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MEMORANDUM REPORT ARBRL-MR-03136

TRAJECTORY PREDICTIONS FOR A 75 MM SOLID
FUEL RAMJET TUBULAR PROJECTILE

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September 1981



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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I. INTRODUCTION

Army interest in Solid Fuel Ramjets (SFRJ) spawned a technology demonstration program for a gun launched tubular projectile with an SFRJ combustion chamber. Chemical Systems Division of United Technologies Corp designed a 75 mm demonstration round after wind tunnel and direct connect tests*. New flight regimes were encountered in the high velocity (Mach 4 plus) at sea level. Almost all ramjet experience has been with either low velocity or high altitude; performance correlations have not been developed for the tubular projectile flight regime. Data remain scarce on regression rate and combustion efficiency dependence on air flow conditions.

Predicting the performance of these SFRJ projectiles requires coupling the solid fuel combustion chamber to the supersonic diffuser inlet. An AFAPL (Air Force Aero Propulsion Laboratory) computer code¹ for ramjet design analysis was modified to compute combustion in the solid fuel chamber. Expected performance of the 75 mm SFRJ tubular projectiles is hereby reported.

II. ASSUMPTIONS

1. Enthalpy versus temperature and pressure for incoming air taken from Keenan and Kaye** properties of air at low pressure. The values were supplied with the AFAPL code. At the nominal launch velocity (Mach 4.29) on a standard day at sea level, the air stagnation temperature and pressure are 1260K and 24.9 MPa.
2. US Standard Atmosphere. For these sea level, standard day trajectories no altitude variations need be considered.
3. Constant drag coefficient (.0645). A value suggested by Chemical Systems Division after its preliminary design studies and some wind tunnel tests. That the coefficient will be velocity dependent has been conveniently ignored.
4. Constant nozzle efficiency (0.98). A reasonable value for conical nozzles. Variations due to chamber conditions and nozzle design have been ignored.
5. Normal shock inlet operation. Pressure loss ratios in the inlet calculated from standard normal shock tables for an ideal gas of 1.4 specific heat ratio. Exact inlet calculations are not made; only area ratios are considered.
6. Adiabatic processes. No heat loss to projectile body.
7. Combustion fully established as initial condition. Ignition transient not considered.

**A direct connect test is a combustion chamber without inlet. Air enters the chamber at flow conditions expected at the inlet dump plane.*

¹K. A. Watson, "Air breathing Missile Design Program-FJ", AFAPL-FJT-TM-77-29, AF Aero Propulsion Laboratory, (November 77).

***Provided without reference citation.*

III. FUEL DATA

Fuel thermodynamic data, supplied by Chemical Systems Division, are shown in Table 1. The values represent complete combustion at the air temperature and equivalence ratio. In the calculations final temperature is corrected for combustion efficiency in the standard method

$$T_f = T_a + \eta_c (T_{t_f} - T_a) ,$$

where η_c = combustion efficiency,

T_f = final temperature,

T_a = incoming air temperature,

T_{t_f} = theoretical final temperature.

Specific heat ratio and molecular weight were assumed unaffected by combustion efficiency. The data are given only for one pressure (3.0 MPa). No corrections were attempted for pressure. (Nominal chamber pressure is near that level.)

IV. COMBUSTION

Flow of fuel from the solid surface into the combustion chamber is governed by the simple

$$\dot{w}_f = \rho_f \dot{r} S.$$

Calculations of regression rate ($\dot{r}$) and surface area (S) provide the only challenge. Regression rate is available for a few fuels from CSD monthly contract reports in the form

$$\dot{r} = a G^n ,$$

where G is the air mass velocity and constants a and n can vary with air stagnation temperature and pressure. CSD's data for the fuel intended for the 75 mm demonstration rounds produces a regression rate correlation of

$$\dot{r} = 0.116 G^{0.64} . \tag{1}$$

TABLE 1. FUEL THERMODYNAMIC DATA

 $P_4 = 440$ psia

ϕ	0.306	0.394	0.499	0.604	0.700	0.796	0.901	1.00
AIR TEMPERATURE (R)	FINAL TEMPERATURE (K)							
1300	1465	1645	1860	2060	2225	2380	2528	2605
1900	1765	1920	2120	2298	2448	2585	2692	2760
2500	2060	2220	2380	2550	2675	2775	2755	2902
3000	2280	2425	2585	2720	2825	2908	2975	3012
SPECIFIC HEAT RATIO								
1300	1.297	1.2875	1.2745	1.2595	1.2435	1.227	1.203	1.176
1900	1.284	1.272	1.2575	1.2425	1.226	1.2045	1.177	1.161
2500	1.266	1.254	1.240	1.220	1.199	1.178	1.1585	1.149
3000	1.248	1.236	1.222	1.1985	1.1785	1.162	1.149	1.142
MOLECULAR WEIGHT								
1300	29.10	29.15	29.20	29.25	29.30	29.30	29.30	29.05
1900	29.10	29.15	29.15	29.25	29.25	29.20	29.12	28.95
2500	29.10	29.10	29.15	29.22	29.17	29.07	28.95	28.75
3000	29.05	29.05	29.15	29.15	29.05	28.92	28.75	28.50

Exposed fuel surface is a straightforward geometry problem. All planned configurations for the gun a launched projectiles are internally perforated cylinders. (The high spin rate precludes the common form spoke gain of guided missile applications). Only one complication is presented - the grain length. The fuel-in-cowl design packs in more fuel but regression shortens the exposed length. Exact surface calculation depends on the specific internal cowl design but the goemetry adjustment is straightforward. Figure 1 shows a typical fuel-in-cowl design.

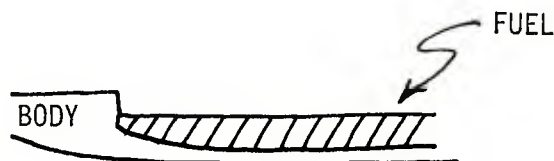


Figure 1. Fuel in Cowl Schematic

Combustion efficiency correlations are also available from CSD monthly contract reports for a few fuels. It is in the form

$$\eta = b \phi^c T_a^d \frac{A_3}{A_i} \quad (2)$$

The equivalence ratio ϕ comes from the fuel and air flow calculations and the step area ratio $\frac{A_3}{A_i}$ from the chamber geometry.

CSD's reported correlation² for the 75 mm fuel is

$$\eta = 0.22 \phi^{-.45} \frac{T_a}{1000}^{1.16} \frac{A_3}{A_i}^{0.38} \quad (3)$$

Both regression rate and combustion efficiency change with time because air conditions change with projectile velocity and because the fuel regresses to increase the step area ratio A_3/A_i .

²Monthly Progress Report No. 22, Chemical Systems Divisions, (August 80).

The combustion efficiency correlation was derived from tests where the efficiency never exceeded 0.90. Extrapolation to the combustion chamber conditions for the 75 mm projectile would predict efficiencies greater than 1.0. Maximum of 1.0 was assigned despite arguments³ for greater measured efficiencies.

Some recent CSD performance calculations for a 35 mm SFRJ-TP used an efficiency expression

$$\eta = \frac{0.18}{\phi^{-.45}} \frac{A_3}{A_i}^{0.3} \frac{T_a}{1000}^{1.1}, \quad (4)$$

although no source was cited.

An independent analysis⁴ of the reported CSD test data for fuel 21862 obtained a least squares fit⁴ of

$$\eta = \frac{.232}{\phi^{-.347}} \frac{A_3}{A_i}^{.491} \frac{T_a}{1000}^{.944}. \quad (5)$$

Figure 2 compares experimental with correlated values of efficiency for Eq. (5). Appendix A gives the data used in the analysis.

The transition from the linear correlation,

$$\eta = a X,$$

where X is the power function of all the influencing variables to a limit of $\eta \rightarrow 1.0$ requires some imagination. The test data do not extend to those conditions. An arbitrary selection of a functional dependence must suffice. It should satisfy a few conditions: (1) for mid range ($0.4 < aX < 0.8$) it should be $\eta = aX$; (2) for $aX < 0.4$ it is irrelevant in present applications, (3) it must approach $\eta = 1$ for $aX < 0.8$ smoothly. Final forms are limited only by the imagination; physics provides few clues. After some acrobatics the following form makes a reasonable estimate

³R. Dunlap, G. E. Jensen, "Combustion Efficiency in a SFRJ at the Fuel Grain Exit Plan", 16th JANNAF Combustion Meeting, Monterey, CA (September 1979).

⁴R. H. Moore, R. K. Zeigler, "The Solution of the General Least Squares Problem with Special Reference to High Speed Computers" Los Alamos Scientific Laboratory Report LA2367 (March 1960).

$$\eta = 1 - \left[4 - \frac{1}{2} (X-3)^2 \right] X e^{-1.1X} \quad (6)$$

For $a = 0.23$ comparison of η with aX is shown in Figure 3.

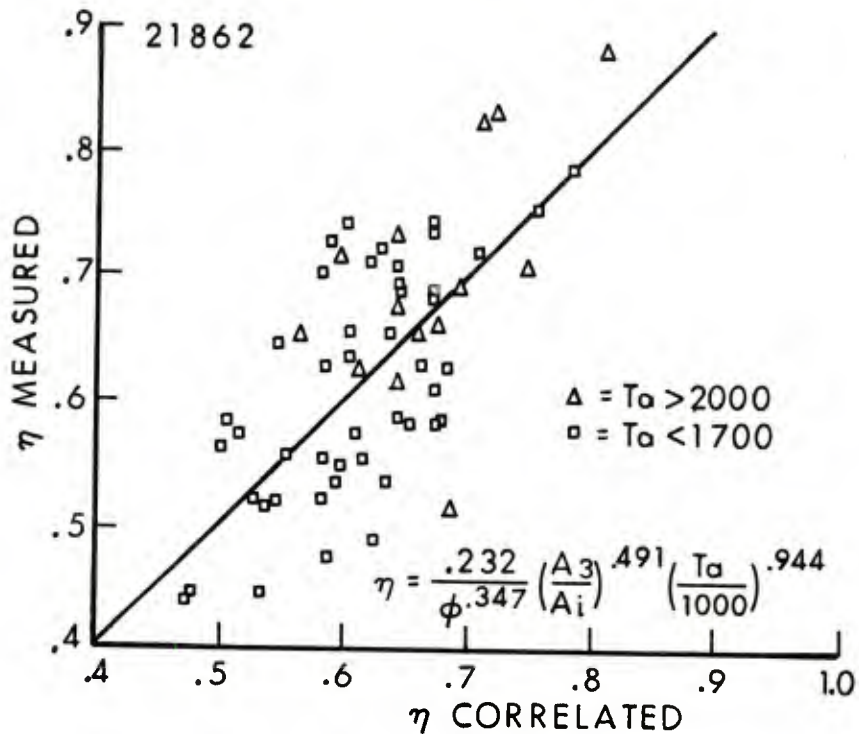


Figure 2. Comparison of Correlated and Measured Combustion Efficiency

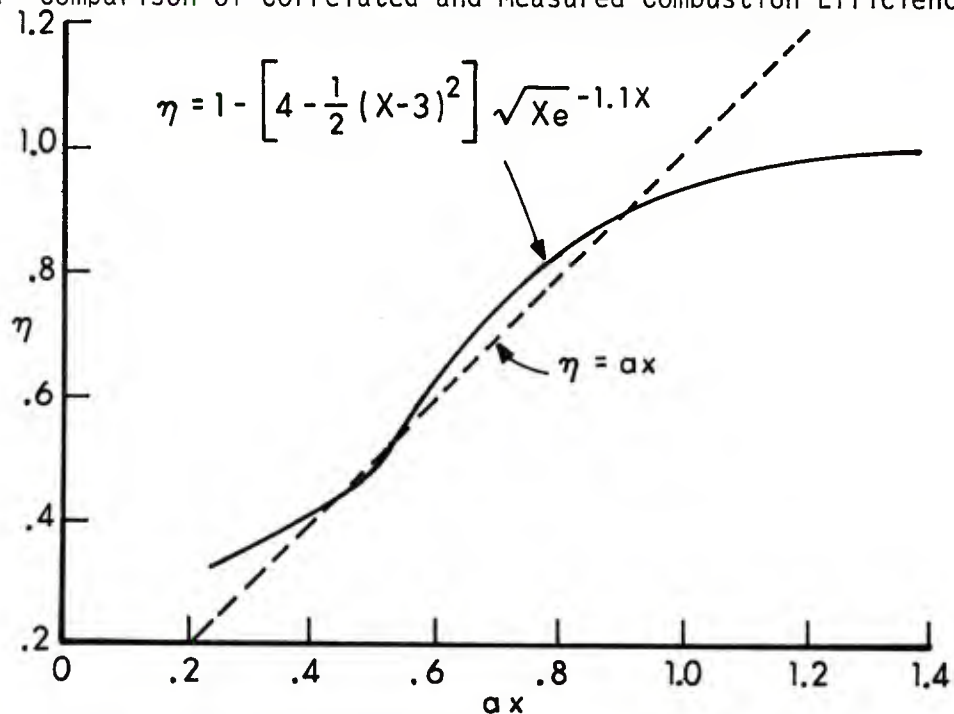


Figure 3. Non-linear fitting function for Combustion Efficiency

Regression rate was also obtained from a least square fit for fuel 21862. With air temperature dependence, the best fit is

$$\dot{r} = .0634 G^{.833} \frac{T_a^{.614}}{1000} \quad (7)$$

The regression rates obtained with this fit are close to those obtained with the CSD reported dependence (Eq. (1)).

V. RESULTS

Trajectories were calculated for the 75 mm SFRJ-TP designed for gun firing demonstration. Figure 4 shows the velocity versus range on non-dimensional scales of velocity divided by initial velocity and range divided by range at burnout. Security classification precludes reporting actual velocities and ranges.

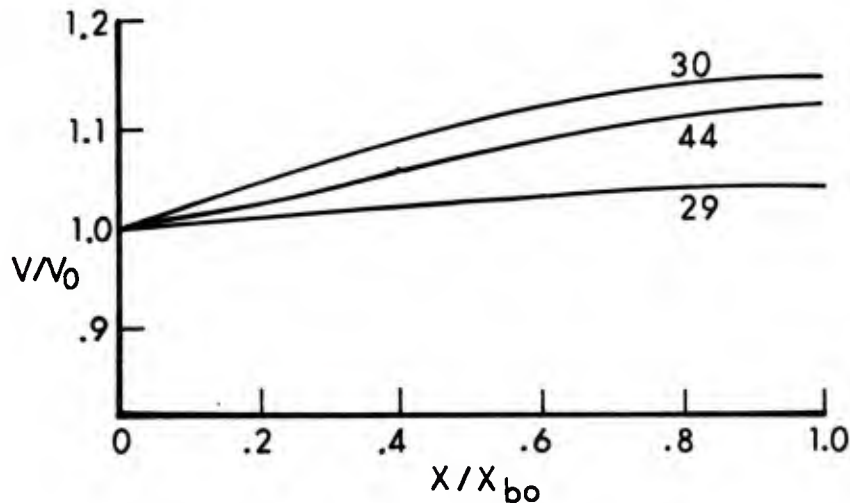


Figure 4. Velocity vs range for 75 mm SFRJ-TP

The three trajectories in Figure 4 come from different assumptions on combustion efficiency. The central curve represents the amended least squares fit of Eq. (6); the upper curve represents the CSD offered efficiency of Eq. (3); the lower curve represents the CSD suggested Eq. (4).

The spread among the calculated trajectories demonstrates the sensitivity to the assumption of combustion efficiency. Since each represents an extrapolation from the test data from which the correlations were derived, they may all be wrong. Both the need for extrapolation and the sensitivity demonstrate the necessity for data in the expected conditions.

Some details of the combustion chamber performance are shown in Figure 5 which displays time history of regression rate and air mass velocity.

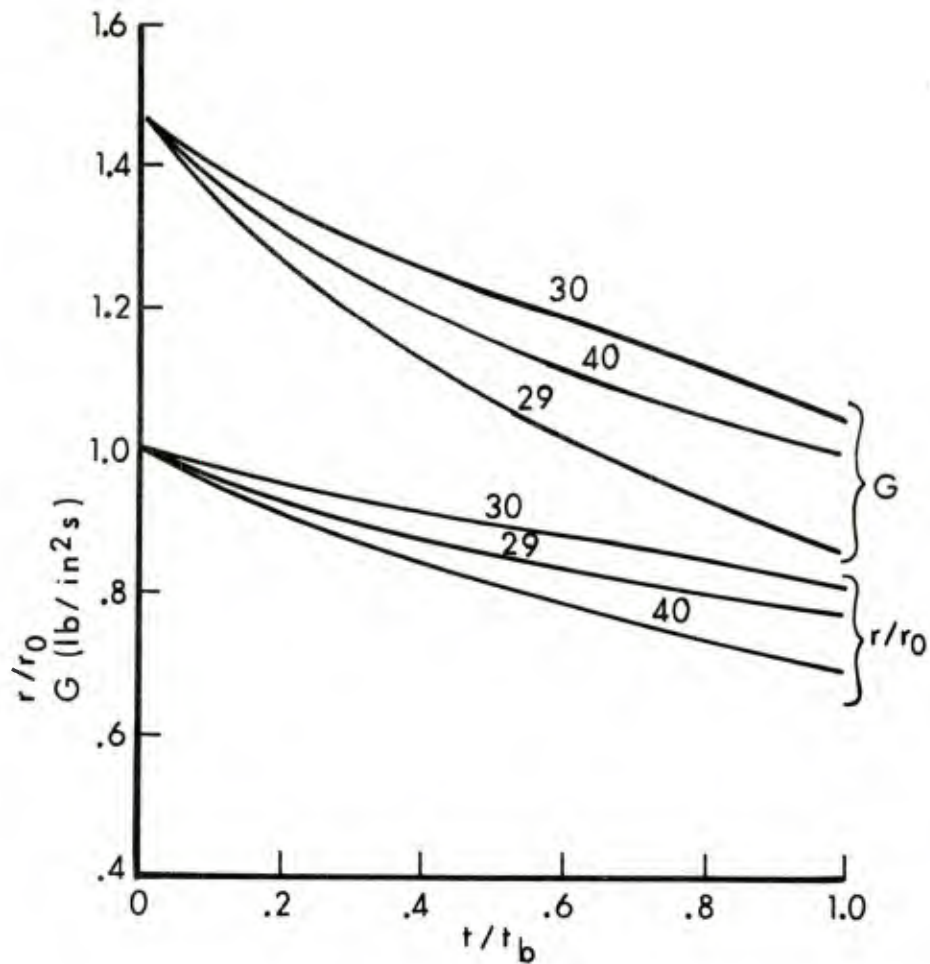


Figure 5. Chamber performance of 75 mm SFRJ-TP

Figure 6 shows the predicted combustion efficiency for various assumptions about its dependence on chamber conditions. Curve 30 uses the CSD Eq. (3); Curve 44 uses the amended fit Eq. (6); Curve 40 uses the re-analyzed CSD data correlation, Eq. (5); Curve 29 uses the CSD correlation of Eq. (4). All the calculations limited the efficiency to 1.0 arbitrarily.

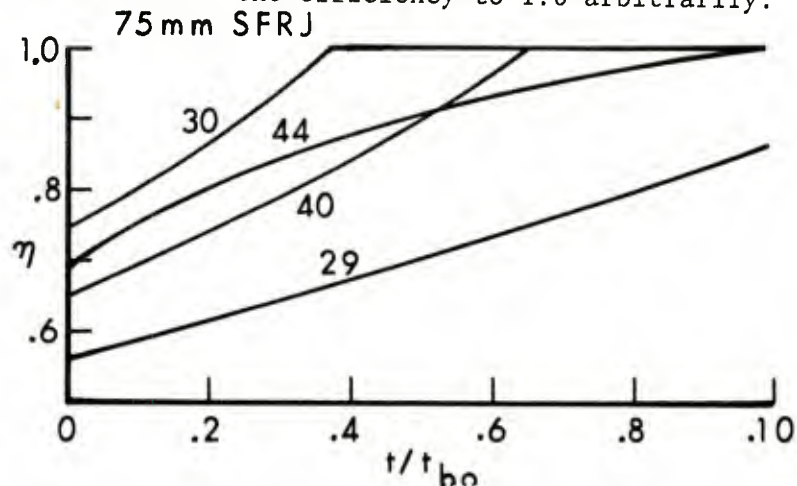


Figure 6. Effect of Combustion Efficiency Correlation on Predicted Efficiency

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1. K. A. Watson, "Air breathing Missile Design Program-FJ", AFAPL-FJT-TM-77-29, AF Aero Propulsion Laboratory, (November 77).
2. Monthly Progress Report No. 22, Chemical Systems Divisions, (August 80).
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4. R. H. Moore, R. K. Zeigler, "The Solution of the General Least Squares Problem with Special Reference to High Speed Computers" Los Alamos Scientific Laboratory Report LA2367 (March 1960).

LIST OF SYMBOLS

G	air mass velocity
r	fuel regression rate
S	Fuel surface area
T_a	Air Temperature (Stagnation)
T_f	Final Combustion Temperature
T_{tf}	Theoretical Final Combustion Temperature
$\dot{W}$	Mass flow rate
n_c	Combustion efficiency
ϕ	Equivalence ratio
ρ_f	Fuel density

APPENDIX A
CSD TEST DATA

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CSD TEST DATA

<u>Test</u>	<u>T_a</u>	$\frac{A_3}{A_1}$	<u>P</u>	<u>G</u>	<u>φ</u>	<u>regr rate</u>	<u>n</u>
7068	1285	2.017	116	.566	.543	.049	.576
7070	1845	2.334	204	.729	.580	.074	.753
7071	1860	2.354	271	.965	.539	.091	.786
7072	1860	2.334	250	.927	.876	.106	.627
7073	1850	1.572	191	.826	.850	.087	.520
7074	1850	1.490	127	.573	.882	.061	.522
7075	2200	1.572	200	.807	.613	.081	.831
7076	2200	2.198	207	.768	.696	.090	.882
7078	2200	1.541	203	.814	.844	.084	.677
7079	2200	1.715	155	.753	.717	.091	.822
6939	1850	1.399	319	1.120	.522	.090	.555
6940	1850	1.394	222	.780	.590	.071	.525
6941	1850	1.391	115	.390	.777	.048	.443
6942	1850	1.405	62	.200	1.069	.033	.447
6943	1860	1.353	269	1.000	.534	.080	.549
6944	1850	1.391	264	.980	.415	.083	.581
6945	1855	1.374	329	.990	.393	.079	.610
6946	1860	1.373	346	1.00	.524	.080	.574
6947	1855	1.432	223	.970	.598	.091	.587
6948	1850	1.449	207	.930	.489	.095	.586
6928	1840	1.419	234	.970	.409	.082	.649
6929	1885	1.410	239	1.00	.408	.084	.625
6930	1885	1.429	236	.980	.433	.088	.580
6931	1885	1.438	238	.980	.432	.088	.581
6933	1910	1.464	244	.970	.574	.088	.489
6934	1880	1.478	247	.960	.599	.091	.510
6935	1850	1.401	323	1.14	.392	.092	.743
6936	1850	1.389	214	.780	.442	.070	.587
6937	1850	1.389	111	.400	.589	.048	.475
6938	1850	1.392	58	.200	.786	.032	.382
6916	1850	1.359	236	1.0	.439	.088	.688
6917	1850	1.391	241	.99	.448	.090	.681
6918	1850	1.401	260	1.02	.586	.092	.624
6919	1850	1.463	267	1.00	.579	.091	.654
6921	1600	1.521	214	.86	.383	.070	.711
6922	2020	1.415	250	.98	.468	.094	.696
6923	2020	1.391	259	1.01	.576	.089	.612
6924	1850	1.409	289	.97	.401	.080	.683
6925	1850	1.392	302	.99	.532	.081	.632
6927	1840	1.030	234	.96	.427	.085	.630
6871	1870	1.589	254	1.40	.498	.113	.689
6872	2050	1.660	271	1.35	.576	.130	.702
6873	2050	1.543	194	1.03	.643	.106	.650
6874	2060	1.313	323	1.54	.564	.148	.733
6875	1850	1.224	180	1.02	.609	.098	.646
6876	1840	1.307	304	1.53	.543	.140	.707

APPENDIX A
CSD TEST DATA

<u>Test</u>	<u>T_a</u>	$\frac{A_3}{A_i}$	<u>P</u>	<u>G</u>	<u>ϕ</u>	<u>regr rate</u>	<u>η</u>
6877	1840	1.688	315	1.61	.508	.138	.736
6878	1845	1.307	326	1.64	.513	.143	.728
6879	2050	1.589	259	1.28	.807	.126	.625
6880	1840	1.319	360	1.80	.496	.153	.743
6881	1770	1.656	362	1.92	.511	.164	.707
6892	1850	1.523	307	1.40	.541	.121	.722
6855	2080	1.719	409	1.62	.542	.149	.705
6856	2080	1.268	237	0.98	.670	.108	.619
6857	1750	1.237	212	.98	.670	.105	.564
6858	1750	1.672	362	1.58	.513	.136	.655
6860	1775	1.488	173	1.01	.664	.105	.556
6861	1770	1.222	326	1.41	.551	.121	.517
6863	2050	1.619	298	1.31	.609	.132	.514
6864	1750	1.223	288	1.42	.762	.128	.440
6865	1750	1.257	314	1.72	.659	.138	.585
6866	2025	1.672	302	1.67	.657	.138	.652
6867	2025	1.254	260	1.34	.739	.120	.655
6868	1850	1.569	258	1.40	.710	.120	.555

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