PERFORMANCE EVALUATION OF A SMALL SIZE ARCJET THRUSTER

Keisuke Ichige*, Makoto Hirakawa*, Hisashi Kihara[†] Ken-ichi Abe[‡] and Michio Nishida[§]
Department of Aeronautics and Astronautics
Kyushu University
Fukuoka 812-8581, JAPAN

Masashi Matsumoto[¶]
Fluid Dynamics & Combustion Department, Research Institute
Ishikawajima-Harima Heavy Ind. Co. Ltd.
Yokohama, 235-0031, Japan

Abstract

This paper describes the current status of the performance evaluation of a laboratory model of a low power arcjet thruster. A 250W-class radiation cooled nitrogen arcjet thruster was developed for the installation on small satellites and verification of the numerical results of arcjet performance. The arcjet thruster was operated using a nozzle with 1.0mm in constrictor diameter. Thrust and anode temperature measurements were conducted for various arc currents and nitrogen mass flow rates. Stable operation was obtained at the power levels of 170W to 350W and nitrogen mass flow rates from 10mg/sec to 35mg/sec. Specific impulses of 140 seconds at 200W and 180 seconds at 300W were achieved. The higher thrust performance may be expected by reducing the size of the throat and the thruster housing to decrease the heat loss from the body surface.

Introduction

The electric propulsion has been expected as advanced propulsion for space applications because of high specific impulse compared with conventional chemical rockets. An arcjet thruster, one of the electric propulsion systems, consists of a cathode, a cylindrical throat and an expansion anode nozzle. The gaseous propellant injected into the discharge section is heated by the high temperature arc column and accelerated in the expansion nozzle.

Arcjet thrusters were intensively studied in 1960s due to its simple structure and easiness of controlling the thrust. However, the investigation of the arcjet thruster became less attractive at the end of 1960s because sufficient electric power was not expected onboard spacecraft at that time.

Recently the evolution of commercial communication satellites has made companies and laboratories to restart the development of the arcjet thruster.

A hydrazine arcjet thruster has been considered as one of the candidates for space missions such as north-south (N-S) station keeping and orbit repositioning of satellites.[1] Actually, several arcjets have been used for the N-S station keeping mission of communication satellites and for this purpose many laboratory hydrazine arcjet thrusters have been designed and evaluated.[2,3,4] However because of power and size limitation, hydrazine arcjet thrusters may not be applicable to the small satellites which attract the attention of the people recently. A very low power nitrogen arcjet may be considered as a powerful electric propulsion device for small satellites.

Kyushu University has focussed on numerical analysis of an arcjet plasma flow to establish a guideline for designing arcjet thrusters.[5,6] In order to verify the numerical results, it is advantageous to have experimental data at our own expense. For these reasons, the development of a small size, low power arcjet thruster started in 1998.

This paper describes the investigation of performance characteristics of a 250W radiation cooled arcjet thruster. The performance parameters measured in the present study were thrust, nozzle temperature, mass flow rate, arc current and arc voltage.

Experimental Apparatus and Procedure

Arcjet Thruster

A cross-sectional schematic and a photograph of an arcjet thruster used in the present study are shown in Figs. 1 and 2, respectively.

*Graduate Student
[†]Research Associate
[‡]Associate Professor
[§]Professor
[¶]Technical Engineer

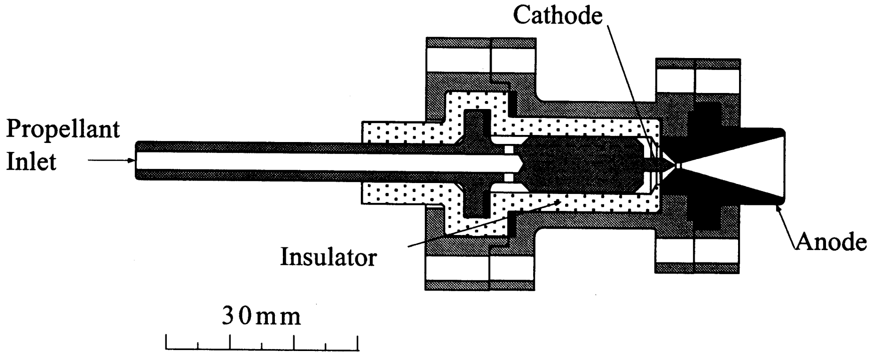

Fig. 1 Cross-sectional schematic of the arcjet thruster

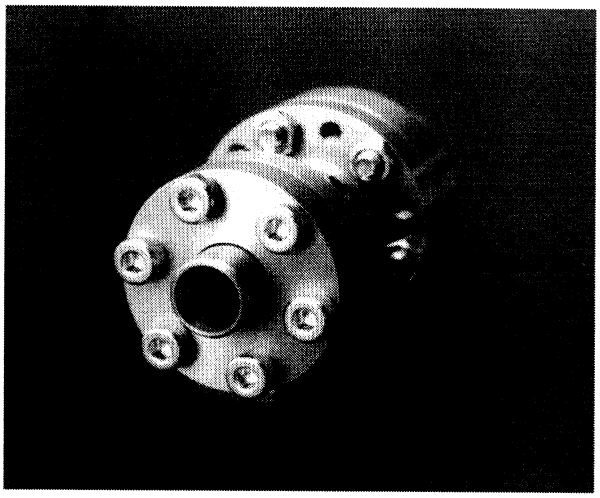

Fig. 2 Photograph of the arcjet thruster

The anode nozzle was made of tungsten against the high temperatures expected at the nozzle throat. Both the converging and diverging sides of the nozzle were conical with half angles of 45° and 15°, respectively. The inlet to the converging side of the nozzle was 6.2mm in diameter and the diameter at the exit plane was 10mm. The constrictor of the nozzle was 1.0mm in diameter and its length was 0.8mm.

The cathode used in the experiments was made of a 2 percent thoriated tungsten rod with 2.0mm in diameter, 5.5mm in length and the tip half cone angle was 30°. The electrode gap (the minimum axial distance between the tip of the cathode and the constrictor inlet) was set to 0.0mm by moving the cathode.

Thrust Stand

Thrust measurements were done using a pendulum type thrust stand which was basically designed based on the concept similar to the model in Ref. 7. The arcjet thruster was attached horizontally to the thrust stand (Fig. 3). The thrust stand was composed of two arms (one vertical and one horizontal), two knife edge supports and balance weights. The ratio of the arms was adjustable in compliance with amount of thrust.

Thrust was determined by measuring a load due to deflection of the arms with a load cell and comparing with calibration curves. Thrust calibration was done by applying known force, measured with another load cell, to the thrust direction. The thrust stand and two load cells were water-cooled to minimize thermal drift from heat conductance and radiation from the arcjet thruster. The uncertainty of the measurement at present system was 1mN.

Thermocouple

For contact measurement of anode temperature, the type-K (Cu/Constantan) thermocouple was used. The thermocouple was attached to the nozzle exterior surface 5mm from nozzle exit plane as shown in Fig. 4.

Propellant Supply System

All experiments were performed using nitrogen gas as a propellant. Nitrogen gas flow was regulated by a thermal conductivity type mass flow controller which was calibrated for nitrogen and had a maximum flow rate of 5000 standard cubic centimeters per minute (SCCM).

Power Supply

The power supply system was composed of a main power supply used to maintain an arc discharge, and a supplementary power supply used to initiate arcjet propellant breakdown. The former was capable of supplying 150V at 200A. The later was a high voltage low current power supply capable of supplying up to 1.5kV.

Arc current was measured with a Hall-effect current probe, and arc voltage was obtained by an isolated digital multimeter. The uncertainty of arc current and arc voltage measurements were 0.1A and 0.1V, respectively.

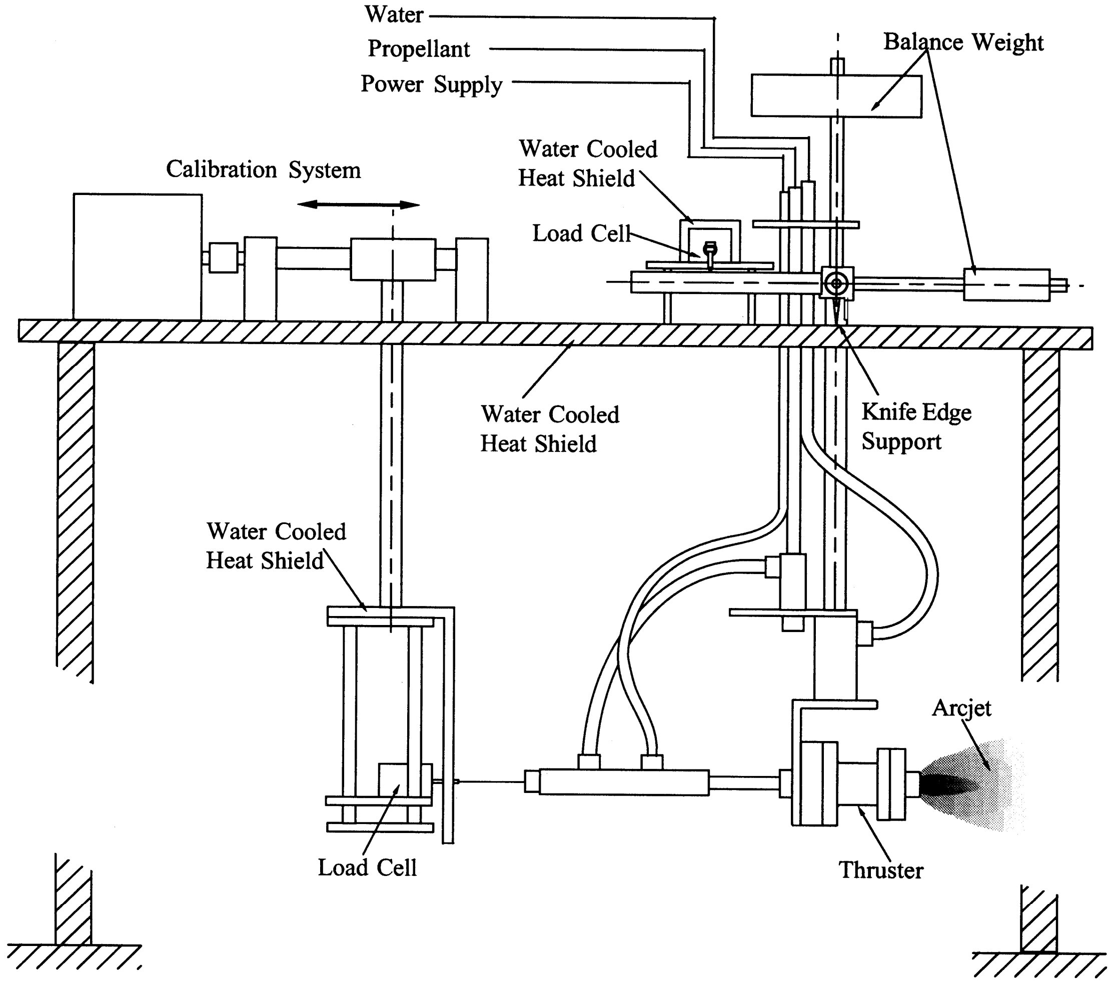

Fig. 3 Pendulum type thrust balance

Test Chamber and Vacuum System

All the tests were performed in a water-cooled 1.0m long vacuum chamber with 1.0m diameter. The test chamber was evacuated with two types of pumps, an oil-sealed rotary vacuum pump and mechanical booster pump allowing an ambient pressure of 4.9Pa at a mass flow rate of 40mg/s nitrogen.[8]

Experimental Procedure

Before starting measurements, every reassembled arcjet thruster was operated until stable operation was obtained.

Thrust calibration was brought out before the arc ignition and immediately after the arc extinction to confirm whether any thermal drift existed or not.

Measurements were begun when the thermal equilibrium was assured by monitoring anode temperature. In a typical test sequence, first of all the discharge was started at the lowest mass flow rate. Then the mass flow rate was gradually raised while the current level was maintained.

Results and Discussion

The objective of this investigation was to obtain a preliminary evaluation of arcjet operating characteristics and performance at low power level. Experimental data were obtained at power levels of 170W to 350W and nitrogen mass flow rates of 10mg/sec to 35mg/sec. Data taken in the tests are shown in Table 1. The thrust efficiency is calculated according to the following equation:

$$\eta = \frac{{I_{sp}}^2}{2P/\dot{m}g^2} \tag{1}$$

where g is the gravitational acceleration, I_{sp} is the specific impulse, $\dot{m}$ is the mass flow rate and P is the input power. In this equation the contribution of the cold gas enthalpy to the thrust efficiency is neglected.

Operational Characteristics

Figure 5 indicates the current-voltage characteristics of the thruster. It is apparent from this figure that the voltage increases with the mass flow rate

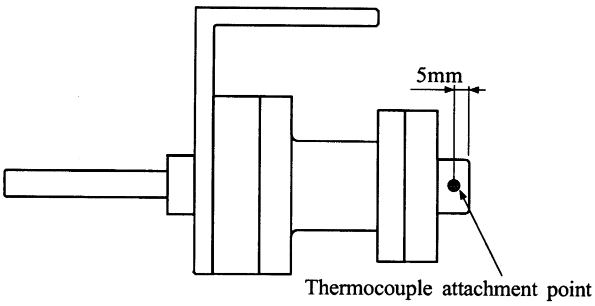

Fig. 4 Surface tempearture measurement point

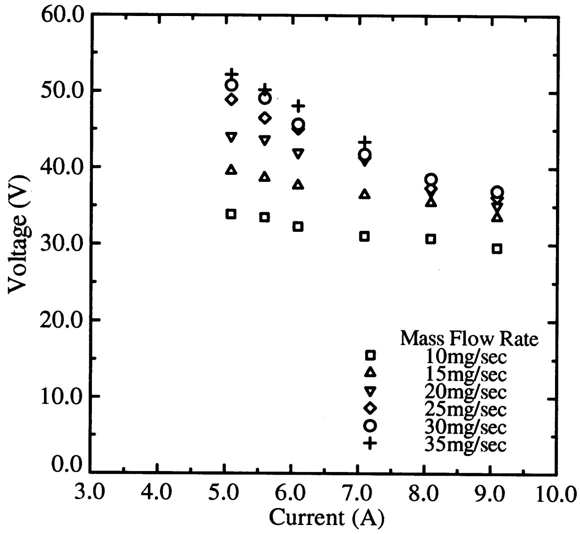

Fig. 5 Current-Voltage Characteristics

and decreases with increasing current. These features are somewhat similar to those observed in the tests of other nitrogen arcjet thruster.[9]

For all the mass flow rates, the arcjet operation became unstable with oscillation of the voltage at current levels between 10 and 20A. Increasing current above 20A made arcjet operation stable again with the voltage levels of 20 to 30V.

The arc was suddenly terminated as current decreases below 5A for the mass flow rates of 15, 20, 25, 30, and 35mg/sec. For the mass flow rate of 10mg/sec, the arc was maintained below 5A with occasional voltage mode change. There were two modes with different arc voltage, one with stable arc voltage of 35V and the other with arc voltage of 15V. Similar phenomenon is reported in the Ref. 10.

At the mass flow rates above 35mg/sec, the arcjet operation was possible only for a short time.

Thrust Performance

The results of the thrust measurements are shown in Figs. 6 to 8. It is seen from the thrust versus input power shown in Fig. 6 that the con-

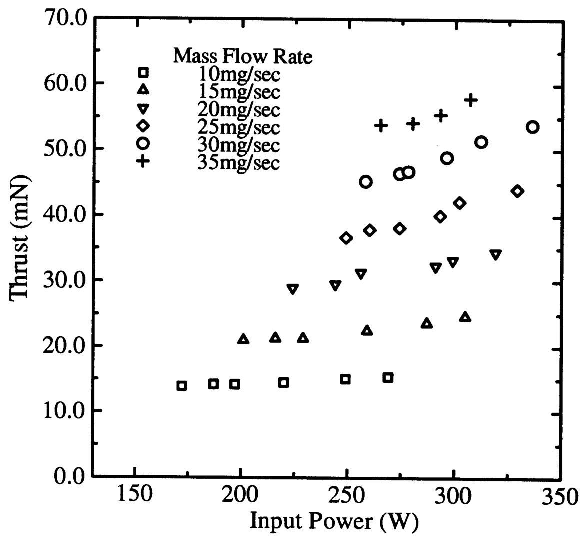

Fig. 6 Thrust versus input power

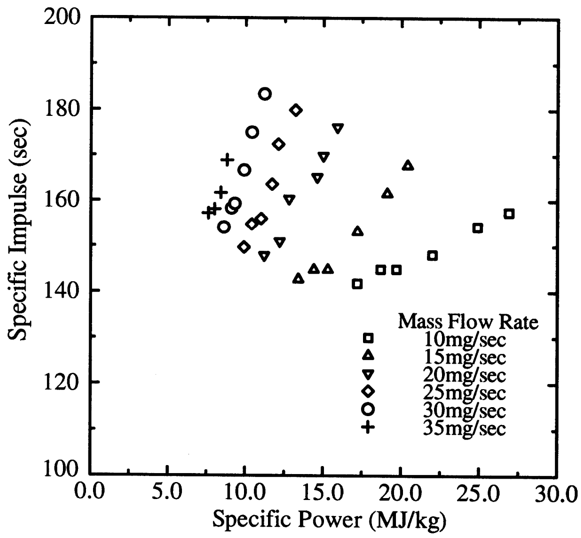

Fig. 7 Specific impulse versus specific power

tribution of the input power to the thrust becomes less conspicuous at lower mass flow rates. Figure 7 shows specific impulse versus specific power. In this figure, the slope of the curve for the lowest mass flow rate is significantly smaller than that for the highest mass flow rate. The observed trends from these two figures indicate that the thrust efficiency is increased with the mass flow rate as shown in Fig. 8. The reason of this tendency might be explained by the high pressure caused by the high mass flow rates at the discharge region. The highly pressurized propellant may prevents arc current from diffusing and reduces energy dissipated at the anode surface by the electrons. The low anode temperatures for the high mass flow rates at given input power shown in Fig. 9 may be the

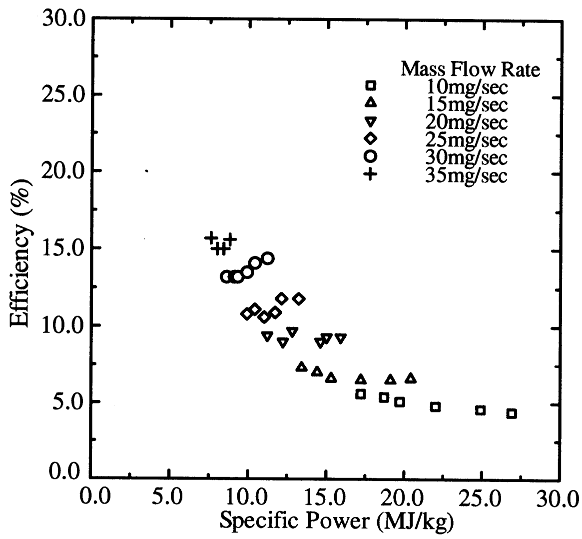

Fig. 8 Thrust efficiency versus specific power

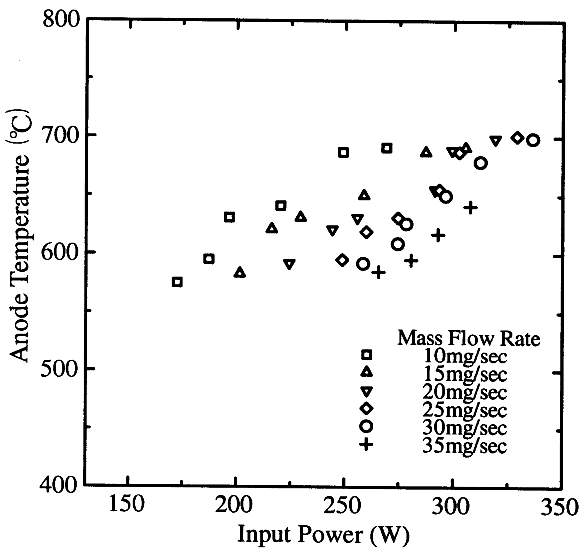

Fig. 9 Anode temperature versus input power

evidence to support this.

The sufficient explanation of the effect requires a more detailed study including the comparison among the different sizes of the constrictor diameters and the comparison among the arcjet thrusters with different anode surface area.

Conclusion

In order to investigate the performance characteristics of a low power arcjet thruster, the measurements of arc current, arc voltage, thrust and anode temperature were conducted for nitrogen as propellant. The results obtained in the present work are summarized as follows:

1. The arcjet thruster was stably operated at the power levels of 170W to 350W with nitorgen mass flow rates of 10mg/sec to 35mg/sec.
2. Specific impulses of 140 seconds at 200W and 180 seconds at 300W were achieved.
3. The thrust efficiency is highly dependent on the mass flow rate.

References

[1] Martinez-Sanchez, M. and Pollard, J.E., "Spacecraft Electirc Propulsion-An Overview," *Journal of Propulsion and Power*, Vol.14, 1998, pp.688-699

[2] Curran, F. M. and Sarmiento, C.J., "Low Power Arcjet Performance Characterization," AIAA Paper 90-2578, 1990.

[3] Riehle, M., Auweter-Kurtz, M. and Kurtz, H. L., "High Specific Impulse Experiments with 1.5- and 5-kW Thermal Arcjets," 23rd Int. Electric Propulsion Conf., Seattle, WA., IEPC-93-210, September 1993.

[4] McFall, K.A., Tilley, D.L. and Gulczinski III, F.S., "Low Power Arcjet Performance Evaluation," 24th Int. Electric Propulsion Conf., Moscow, Russia, IEPC-95-18, September 1995.

[5] Kuchi-ishi, S. and Nishida, M., "Thermochemical Nonequilibrium Modeling for a Nitrogen Arcjet Thruster," 26th Int. Electric Propulsion Conf., Kitakyushu, Japan, IEPC-99-029, Oct. 1999.

[6] Hayatani, M. and Nishida, M., "Simple Estimation of the Performance of a Low Power Nitrogen Arcjet Thruster," 26th Int. Electric Propulsion Conf., Kitakyushu, Japan, IEPC-99-029, Oct. 1999.

[7] Yamamoto, Y., Onoe, K., Tahara, H., Yoshikawa, T., Ishii, M. and Sato, K., "Thrust Performance and Life Evaluation of a 1-kW-Class Arcjet Thruster," 19th Int. Symposium on Space Technology and Science, Yokohama, Japan, ISTS 94-a-53, May 1994.

[8] Hirakawa, M., Ichige, K., Aso, S. and Nishida, M., "Performance Characteristics of an Arc-Heated Wind Tunnel," 21st Int. Symposium on Space Technology and Science, Omiya, Japan, ISTS 98-d-23, May 1998.

[9] King, D.Q. and Butler, G.W., "Modeling and Measurement of N_2 Arcjet Performance," AIAA Paper 90-2616, 1990.

[10] Ogiwara, K., Hosoda, S., Suzuki, T., Toki, K., Kuriki, K., Matsuo,S., Nanri, H. and Nagano, H., "Development and Testing of a 300W-class Arcjet," 24th Int. Electric Propulsion Conf., Moscow, Russia, IEPC-95-017, September 1995.

Table 1 Obtained thrust performance data

mass flow rate mg/s	current A	voltage V	input power W	anode temperature ℃	thrust mN	specific impulse sec	specific power MJ/kg	efficiency %
10.0	5.1	33.9	172	575	13.9	142	17.2	5.6
10.0	5.6	33.5	187	595	14.2	145	18.7	5.4
10.0	6.1	32.3	197	631	14.2	145	19.7	5.1
10.0	7.1	31.1	220	641	14.5	148	22.0	4.8
10.0	8.1	30.8	249	687	15.1	154	24.9	4.6
10.0	9.1	29.6	269	691	15.4	157	26.9	4.4
15.0	5.1	39.6	201	583	21.0	143	13.4	7.3
15.0	5.6	38.7	216	621	21.3	145	14.4	7.0
15.0	6.1	37.7	229	631	21.3	145	15.3	6.6
15.0	7.1	36.5	259	650	22.5	153	17.2	6.5
15.0	8.1	35.5	287	687	23.7	162	19.1	6.5
15.0	9.1	33.6	305	691	24.7	168	20.4	6.6
20.0	5.1	44.1	224	592	29.0	148	11.2	9.4
20.0	5.6	43.7	244	621	29.6	151	12.2	9.0
20.0	6.1	42.0	256	631	31.4	160	12.8	9.7
20.0	7.1	41.1	291	655	32.4	165	14.6	9.0
20.0	8.1	37.0	299	689	33.3	170	15.0	9.3
20.0	9.1	35.1	319	699	34.5	176	15.9	9.3
25.0	5.1	48.9	249	595	36.7	150	9.9	10.8
25.0	5.6	46.5	260	619	37.9	155	10.4	11.1
25.0	6.1	45.1	274	631	38.2	156	11.0	10.6
25.0	7.1	41.4	293	655	40.1	164	11.7	10.9
25.0	8.1	37.4	302	687	42.2	172	12.1	11.8
25.0	9.1	36.2	329	701	44.1	180	13.2	11.8
30.0	5.1	50.8	258	592	45.3	154	8.6	13.2
30.0	5.6	49.1	274	609	46.5	158	9.1	13.2
30.0	6.1	45.7	278	626	46.8	159	9.3	13.2
30.0	7.1	41.8	296	650	49.0	167	9.9	13.5
30.0	8.1	38.6	312	679	51.5	175	10.4	14.1
30.0	9.1	37.0	336	699	53.9	183	11.2	14.4
35.0	5.1	52.2	265	585	53.9	157	7.6	15.7
35.0	5.6	50.2	280	595	54.2	158	8.0	15.0
35.0	6.1	48.1	293	617	55.5	162	8.4	15.0
35.0	7.1	43.4	307	641	57.9	169	8.8	15.6