AeroTech Warp-9™ Propellant White Paper

Gary Rosenfield, President
AeroTech Division, RCS Rocket Motor Components, Inc.
2113 W. 850 N. St., Cedar City, UT 84720

"Warp-9™" is one of the latest propellants to be offered in rocket motor reload kits intended for use in AeroTech's Reloadable Motor System™ (RMS™). AeroTech has been able to develop and release a number of high-performance reloads using Warp-9, most notably the H999N-P which is the highest-thrust 'H' class motor available to the certified consumer market. Since its release in April 2006, the sport rocket community has expressed an interest in the design, performance, physical characteristics and stability of Warp-9, and this paper seeks to provide additional information about this remarkable propellant technology.

Warp-9 propellant (RCS part no. ISP-P-8223AL) was originally developed in the late '80s by Industrial Solid Propulsion (ISP), Inc. for the "fin motors" used in Orbital's (then Space Data Corp.) Pegasus™ launch vehicle. Nine of these motors were to be used on each flight. To meet the Pegasus mission profile, a rocket motor was needed that would produce over 200 lbs vacuum thrust for over 20 seconds at temperatures as low as 0 deg F, in a dimensional envelope of 5" diameter by 17" long.

While it may have been possible to deliver a burn time of nearly 20 seconds with an offset-port grain geometry using a more conventional slower-burning propellant, the requirement of near-constant thrust during motor operation precluded that design option. Therefore, it was necessary to configure the fin motors with an end-burning grain geometry. To meet the thrust duration requirement, a propellant was formulated that would burn at a rate of at least 0.8 inches per second at 800 PSI.

Hundreds of Pegasus fin motors were eventually manufactured by ISP for Orbital, with most of them being used on actual Pegasus flight missions.

Warp-9 has been used in other ISP motor programs including:

• A 0.46 second burn, 646 in-lb peak torque spin motor for the Textron Defense Systems "Damocles" sub-munition program (1989)

• A 0.19 sec burn time, 948 lb. peak thrust spin motor built for a proprietary British Aerospace Defence LTD development program (1993)

• A 1.9 second burn time, 21 lb. peak thrust end-burning motor built for a proprietary British Aerospace Defence LTD development program (1993)

• A 0.46 second burn, 780 lb peak thrust tractor motor for Westinghouse Marine Systems Division (1993)

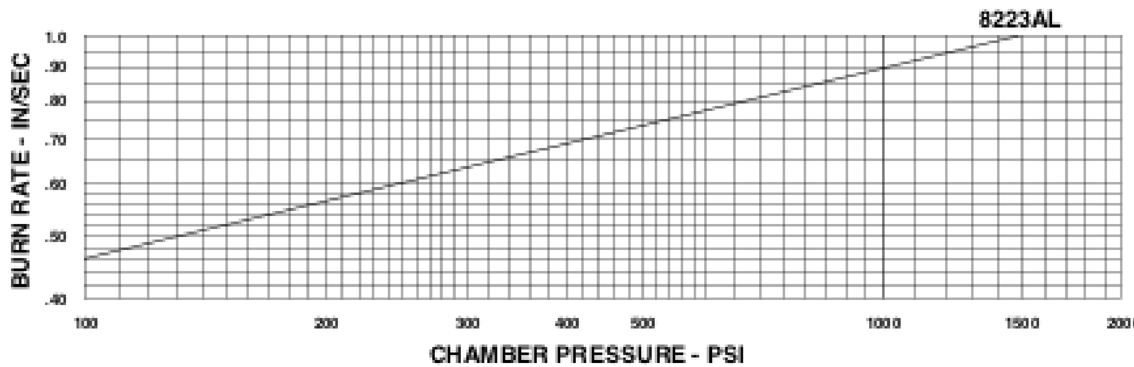

Fig.-1. Warp-9 (8223AL) Burn Rate Vs. Pressure

The thermodynamic properties of Warp-9 are listed below, calculated using the Air Force Chemical Equilibrium Specific Impulse Code (AFCESIC) at standard conditions (1,000 PSI chamber/14.7 PSI exit, optimum expansion at sea level):

DENSITY = 1.643
CSTAR = 4987.04

	CHAMBER	THR(SHIFT)	EXH(SHIFT)
PRESSURE (PSIA)	1000.000	560.031	14.700
EPSILON	.000	1.000	8.276
ISP	.000	105.875	244.867
ISP (VACUUM)	.000	192.683	263.725
TEMPERATURE(K)	2780.640	2521.988	1269.499
MOLECULAR WEIGHT	23.669	23.724	23.769
MOLES GAS/100G	4.225	4.215	4.207
CF	.000	.683	1.580
PEAE/M (SECONDS)	.000	86.808	18.858
GAMMA	1.229	1.231	1.268
HEAT CAP (CAL)	45.118	44.575	39.505
ENTROPY (CAL)	246.939	246.941	246.939
ENTHALPY (KCAL)	-45.237	-58.114	-114.117
DENSITY (G/CC)	7.05857E-03	4.36861E-03	2.28238E-04

Fig.-2. Warp-9 Thermodynamic Properties

In 1994, Warp-9 was tested by the U.S. Bureau of Mines and found to meet safety standards that are applied to all propellants in evaluating safety and stability for shipping. The DOT subsequently issued ISP an EX-Number authorization for the commercial transportation of Warp-9 in cartridge form.

When designing short burn, high thrust motors, the use of a “fast” propellant alone may not be sufficient. The unusual performance characteristics of AeroTech’s Warp-9 motors are made possible by carefully considering the trade-offs and optimization of a number of propellant and motor design factors including (but not limited to):

- Solids loading
- Metal vs. oxidizer content
- Oxidizer particle sizes
- Oxidizer particle size distribution
- Burn rate catalyst
- Burn rate exponent
- Operating pressure
- Propellant web thickness
- Nozzle expansion ratio

Let’s examine these factors in more detail:

Solids Loading. Generally speaking, the higher the weight percent solids loading of a propellant, the higher the burn rate. This is especially true when the solids loading increase is predominantly oxidizer. To produce the highest burn rate (and indirectly, the highest delivered specific impulse), the propellant chemist should choose a solids loading that is as high as possible. Burn rate and I_{sp} will increase up to a solids loading of about 90% by weight. Mitigating factors that affect this decision include propellant castability and nozzle erosion that can be adversely affected by extremely high solids loading. Warp-9 uses a moderate solids loading compared to other hobby rocket propellants.

Metal vs. Oxidizer Content. Again, to produce a higher burn rate it is common practice to increase the oxidizer percentage while minimizing the weight fraction of energetic metals (this is not necessarily true when using nanoparticle Aluminum, but this ingredient has not yet found widespread usage in non-professional rocketry for a number of reasons). Warp-9 was specifically formulated with the minimum percentage of energetic metals necessary to suppress combustion instability.

Oxidizer Particle Sizes. Because Ammonium Perchlorate (AP) of acceptable fine particle size is not generally available commercially, AeroTech manufactures its own from larger (standard size) feedstock. Warp-9 utilizes a higher percentage of fine AP oxidizer than other AeroTech propellants, and most likely a higher percentage (and a smaller particle size) than other commercial hobby propellants. Fine oxidizer increases propellant burn rate, and in general the smaller the AP particles the faster the burn rate. Warp-9's fine oxidizer particle size was chosen to optimize burn rate while not reducing castability to an unacceptable level. If too fine an oxidizer particle size is used, the mixed propellant will not be castable without using processing "tricks" that can adversely affect safety, quality and productivity.

Oxidizer Particle Size Distribution. To maintain castability especially when using fine oxidizer particles, careful control of the oxidizer particle size distribution (or ratio of the discrete oxidizer particle sizes) is necessary. The particle size distribution of oxidizer in Warp-9 represents a strategic balance between high burn rate and propellant processability. If the improper ratios of AP particle sizes are used, the mixed propellant will not be castable at the solids loading necessary for high burn rate and high performance, and the desired high burn rate will not be achieved.

Burn Rate Catalyst. AeroTech chose to use an extremely effective burn rate catalyst in a weight percentage well within acceptable formulation safety limits. Military and aerospace contractors validated these limits by testing in the early '90s. AeroTech has been using this catalyst since the mid-'80s in military, commercial and hobby rocket motor applications. Motors up to 18 years old using this catalyst and stored under uncontrolled ambient environmental conditions have been static tested and found to deliver ballistic performance within their original design parameters.

Burn Rate Exponent. The burning rate exponent "^{n}", or "slope" of a Log-Log graph of propellant burn rate vs. pressure (see Fig.-1), is an indication of the sensitivity of a propellant's burn rate to minor changes in burning surface area (if the nozzle is a fixed diameter), or changes in nozzle throat area (if the propellant burning surface is constant), or both. It is generally desirable that propellants have a low burn rate exponent, i.e., <0.4. A propellant's burn rate exponent can be suppressed or increased by controlling a number of formulation variables such as solids ratio, metals content, AP particle size ratios and the choice and percentage of burn rate catalyst. The burn rate exponent of Warp-9 is considered in the "low" range (0.287) and contributes to its successful application over a wide variety of operating pressures and grain geometries.

Operating Pressure. It is common knowledge in rocketry that, with few exceptions, solid propellants burn faster at higher chamber pressures. This factor was used to AeroTech's advantage in the design of Warp-9 motors. 38mm RMS Warp-9 motors (including the H999N) operate at over 1,400 PSI. While this may seem high for sport rocket motors, the 38mm RMS™ case has been hydrostatically tested at up to 3,800 PSI without failure. 54mm motors, with their lower casing wall thickness to diameter ratio, operate at about 850 PSI. 75mm motors run at about 1,100 PSI while 98mm motors are designed to operate at a maximum pressure similar to the 54mm motors, up to 850 PSI. In all cases, the motor operating pressures are as high or higher than those produced by the "standard" AeroTech propellants such as Blue Thunder; in some cases much higher. Even with Warp-9's low burn rate exponent, high motor chamber pressure enhances burn rate, thrust levels and permits the efficient use of higher expansion ratios which result in even higher levels of performance.

Propellant Web Thickness. The propellant web thickness, defined as ((propellant grain diameter - core diameter)/2), of Warp-9 motors was chosen as a balance between loading efficiency and desired burn time. Careful consideration was given to choosing core diameters that were not too large but created web thicknesses that would result in the shortest burn time and highest average thrust possible. On the other hand, the core diameter had to be large enough to prevent excessively high core K_n, defined as the ratio of to exposed propellant surface area to port area, (especially on multiple grain motors) in order to avert choked flow in the core and possible resulting motor catastrophic failure.

Nozzle Expansion Ratio. A relatively high nozzle expansion ratio was chosen for most Warp-9 motors not only to maximize delivered propellant specific impulse but also to help produce thrust levels as high as possible. Fortunately, AeroTech has at its disposal a number of phenolic nozzle "blanks" that were designed with high as-molded expansion ratios. These nozzles are normally used as-is or drilled to larger throat diameters to accommodate various motor designs and propellants. Each nozzle blank may accommodate a range of throat diameters while maintaining an acceptable expansion ratio.

(GRAMS/100 GRAMS)	CHAMBER	THR(SHIFT)	EXH(SHIFT)
H2	1.36016	1.38661	1.83134
H2O	21.66542	21.50577	17.77137
N2	9.79498	9.80032	9.80256
CLH	23.79028	24.00467	24.20424
CO	25.73135	25.33216	19.31842
CO2	11.26633	11.90388	21.48137

Fig.-3. Warp-9 Significant Combustion Products at 1000/14.7 PSI

In conclusion, rocket motors using AeroTech's Warp-9 propellant deliver exceptional performance not only as a result of the use of a particular burn rate catalyst or any other single factor, but because several propellant and motor performance parameters were considered and brought together to work in a balance of burn rate, loading efficiency, processing and performance.