NH	1.15E-06 CNHO	

THE MOLECULAR WEIGHT OF THE MIXTURE IS 24.331

******************************EXHAUST RESULTS FOLLOW ******************************

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
1635.	2483.	0.82	12.00	-116.55	245.29	1.2356	3.946	0.207

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL= 9.415 10.103
NUMBER MOLS GAS AND CONDENSED= 3.9458 0.1242

0.92897 H2O	0.91534 H2	0.84115 CO	0.65603 HCl
0.33213 N2	0.27179 CO2	0.12415 Al2O3&	0.00016 H
9.22E-05 Cl	7.39E-06 HO	4.52E-06 NH3	

THE MOLECULAR WEIGHT OF THE MIXTURE IS 24.570

***********PERFORMANCE: FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE***********

IMPULSE	IS EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M	EX-T
235.6	1.2177	2654.	19.08	4958.3		5.98	416.0	0.30829	1511.
240.3	1.1844	2703.	19.30	5019.3	193.5	6.20	424.3	0.31208	1635.

Formulas

F: Force
Pc: chamber Pressure
At: Area of Throat
CF: Thrust Coefficient of Nozzle

1. $F = Pc * At * CF$

$(260 = 450 \times .385 \times 1.5)$

2. $r = a\,(Pc)^n$

$(.214 = .021\,(450)^{.38})$

? → r: burn rate
a: seconds
Pc: chamber Pressure

3. $Kn = Ab/At$

$(300 = 115.5/.385)$

? → Kn: Burn Rate Ratio
Ab: Area of burn
At: Area of throat

4. $Isp = It/Wt$

$(227 = 640/2.82)$

ISP: specific Impulse
It: total impulse
Wt: weight of Propellant

.021
450

.259480

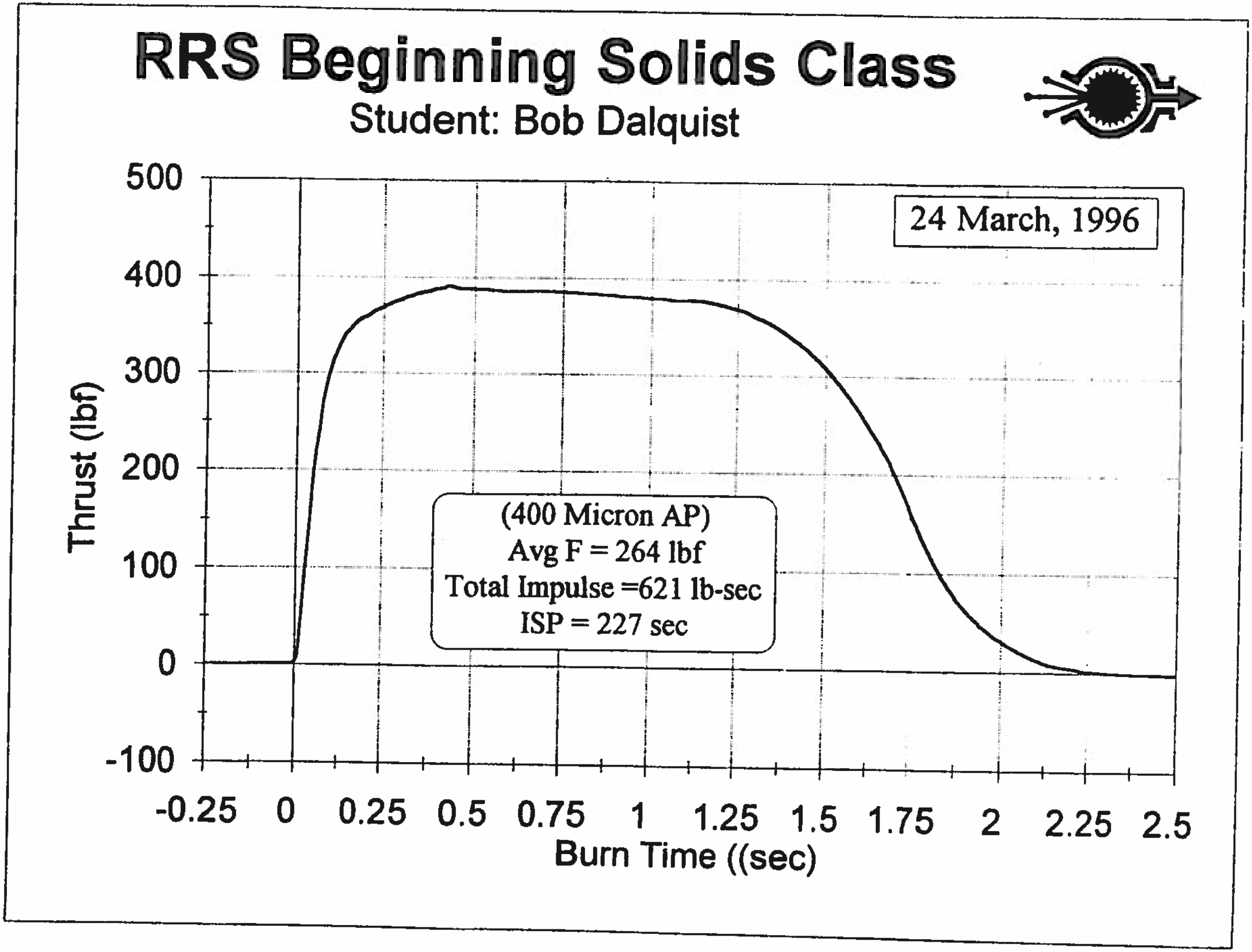
Burn Rate in inches/second

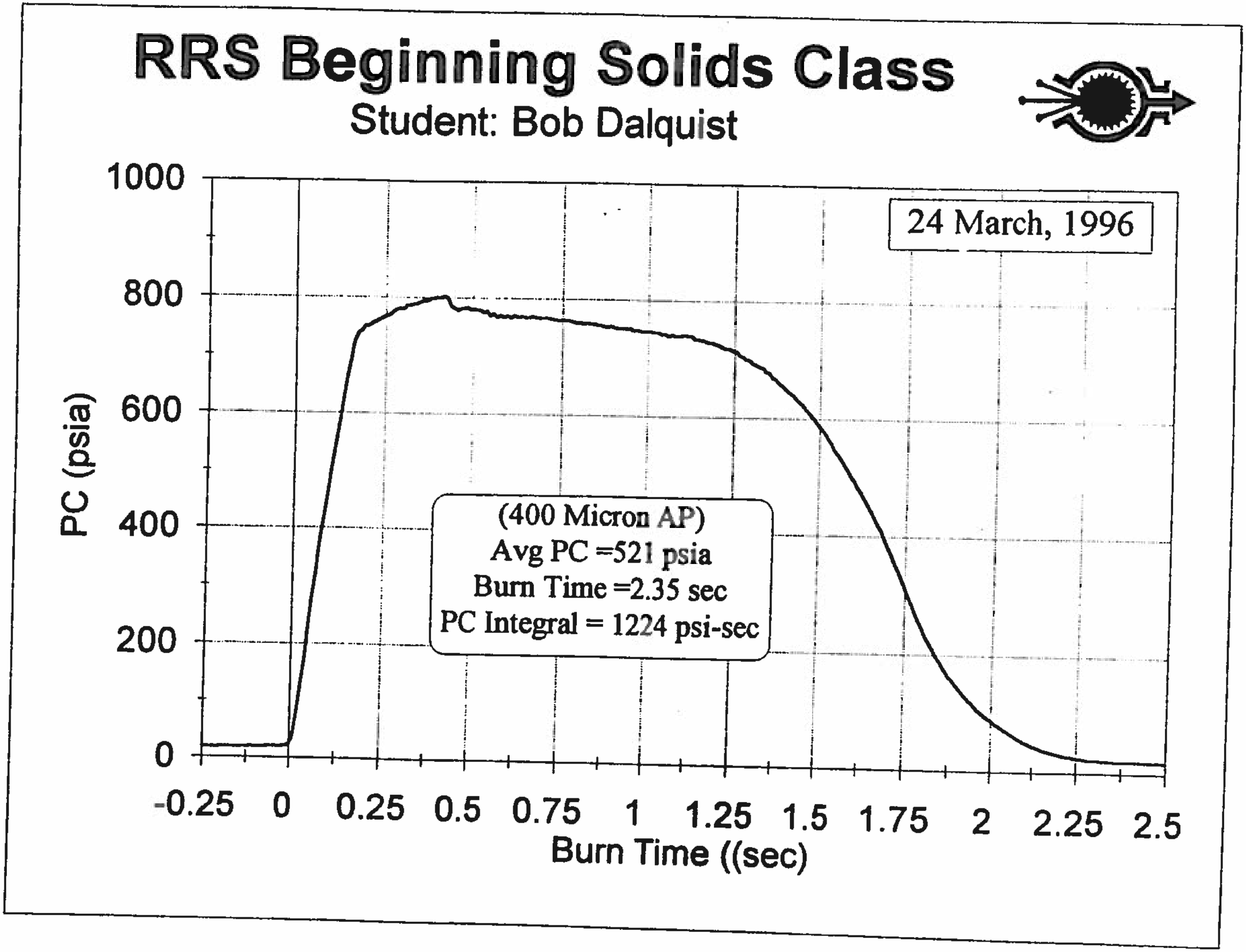
$r = aPc^{n}$

a = .021

Burn Rate Exponent = n .38

Chamber Pressure		0.38	0.39	0.4	0.41	0.42
	300	0.183	0.194	0.206	0.218	0.23
	400	0.205	0.217	0.231	0.245	0.26
	500	0.223	0.237	0.252	0.268	0.286
	600	0.239	0.255	0.271	0.289	0.308
	700	0.0253	0.27	0.288	0.308	0.329
	800	0.266	0.285	0.304	0.325	0.348
	900	0.279	0.298	0.319	0.342	0.366
	1000	0.29	0.311	0.333	0.357	0.382


RRS Beginning Solids Class
Student: Bob Dalquist
24 March, 1996
(400 Micron AP)
Avg F = 264 lbf
Total Impulse =621 lb-sec
ISP = 227 sec
Thrust (lbf)
500
400
300
200
100
0
-100
-0.25
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Burn Time ((sec)


RRS Beginning Solids Class
Student: Bob Dalquist
24 March, 1996
(400 Micron AP)
Avg PC =521 psia
Burn Time =2.35 sec
PC Integral = 1224 psi-sec
PC (psia)
1000
800
600
400
200
0
-0.25
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Burn Time ((sec)

RRS Beginning Solids Class

Summary of Student Static Firings

21 April 1996

	Tom Cagwin	Bruce Patrick	Randy Thompson	Tim Cagwin	John Spohnheime	John Rahkonen	Kurt Theis	Mark Sullivan	Rand Heaslip	Mike Dilsaver	Thomas McGaffey	Ron Bremer	Jim Phillips	Tom Mueller	*Class Average*	*Class S.D*
Propellant Mass (lbm)	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	*2.74*	*8E-10*
Throat Area (in^2)	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.388	*0.388*	*0.000*
Burn Time (sec)	2.688	2.707	2.746	2.610	2.678	2.787	2.745	2.735	2.774	2.629	2.729	2.775	2.658	2.814	*2.720*	*0.061*
Avg F (lbf)	234.7	231.9	229.4	241.4	235.1	223.4	229.1	229.5	227.1	241.4	226.9	226.6	237.0	223.3	*231.2*	*5.94*
Avg PC (psia)	428.3	452.2	452.4	438.6	468.4	455.8	426.0	460.4	509.5	444.6	462.2	469.8	432.3	462.0	*454.5*	*21.40*
Total Impulse (lb-sec)	630.9	627.8	630.0	630.0	629.6	622.6	628.9	627.6	629.9	634.5	619.3	628.9	630.1	628.5	*628.5*	*3.65*
Cstar (ft/sec)	5247	5579	5662	5218	5718	5790	5330	5739	6442	5328	5749	5942	5237	5925	*5636*	*346*
Isp (sec)	230.3	229.1	229.9	229.9	229.8	227.2	229.5	229.1	229.9	231.6	226.0	229.5	229.9	229.4	*229.4*	*1.33*

	RRS House Motors				
	House1	House2	House3	*Average*	*S.D*
Propellant Mass (lbm)	2.74	2.74	2.74	*2.74*	*0.00*
Throat Area (in^2)	0.416	0.416	0.416	*0.416*	*0.00*
Burn Time (sec)	2.813	2.755	2.787	*2.785*	*0.029*
Avg F (lbf)	219.6	225.1	219.7	*221.5*	*3.1*
Avg PC (psia)	395.1	406.0	377.7	*393.0*	*14.3*
Total Impulse (lb-sec)	617.8	620.1	612.4	*616.8*	*3.9*
Cstar (ft/sec)	5432	5467	5146	*5348*	*176*
Isp (sec)	225.5	226.3	223.5	*225.1*	*1.4*

Hardware Selection

6061-T6 Aluminum Tubing for case
2.50 outside diameter
.125 wall thickness

6061-T6 Aluminum bulkhead
Ignitor port
Pressure tap

Snap rings for retaining internal components
Simplicity in manufacturing

Silicone O-rings
Elevated temperature use
Used for sealing at nozzle & bulkhead
Also used as spacer between Bates segments

Graphite nozzle
Type 580 - good service, moderate price
G-10 ~~Steel~~ spacer to protect nozzle
Radius inlet to keep overall length short

PVC Liners
Inexpensive and easy to machine

Sources for Materials

Aluminum Tubing	Tube Service 9351 S. Norwalk Blvd. Santa Fe Springs, CA 90670
Aluminum Bar Stock	Industrial Metal Supply 2052 Alton Avenue Irvine, CA 92714
Snap Rings # N 5000 - 225	Bearing Engineers 27 Argonaut Aliso Viejo, CA 92656
O-Rings	All Seals 404 W. Roland Avenue Santa Ana, CA 92707
PVC Liners	Any Building Supply
Graphite	E. A. Wilcox 6436 Corvette Los Angeles, CA

First Aid Items "Water Gel"

References

Rocket Propulsion Elements
An Introduction to the Engineering of Rockets
George P. Sutton, Sixth Edition

Ammonium Perchlorate Composite Basics
Randall R. Sobczak #247
High Power Rocketry, May/June 1993

General Information on the Art of Solid Propellant Mixing
John Rahkonen
Prodyne, Inc. February 15, 1995

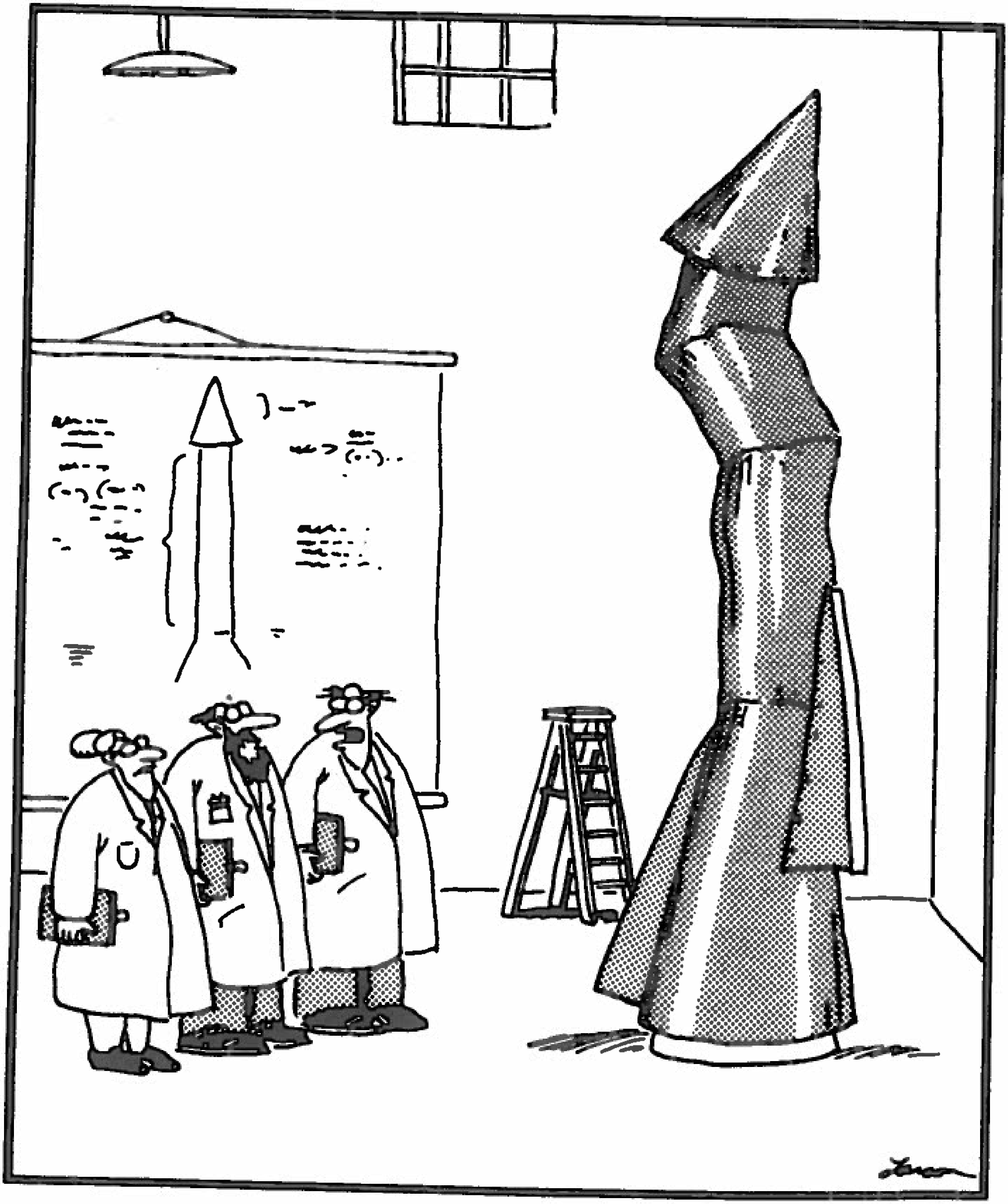
Plastic Resin Bonded High Energy Rocket Fuel Systems
Gary W. Purrington
Firefox Enterprises Inc.

Books # "Angle of Attack"
"Space Craft propulsion"

Acknowledgements

Many members within the society have been very helpful in assisting with this project. As is normal for any group of people, there seems to always be a "core" group of individuals who extend immense effort to see a project to completion. We are very grateful for their assistance. In addition, we would like to acknowledge the work of others in the society who have preceded us in the composite field, especially Larry Teebken/Bob Anderson and Jim Gross whose reports were helpful in our endeavor.

"Composite techs"



"It's time we face reality, my friends. ... We're not exactly rocket scientists."

CANNONS AND GRAIN DESIGN

By
Bob Dahlquist

What does a CANNON have to do with a ROCKET MOTOR, anyway? What do cannons burn? Cannons burn gunpowder, of course. But not just any gunpowder will do. Using the wrong type of gunpowder may cause the cannon to explode. You need a powder that burns at a rate appropriate for the gun it will be used in. You don't use pistol powder in a cannon, or cannon powder in a pistol.

Controlling the burning rate of gun propellant is a science that developed over several centuries. Gunpowder was invented in the Orient, or perhaps in the Middle East, and has been used for fireworks there since the 11th Century. The Chinese were propelling rockets with it in the 13th Century. By the 14th Century, it was being used in cannons.

Originally, gunpowder was a simple mixture of three powders: potassium nitrate, sulfur, and charcoal. The burning rate of 13th and 14th century black powder varied, not entirely predictably, according to how tightly it was packed into the barrel. This made gunfire inaccurate. Early cannons had short barrels, and used loose-fitting projectiles to prevent too much pressure building up in the barrel and bursting it.

In the 15th Century, a method of granulating the powder was developed. The powder was pressed into a flat cake while damp, then broken up into grains of roughly equal size. This made the burning rate much more consistent and predictable. But it was highly regressive; because as the grains burned, their surface area decreased on all sides. This was exactly the opposite of the burning rate profile needed for guns.

As longer, more powerful cannons began to be used in the 19th Century, many exploded, killing their crews. A progressive, slower burning propellant was sorely needed to make these guns safer and more effective. Captain Thomas Jackson Rodman of the U.S. Army (later promoted to Brigadier General) solved the problem between about 1845 and 1860, by developing ported and grooved grains, much larger than any that had been made before. His large grains had a relatively small surface area per unit mass, initially. As they burned, the ports or grooves grew larger, increasing the surface area. Thus, the burning rate started out slow, and then increased so that the rate of gas production would keep up with the acceleration of the shell as it traveled down the barrel.

Rodman kept track of the burning rate profile by actually measuring the relative gas pressure inside the barrel at many points along its length. In this way, he acquired the data he needed to design and perfect his propellant grains scientifically. Hexagonal, perforated grains about 1 inch across and 1 inch long were developed; these worked so well that before long, they were in use all over the world. These grains were made by pressing the black powder into molds.

Today, as then, any single piece of solid propellant is called a grain, regardless of its size. Thus, naval guns can use a "powder" that consists of grains 2 inches long and 5/8 inch in diameter. And a segment of solid rocket propellant may be 6 feet in diameter and 30 feet long, and still be called a grain; even though the term originated from gunpowder grains the size of grains of wheat or barley.

Because about half of the products of combustion of black powder are solid salts, it produces vast clouds of smoke when used in battle. Not only does this give away one's position, it fouls the barrel; and the hot solid residue can ignite the next charge during loading, if the barrel isn't swabbed after every shot. A smokeless powder was needed.

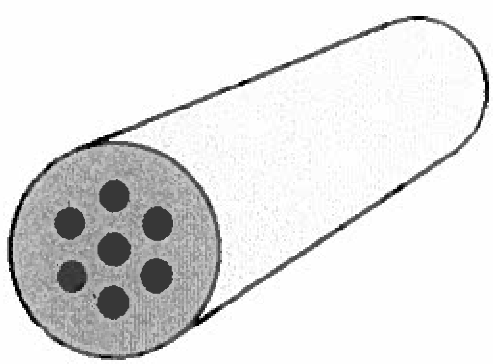
In 1846, Christian F. Schönbein invented nitrocellulose (guncotton). He nitrated cotton lint by treating it with a mixture of nitric and sulfuric acids. Unfortunately, his nitrocellulose burned too quickly and violently to be used as a gun propellant.

Around 1885 to 1887, Paul Marie Eugéne Vieille, of Paris, mixed nitrocellulose with alcohol and ether to form a colloid that could be easily molded or extruded. (The grade of nitrocellulose used for this purpose has about 13% nitrogen by weight and is called pyrocellulose.) Vieille molded the colloid into grains of controlled surface area, to produce smokeless powder with an optimum burning rate for the guns it would be used in. The grain geometry principles developed by Rodman were applied to the new compound and the new smokeless powder was quickly adopted by the French army.

In 1888, Vieille developed the burning rate formula,

$$r = cP^n$$

where
- r = Recession rate, in linear units
- c = A constant, characteristic of the chemical composition
- P = Absolute pressure in the barrel
- n = The pressure exponent, a constant, usually between 0.8 and 1.0 for gun propellants



Propellant Grain for Large Naval Gun

This formula was named Vieille's Law in his honor. Although he developed it for gun propellants, it is the basis of the burning rate formula we use for rocket propellants today.

The recession rate, r, is the rate at which the surface of the propellant recedes as it burns away. Multiply this rate by the burning surface area, and you get the volume of solid propellant consumed per second. Then multiply by the density of the propellant, and you get the mass flow rate. (See Equation 1, in Safety and the Burning-Rate Exponent, by Dahlquist.)

One can design the burning surface area to increase, decrease, or remain essentially constant over time. This is accomplished by choosing an appropriate shape for the grain, using the principles discovered 150 years ago by Rodman. Appropriate dimensions for each grain are calculated and the number, size, and shape of ports or grooves to be used is established. One or more surfaces of the grain may be inhibited (coated or bonded in such a way as to prevent burning) to further control burning. (See, for example, Analytic Development of Near-Neutral Burning BATES Grains, by Teebken.)

The same basic principles apply whether one is designing a solid rocket propellant or a gun propellant. Thus, when we design our solid propellant grain to give a rocket motor the thrust profile we want, we are making use of the principles discovered by Rodman and Vieille in their scientific work with cannon propellants more than a century ago.