JOURNAL OF PROPULSION AND POWER
Vol. 27, No. 2, March–April 2011

Technical Notes

Design, Fabrication, and Test of a Microelectromechanical-System-Based Millinewton-Level Hydrazine Thruster

Tony Yuan,* Awankana Li,† Berlin Huang,‡
Yu-Ta Chen,‡ and Cetera Chen§
National Cheng Kung University,
Tainan 701, Taiwan, Republic of China

DOI: 10.2514/1.50055

Nomenclature

I_{sp} = specific impulse, s
x = extent of ammonia dissociation

I. Introduction

THE miniaturization of space systems, such as microsatellites, has become an important development trend. Using a cluster of microspacecraft with a constellational architecture to replace a traditional spacecraft can greatly reduce the costs of production and launch, increase flexibility, and disperse the risks of a mission. Miniaturized spacecraft are classified based on mass, power, and dimensions. Spacecraft with a mass of less than 20 kg are classified as class I microspacecraft [1] and require millinewton-level thrusts for spacecraft control. For microspacecraft, the onboard thrusters must be extremely small and lightweight; microelectromechanical systems (MEMS) are thus employed in microthruster design and fabrication [2].

A number of micropropulsion systems have been proposed. Micro cold-gas systems have been constructed and used in practice [3,4]; however, a rather low specific impulse (60–80 s) limits their usage. Micro electric-type thrusters provide a high specific impulse [5], but the requirement of high power for operation limits them to larger spacecraft. Miniaturized solid-propellant thrusters have a simple structure and a high specific impulse [6], but their relatively high thrust level (10^1–10^2 mN) and single use restrict their application.

Monopropellant thrusters are appropriate for miniaturization due to their simplicity and acceptable working temperatures [7]. The catalytic reaction of monopropellant systems mitigates the constraints of radical quenching and mixing prohibition found in the microcombustion of bipropellant systems. Although hydrogen peroxide/silver systems have been tested and effectively reacted in microreactors, hydrazine is considered a better monopropellant for actual microthruster design and operation [7].

A millinewton hydrazine (N_2H_4) monopropellant thruster is presented in this work. MEMS technologies are employed in the design. The design considerations and component fabrication are discussed. The vacuum thrust of the designed thruster was measured and its propulsive performance was analyzed.

II. System and Component Designs

Materials commonly adopted for MEMS devices, silicon and silicon dioxide, are not suitable for working temperatures higher than 1200 K. Structural problems such as bonding failure also limit the working pressure of MEMS devices. Under these constraints, the designed operation temperature and pressure of the micro hydrazine thruster were set to 900 K and 690 kPa (∼100 psi), respectively. Using one-dimensional ideal rocket theory [8], the corresponding propellant flow rate was calculated to be 0.48 mg/s. At a 1 mN thrust output, the thruster is expected to have an ideal specific impulse I_{sp} of 214.6 s.

For N_2H_4 dissociation, the reactions are considered to be N_2H_4 dissociating into NH_3 and N_2, followed by NH_3 dissociating into N_2 and H_2. Since NH_3 dissociation is endothermic, the overall heat release depends on the extent of ammonia dissociation (x). Although typical x values are controlled to be in the range 0.4–0.7 in conventional hydrazine thrusters [9], in order to reduce the chamber temperature, a higher x was preferable in the present research.

The designed MEMS-based microthruster weighs 0.18 g and has dimensions of $8.48 \times 4.0 \times 2.0$ mm. It consists of an insulator, a microreactor, and a micronozzle, as shown in Fig. 1. Since hydrazine is highly corrosive to silicon-based materials, a layer of titanium was

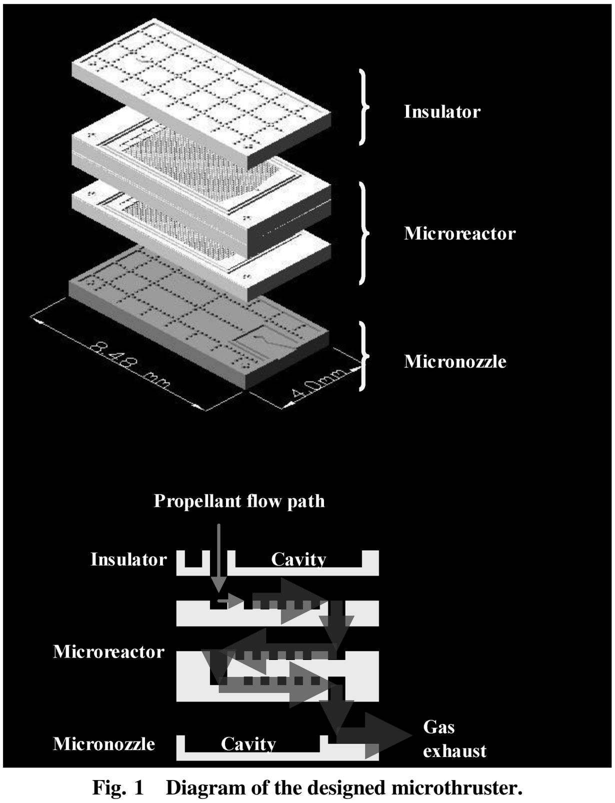


Fig. 1 Diagram of the designed microthruster.

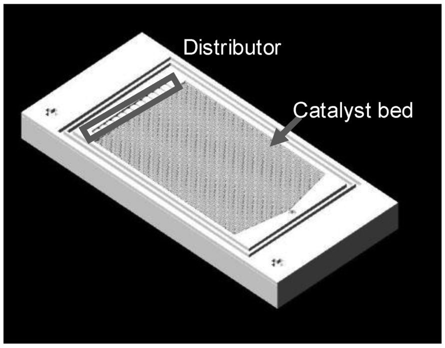
Presented as Paper 2009-5201 at the 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Denver, CO, 2–5 August 2009; received 25 March 2010; revision received 10 November 2010; accepted for publication 12 November 2010.

*Associate Professor, Department of Aeronautics and Astronautics, Institute of Aeronautics and Astronautics, No. 1 University Road; yahn@mail.ncku.edu.tw. Member AIAA.

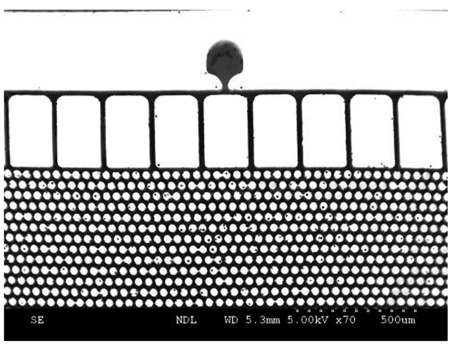
†Graduate Student, Department of Aeronautics and Astronautics, Institute of Aeronautics and Astronautics, No. 1 University Road; awankana@gmail.com. Member AIAA.

‡Graduate Student, Department of Aeronautics and Astronautics, Institute of Aeronautics and Astronautics, No. 1 University Road.

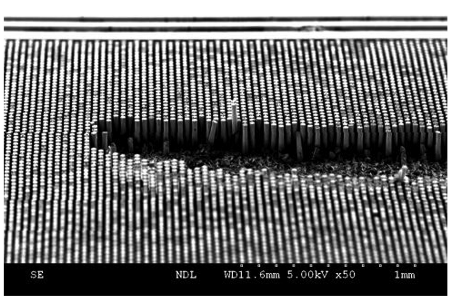
§Postdoctoral Researcher, Department of Aeronautics and Astronautics.



a)



b)



c)

Fig. 2 Views of the reactor unit: a) diagram of the unit, b) SEM image of the inlet and the distributor, and c) SEM image of the catalyst bed.

deposited on all surfaces of devices in contact with hydrazine to prevent corrosion [10].

The insulator was designed to reduce heat loss from the reactor. It was fabricated by using inductively coupled plasma etching. The insulator reduced the contact surface with the reactor by 72%. To control x, the microreactor was designed to comprise one or multiple reactor units (see Fig. 2a). In each reactor unit, the propellant enters the catalyst bed through a multichannel distributor (see Fig. 2b). The catalyst bed was shaped into closely packed circular pillars (14 μm) to maximize the reaction surface. The spacing between pillars was 15 μm, and the depth of the pillars was about 160 μm (see Fig. 2c), which provides a flow-channel depth-to-width ratio of over 10 to minimize the endwall boundary-layer effect [3]. The design provides a reactor surface-to-volume ratio of 84 mm^2/mm^3.

Before the deposition of iridium onto the bed surface, a layer of SiO_x was deposited onto the silicon substrate using plasma-enhanced chemical-vapor deposition, followed by the deposition of a titanium thin film as a supporting layer. The SiO_x was deposited to prevent silicidation between silicon and titanium. Iridium, with an extremely high melting point (~2466°C) and high activity with hydrazine [11], was then deposited on the titanium film using electron beam evaporation. Annealing processes were then conducted to increase the bonding strength between iridium and titanium.

Considering the momentum loss in the gas flow [12], the throat of the converging/diverging micronozzle was designed to be 60–77 μm, which is much larger than that (32 μm–77 μm) obtained from the ideal nozzle calculation. The diverging half-angle of the nozzle was 22.5 deg with an expansion ratio of 12; the converging area ratio was 3.3. Figure 3 shows a scanning electron micrograph (SEM) image of the designed micronozzle. To reduce heat loss, an 80–77 μm ditch envelops the nozzle; in addition, 74% of the contact surface of the nozzle with the reactor was etched away. Layers were bonded by TiSi solid-state amorphization [13] under a downforce of 19.6 N on the target chips. The bonding temperature was over 570 K and the bonding time was over 4 h.

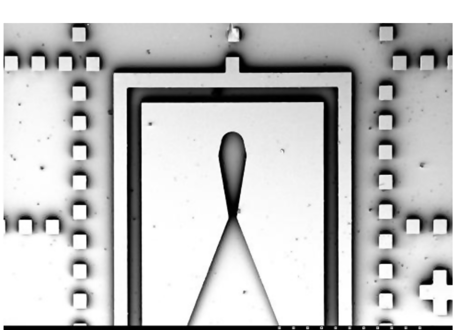


Fig. 3 SEM image of the fabricated micronozzle.

III. Experimental Setup

The performance of the designed microthruster assembly was tested in this study. The dissociations of hydrazine at various flow rates (0.34–0.91 mg/s) and various numbers of reactor units were determined before the thrust tests. The exhaust from the reactor was collected by a syringe and injected into a gas chromatograph to determine x values of the reactions.

A millinewton-level thrust stand was constructed as shown in Fig. 4. Four strain gauges were attached on both sides of a flexible steel plate with a bridge-type connection to compensate for the thermal effect on the test system. The microthruster was glued to the steel plate at a right angle and calibrated against weights equivalent to 0–2.06 mN. The linear calibration curve with a standard deviation of 0.18 mN is shown in Fig. 5. The calibration results show that although the thrust stand exhibited relatively low sensitivity and precision, it had a linear response to the thrust in the range of interest. The thrust measurements were performed in a vacuum chamber at 1.0 torr.

IV. Experimental Results and Discussion

For the hydrazine flow rates (0.43–1.20 mg/s) investigated, the ammonia dissociations of the reacted gases from the microreactors were in a small range of 92.3–94.6%, as shown in Fig. 6. The distribution of x indicates that a reactor with a single unit provides sufficient reaction surface area. Although not obvious, x decreased with increasing hydrazine flow rate. The fluctuation of the measured x was caused by the inevitable leakage of the surrounding air into the syringe while sampling.

The chamber pressure in the microreactor was not measured directly; instead, the pseudo chamber pressure, defined as the monitored feed-line pressure minus the estimated pressure drop between the feed-line pressure transducer location and the inlet of the catalyst bed, was used for analysis. The pressure drops at various experimental flow rates were estimated by flow simulation using the FLUENT software package. As shown in Fig. 7, since the pressure drops were relatively small, the pseudo chamber pressures are adequate substitutes for the chamber pressures for analysis. The typical onsets of pseudo chamber pressure and measured thrust are given in Fig. 8. The pressure trace indicates a relatively long startup delay (134 ms) of the microthruster, which is believed to be due to a

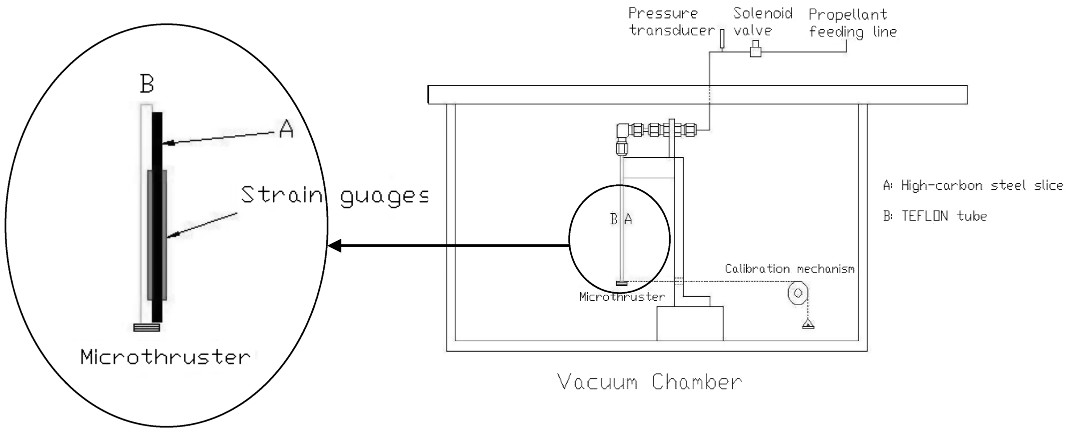


Fig. 4 Diagram of the microthrust stand. Four strain gauges and a Teflon tube were attached to the steel plate.

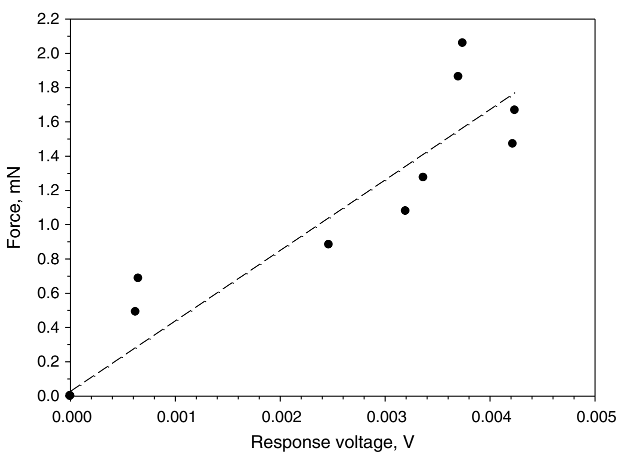


Fig. 5 Calibration of the microthrust stand.

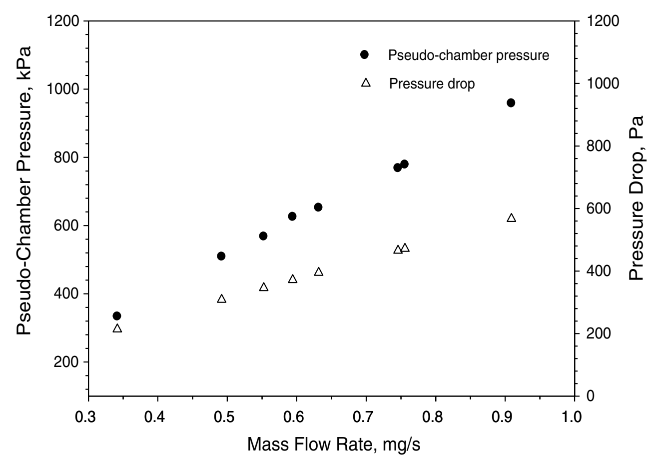


Fig. 7 Chamber pressure at various N_2H_4 flow rates.

long induction period for microchannel flow to fully develop. The lag between the thrust rise and the pressure rise is believed to be mainly caused by the creeping of the Teflon tube used for the hydrazine supply.

The measured thrusts show a nearly linear response to hydrazine flow rate, as shown in Fig. 9. The I_{sp} values obtained are much lower than that (~230 s) of conventional macroscale hydrazine thrusters. Since hydrazine overreacted under all test conditions, an increase in the hydrazine flow rate resulted in increased chamber temperature, leading to better thruster performance. However, a peak I_{sp} value was obtained at a hydrazine flow rate of 0.63 mg/s, where the pseudo chamber pressure was 652.3 kPa, the vacuum thrust was 1.01 mN, and the I_{sp} was calculated to be 162 s. At hydrazine flow rates higher than 0.63 mg/s, there was an obvious decrease in specific impulses.

For microdevices with high surface-to-volume ratios, frictional and heat losses are generally considerable. FLUENT was used to simulate the flow in the microreactor to estimate the frictional loss by simplifying the microreactor as 266–160 μm rectangular channels. At inlet conditions of 620 kPa and 800 K, the energy loss due to friction was estimated to be ~0.45% of the total heat release from dissociation reactions, which is considered insignificant. From the experimental values of I_{sp}, pseudo chamber pressure, and x, the

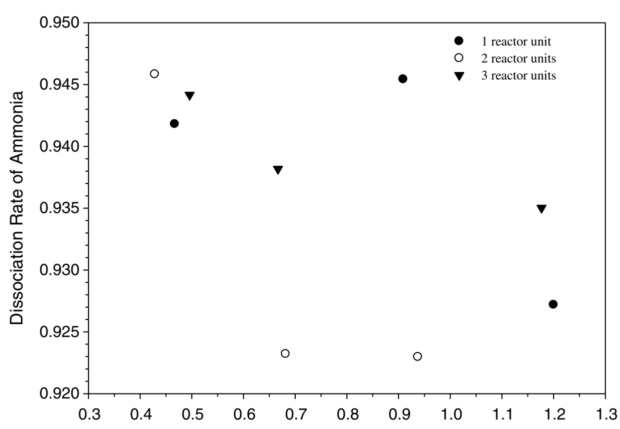


Fig. 6 Extent of ammonia dissociation for various numbers of reactor units at various N_2H_4 flow rates.

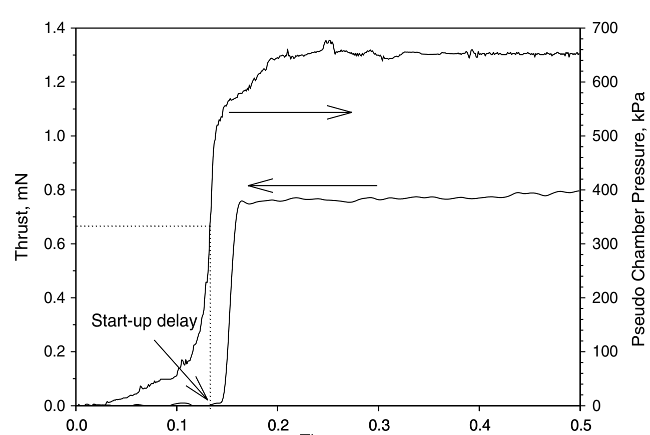


Fig. 8 Onset of thrust and chamber pressure at N_2H_4 flow rate of 0.63 mg/s.

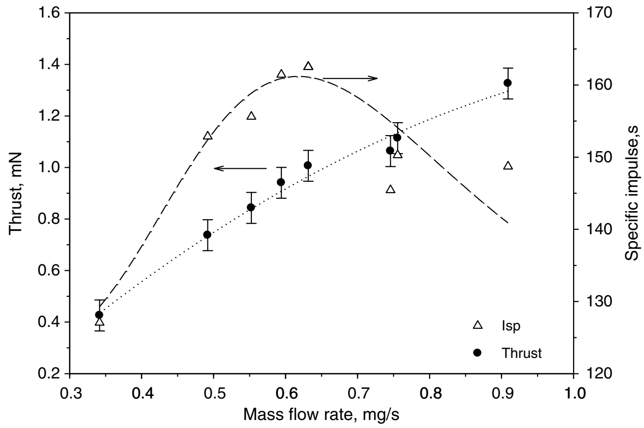


Fig. 9 Measured thrusts and specific impulses at various N_2H_4 flow rates.

chamber temperatures were estimated to be 400–500 K, which are much lower than macroscale reaction temperatures (greater than 1000 K). These analyses indicate that the lower I_{sp} of the microthruster was mainly due to stray heat loss and that the decrease of I_{sp} at higher propellant flow rates was caused by increasing heat loss at higher chamber temperatures.

V. Conclusions

The fabrication and performance of a $\sim$1 mN MEMS-based hydrazine thruster composed of a microreactor and a micronozzle were presented. The designed catalyst bed (iridium deposited on a $Ti/SiO_x/Si$ support) had a high surface-to-volume ratio of 84 mm^2/mm^3, yielding a high ammonia dissociation (92.3–94.6%) for the tested N_2H_4 flow rates (0.43–1.20 mg/s). The peak performance of the microthruster was obtained at a N_2H_4 flow rate of 0.631 mg/s, at which a vacuum thrust of 1.01 mN was produced with an I_{sp} close to 162 s, which was mainly due to heat loss. Although a better microthrust stand and more careful measurements are required to further characterize the designed thruster, the preliminary test results demonstrate the feasibility of using hydrazine in MEMS-based microthruster operation.

Acknowledgments

The authors would like to thank the National Science Council and the National Nano Device Laboratories of the Republic of China for funding and long-term support of the research.

References

[1] Mueller, J., "Thruster Options for Microspacecraft: A Review and Evaluation of State-of-the-Art and Emerging Technologies," *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by M. Micci, and A. Ketsdever, AIAA, Reston, VA, 2000, Chap. 3.

[2] Danzmann, K., and the LISA Study Team, "LISA-An ESA Cornerstone Mission for the Detection and Observation of Gravitational Waves," *Advances in Space Research*, Vol. 32, No. 7, 2003, pp. 1233–1242. doi:10.1016/S0273-1177(03)90323-1

[3] Bayt, R. L., "Analysis, Fabrication and Testing of A MEMS-Based Micropropulsion System," Ph.D. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, 1999.

[4] Usbeck, T., Wohlfart, J., and Schelkle, M., "A Flexible Cold Gas Propulsion System Concept for Different Space Applications," *Proceedings of 4th International Spacecraft Propulsion Conference*, Sardinia, Italy, June 2004.

[5] Khayms, V., and Sanchez, M. M., "Fifty Watt Hall Thruster for Microsatellites," *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by M. Micci, and A. Ketsdever, AIAA, Reston, VA, 2000, Chap. 9.

[6] Zhang, K. L., Chou, S. K., Ang, S. S., and Tang, X. S., "A MEMS-Based Solid Propellant Microthruster with Au/Ti Igniter," *Sensors and Actuators A (Physical)*, Vol. 122, 2005, pp. 113–123. doi:10.1016/j.sna.2005.04.021

[7] Hitt, D. L., Zakrzwski, C. M., and Thomas, M. A., "MEMS-Based Satellite Micropropulsion via Catalyzed Hydrogen Peroxide Decomposition," *Smart Materials and Structures*, Vol. 10, Nov. 2001, pp. 1163–1175. doi:10.1088/0964-1726/10/6/305

[8] Sutton, G. P., and Biblarz, O., *Rocket Propulsion Elements*, 7th ed., Wiley, New York, 2001, pp. 731–732.

[9] Shen, J.-S., "Experimental Analysis of Ammonia Dissociation of a Hydrazine Propulsion System," M.S. Thesis, Dept. of Aeronautics and Astronautics, National Cheng Kung Univ., Taiwan, ROC, 1995.

[10] Schmidt, E. W., *Hydrazine and Its Derivatives—Preparation, Properties, Applications*, 2nd ed., Wiley, New York, 2001, p. 692.

[11] Gaidei, T. P., and Tyuryaev, I. Y., "Hexachloroiridic Acid as a Component in Production of Aluminoiridium Catalyst," *Russian Journal of Applied Chemistry*, Vol. 71, No. 2, 1998, pp. 265–270 (English translation).

[12] Alexeenko, A. A., Gimelshein, S. F., Levin, D. A., and Collins, R. J., "Numerical Modeling of Axisymmetric and Three-Dimensional Flows in MEMS Nozzles," 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA Paper 2000-3668, Huntsville, AL, July 2000.

[13] Yu, J., Wang, Y., Lu, J. Q., and Gutmann, R. J., "Low-Temperature Silicon Wafer Bonding Based On Ti/Si Solid-State Amorphization," *Applied Physics Letters*, Vol. 89, 2006, Paper 092104. doi:10.1063/1.2338574

C. Segal
Associate Editor