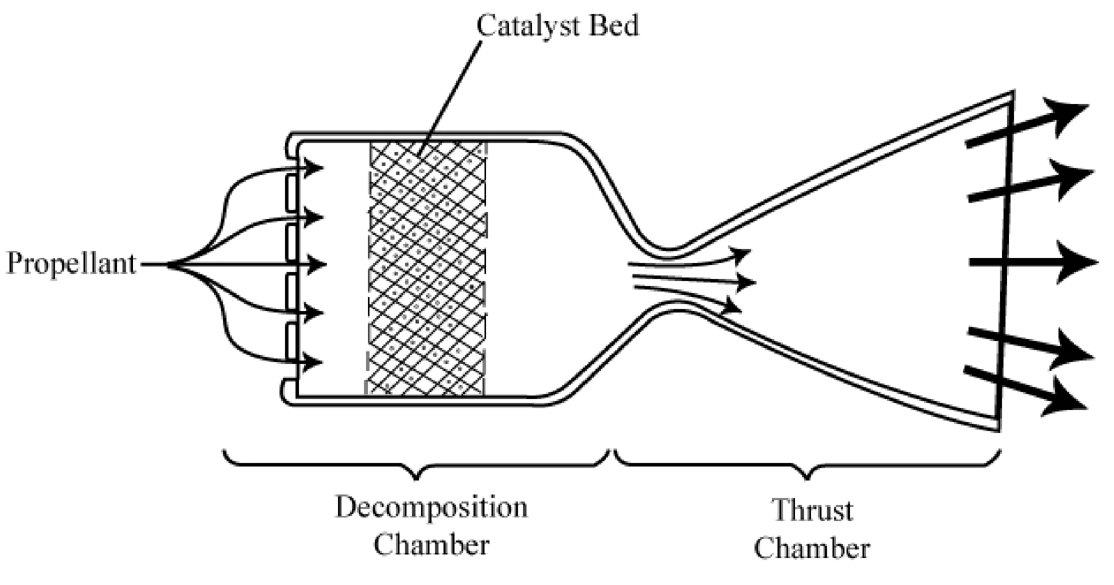
16.522, Space Propulsion
Prof. Manuel Martinez-Sanchez

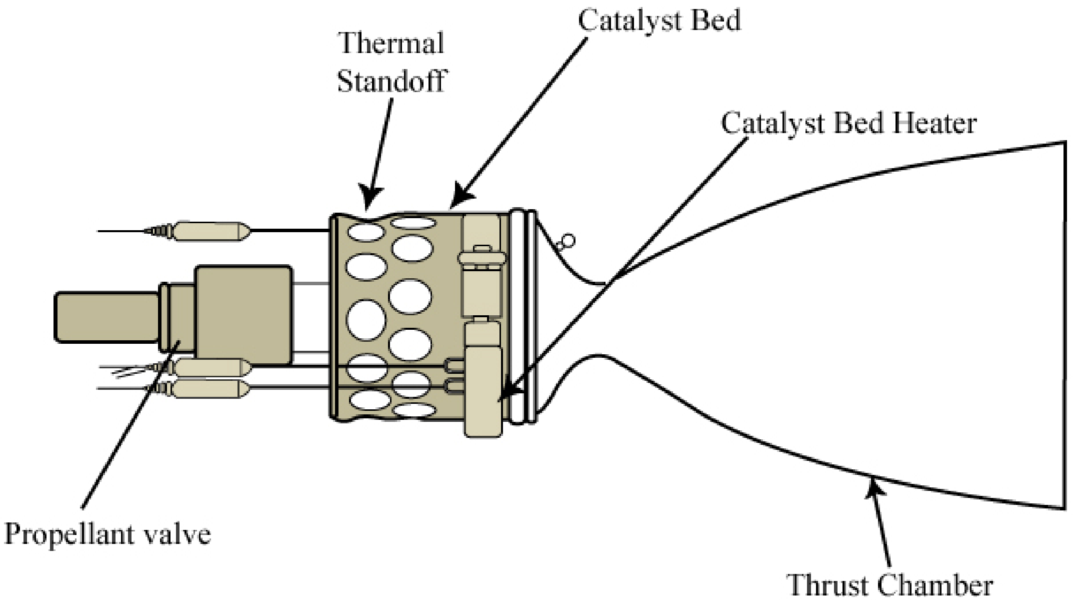
Lecture 7: Bipropellant Chemical Thrusters and Chemical Propulsion Systems Considerations (Valving, tanks, etc)

Characteristics of some monopropellants (Reprinted from H. Koelle, *Handbook of Astronautical Engineering*, McGraw-Hill, 1961.)

Chemical	Density	Flame temp, °F	C^*,fps	I_{sp},S	Sensitivity
Nitromethane	1.13	4002	5026	244	Yes
Nitroglycerine	1.60	5496	4942	244	Yes
Ethyl nitrate	1.10	3039	4659	224	Yes
Hydrazine	1.01	2050	3952	230	No
Tetronitromethane	1.65	3446	3702	180	Yes
Hydrogen peroxide	1.45	1839	3418	165	No
Ethylene oxide	0.87	1760	3980	189	No
n-Propyl nitrate	1.06	2587	4265	201	Yes



Monopropellant concept.
Image adapted from:
SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1996



Typical monopropellant thruster. (Courtesy Hamilton Standard.)
Image adapted from:
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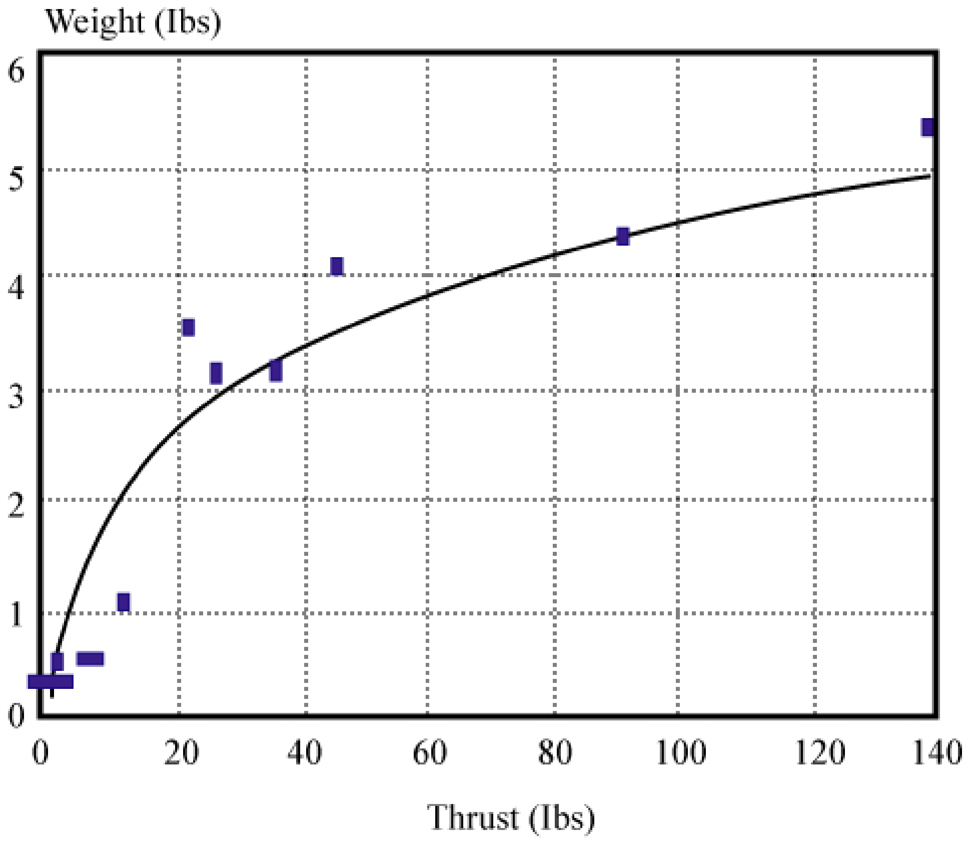


Monopropellant thruster weight
Image adapted from:
SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1996

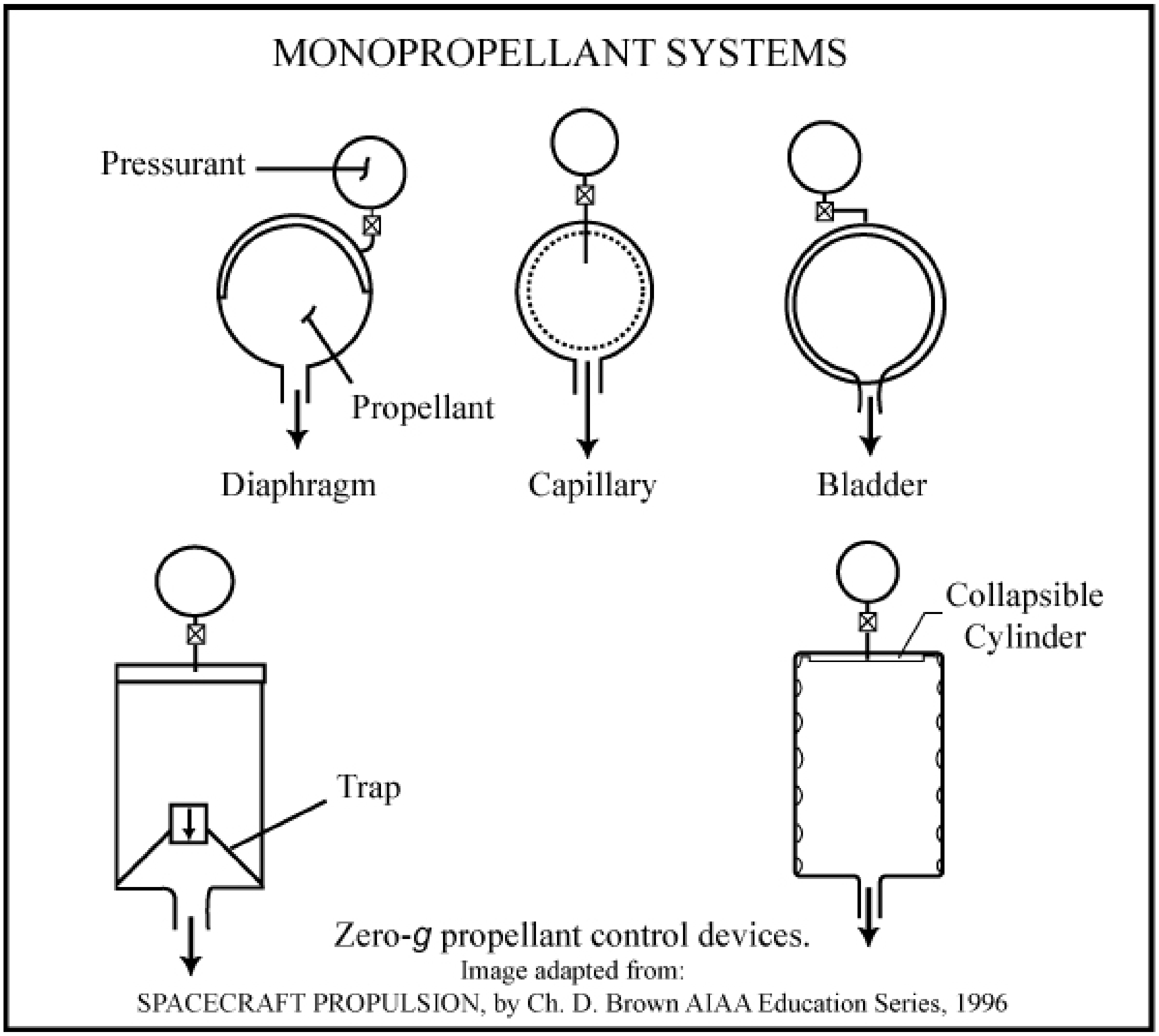
Thruster Weight

A least-square curve fit of the weight of nine different thruster/valve designs with thrust levels from 1 to 150 lb produces the following relation:

$$W_t = 0.34567F^{0.55235}$$

The figure above shows the correlation; the correlation coefficient is 0.97.

For low thrust levels, the thruster weight approaches the valve weight, an effect that Equation (4.5) will not predict. Use 0.4lb as a minimum thruster/valve weight for low thrust levels. Note that figure above is for a thruster with single valves.



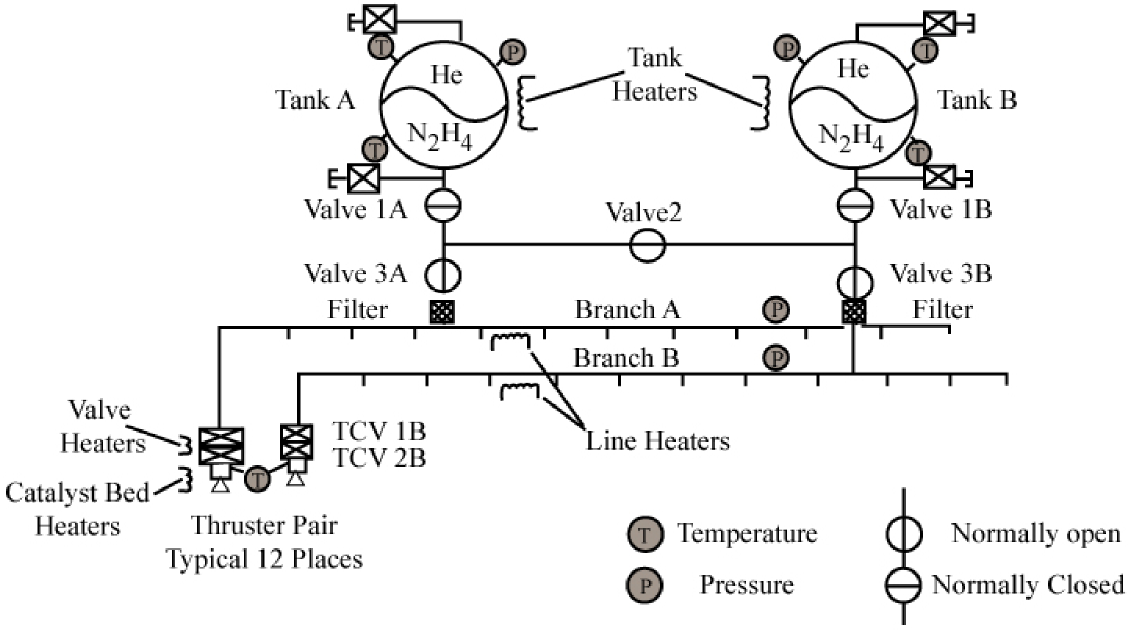
Zero-*g* propellant control devices.
Image adapted from:
SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1996

1) *Capillary devices*, which use surface tension forces to keep gas and liquid separated. These are particularly useful for bipropellant systems like the space Shuttle and Viking Orbiter because they are compatible with strong oxidizers.

2) *Diaphragms and bladders*, which are physical separation devices made of elastomer or Teflon. These are used by Voyager, Mariner 71, and Magellan. Elastomer types are not compatible with oxidizers.

3) *Bellows,* a metal separation device, used by Minuteman.

4) *Traps*, a check valve protected compartment, used by Transtage.



System functional schematic.
Image adapted from:
SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1996

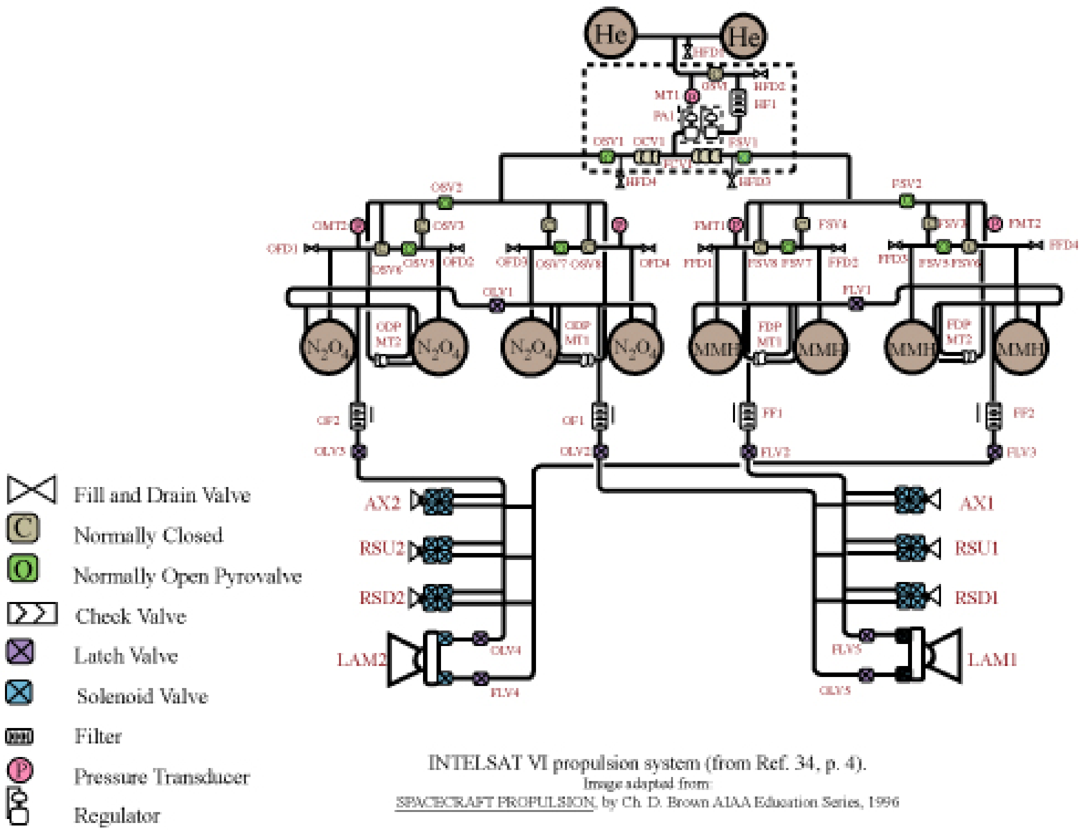
Image adapted from: SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1995
Flight monopropellant systems

	Mariner 4	Landsat	Viking	HEAO	Voyager	Pioneer Venus	Intelsat V	IUS	Magellan
Launch date	1964	1972	1976	1977	1977	1978	1980	1982	1989
Altitude control	3 Axis	3 Axis	3 Axis	3 Axis	3 Axis	Spin	3 Axis	3 Axis	3 Axis
No. thrusters	1	3	4, 3	12	16, 4, 4	7	20	12	12, 4, 8
Initial thrust, lb	50	1.0	10,600	1.1	0.2, 5, 100	1.5	0.1, 0.6, 5		0.2, 5, 100
Pressurization	Regulated	Blowdown	Blowdown	Blowdown	Blowdown	Blowdown	Blowdown	Blowdown	Blowdown
Pressurant	N_2	N_2	N_2	N_2	N_2	He	N_2	N_2	He
No. prop tanks	1	1	2	2	1	2	2	1,2, or 3	1
Initial pressure, psia			530	350	450	350	270		450
Blowdown ratio	-	3.3		3.5		1.8	1.8		4
Repressurization	-	No	No	No	No	No	Yes	No	Yes
Propellant Control	Bladder	Diaphragm	Deceleration	Diaphragm	Diaphragm	5 rpm spin	Capillary	Diaphragm	Diaphragm
Tank shape	Spherical	Spherical	Spherical	Spherical	Spherical	Conosphere	Barrel	Spherical	Spherical
Crossover	-	-	-	Yes	-	Yes	Yes	Yes	No
Dry mass, lb	26.7			56.2			78		135
Propellant mass	21.5	67	185	300	230	86.2	410	123/Tank	293.2
Features	Slug starts	Simplicity	Throttlable		400,000 cycle pulsing		Electrothermal thrusters	Removable tanks	
Primary Reference	23	24	25	30	16	27	28	26	29

Image adapted from: SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1995

Spacecraft bipropellant systems

	Transtage RCS	Viking Orbiter	Shuttle RCS	Galileo	Intelsat VI	Mars Global Surveyor
First launch	1964	1975	1981	1989	1989	1996
No. thrusters	8	1 (ACS by cold gas)	44	13	8	13
Thrust, lb	25,45	300	25,870	2.25,90	5,110	1,134
Engine cooling	Ablative	Beryllium	Radiation cooled and insulated	Radiation	Radiation	Radiation
Fuel	50/50 mix of hydrazine and UDMH	MMH	MMH	MMH	MMH	Hydrazine
Oxidizer	Nitrogen tetroxide	Nitrogen tetroxide	Nitrogen tetroxide	Nitrogen tetroxide	Nitrogen tetroxide	Nitrogen tetroxide
Mixture ratio	1.60	1.50		1.6	1.6	
Propellant control	Teflon diaphragms	Capillary vane devices	Capillary screens	Centrifugal 10(rpm)	Centrifugal	Capillary vane
Propellant tanks	Titanium equal volume spherical	Titanium equal volume barrel	Titanium equal volume, spherical	Four equal volume, titanium, spherical	Eight equal volume, titanium, spherical	Three equal volume, titanium, barrel
Pressurization	Regulated nitrogen	Regulated helium		Regulated helium	Regulated helium	Regulated helium
Vapor mixing prevention	Single, soft seat check valves	Series soft seat check valves		Single soft seat check valves, low leak design	Single check valves	Pyro-valves
Dry mass, lb	55	442				139
Propellants, lb	120	3137		2040	5100 to 5990	836
Primary reference		32		33	34	
features	Early design	Beryllium cooling	Large size, multiuse	Spinner, flushing burns	Spinner, redundant half-system	Dual-mode operation



INTELSAT VI propulsion system (from Ref. 34, p. 4).
Image adapted from:
SPACECRAFT PROPULSION, by Ch. D. Brown AIAA Education Series, 1996

Additional Reading for System Design:

Mayer, N. L. “AIAA 96-2869, Advanced X-ray Astrophysics Facility – Imaging (AXAF-I) Propulsion Subsystem.” 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference. Redondo Beach, CA: TRW Space & Electronics Group. July 1-3, 1996. pp. 1-10.

Some Examples of Small Solid Propellant Rockets for In-space Propulsion

The STAR 13B incorporates the lightweight case developed for the STAR 13 with the propellant and nozzle design of the earlier TE-M-516 apogee motor. The motor case has been stretched 2.2 inches to provide for increased propellant loading. The motor has been used to adjust orbit inclination of a satellite from a Delta launch.

MOTOR PERFORMANCE (70 ˚F Vacuum)

Burn Time/Action Time, sec	14.8/16.1
Ignition Delay Time, sec	0.02
Burn Time Average Chamber Pressure, psia	823
Action Time Average Chamber Pressure, psia	787
Maximum Chamber Pressure, psia	935
Total Impulse, lbf-sec	26,040
Propellant: Specific Impulse, lbf-sec/lbm	286.6
Effective Specific Impulse, lbf-sec/lbm	285.7
Burn Time Average Thrust, lbf	1708
Action Time Average Thrust, lbf	1577
Maximum Thrust, lbf	2160

SPIN CAPABILITY, rpm	120

WEIGHTS, lbm

Total Loaded	103.7
Propellant	90.9
Case Assembly	5.64
Nozzle Assembly	3.72
Igniter Assembly	0.68
Internal Insulation	2.34
Liner	0.14
Miscellaneous	0.28
Total Inert (excluding igniter propellant)	12.80
Burnout	12.30
Propellant Mass Fraction	0.87

TEMPERATURE LIMITS

Operation	40 to +110°F
Storage	40 to +110°F

CASE

Material	6Al-4V Titanium
Minimum Ultimate Strength, psi	165,000
Minimum Yield Strength, psi	152,000
Hydrostatic Test Pressure, psi	1330
Yield Pressure, psi	1394
Hydrostatic Test Pressure/Maximum Pressure	1.05

Nominal Thickness, In.	0.035

NOZZLE

Exit Cone Material	Vitreous Silica Phenolic
Throat Insert Material	ATJ Graphite
Initial Throat Area, in^2	1.14
Exit Diameter, In.	8.02
Expansion Ratio, Initial/Average	49.8/41.0
Expansion Cone Half Angle, deg	17
Type	Fixed
Number of Nozzles	1

LINER

Type	TL-H-304
Density, lbm/ $in.^3$	0.045

IGNITION TRAIN

Components	S&A/ETA/TBI/pyrogen igniter
Minimum Firing Current per Detonator, amperes	5.0
Circuit Resistance per Detonator, ohms	1.0
No. of Detonators and TBIs	2
Squib or TBI compatible	

PROPELLANT

Propellant Designation and Formula	TP-H-3082
AP-70%	
Al-16%	
CTPB Binder-14%	

PROPELLANT CONFIGURATION

Type	Internal burning, 8-point star
Web, In.	4.187
Web Fraction, %	62
Silver Fraction, %	2
Propellant Volume, $in.^3$	1446
Volumetric Loading Density	92
Web Average Burning Surface Area, $in.^2$	345
Initial Surface to Throat Area Ratio	316

PROPELLANT CHARACTERISTICS

Burn Rate at 1000 psia, in./sec	0.301
Burn rate Exponent	0.31
Density, $lbm/in.^3$	0.0628
Temperature Coefficient of Pressure, %/°F	0.10
Characteristic Exhaust Velocity, ft/sec	5025
Adiabatic Flame Temperature, °F	5662
Effective Ratio of Specific Heats (chamber)	1.16

(Nozzle Exit)	1.21
CURRENT STATUS	Production
	BC1355B 4/91