Heat sealable, novel asymmetric aromatic polyimide having excellent space environmental stability and Application for solar sail, IKAROS membrane

R. YOKOTA(横田力男), M. Suzuki(鈴木妥基), A. Ando(安藤あゆみ), K. Kazama(風間健一), M. MIYAUCHI(宮内雅彦), Y. ISHIDA(石田雄一)[1)]

Institute of Space and Astronautical Science, JAXA, Yoshinodai, Chuo-ku, Sagamihara-shi, Kanagawa Japan 252-5210, Tel: +81-50-3362-5710, E-mail: yokota.rikio@jaxa.jp,

[1)] Institute of Aerospace Technology, Japan Aerospace Exploration Agency (JAXA), 6-13-1 Ohsawa, Mitaka-shi, Tokyo 181-0015

1, Introduction

Aromatic polyimides (PIs) such as PMDA/4, 4'-ODA and s-BPDA/4, 4'-ODA are well known as the outstanding thermal and environmental stabilities due to their planar structures in addition to their rigid wholly aromatic structures. However, these advantages cause some limitations in applications for molding or fabrication in heat sealing because of their insolubility and infusibility. Among many methods for improving the processability of aromatic polyimides, we have reported that the PI derived from an asymmetric aromatic tetra carboxylic acid dianhydride, i.e., 2,3,3',4'-BPDA:(a-BPDA) led to higher Tg's than the corresponding PIs from a symmetric one(s-BPDA) with the same diamines. In addition, the asymmetric PIs indicate high thermo-plasticity than the corresponding symmetric PIs on the basis of their non-planar biphenyl-imide structures inhibiting intermolecular interaction (no ordered structure formation). Thus, the sterically bent/distorted but rotation-restricted structural unit induced by asymmetric aromatic monomers was greatly expected for developing new high performance polyimides[1)]. We have successfully invented that asymmetric aromatic addition-type imide oligomers (TriA-PI:a-BPDA/4.4'-ODA/PEPA) having high Tg and good processability. Based on this asymmetric structure chemistry, we have being started the development of heat sealable polyimide with having high space environmental stability in application for solar sail membrane in Aug. 2007. This paper presents the development of novel heat sealable asymmetric polyimide thin film and application for solar sail IKAROS membrane[2,3)].

2, Development of novel asymmetric aromatic polyimide; a-ODPA/4,4'-ODA

As shown in Figure 1, asymmetric a- or i-ODPAs(supplied by Manac co.) are a moderate stereo irregular and more or less flexible in comparison to isomeric BPDA . Figure 2 shows synthetic root of thermo-plastic and heat sealable a-ODPA/4,4'-ODA : ISAS-TPI. ISAS-TPI has been obtained by common two step method with rapid thermal imidization. Figure 3 shows dynamic tensile properties of s- and a-ODPA/4,4'-ODA polyimides, and PMDA/4,4'-ODA polyimide. Tg of a-ODPA/4, 4'-ODA is higher than that of symmetric s-ODPA/4, 4'-ODA and shows a large drop of storage modulus, E' without rubbery plateau above Tg as isomeric BPDAs. It means that this asymmetric polyimide can be used for heat sealable film due to very high drop of modulus E' above Tg. Mechanical properties of ISAS-TPI thin film prepared is excellent such as modulus E=2.8GPa and elongation at break ε_b=92%. Compared with symmetric s-ODPA/4,4'-ODA film, 7.5μm thin film of a-ODPA/4,4'-ODA prepared from 14% polyimide solution in DMAc is easily sealed at 350℃, 20 seconds, 0.1Mpa without any problems. Proton and electron irradiation have been done by JAERI and UV radiation had been done by JAXA Tukuba. Physical and mechanical properties of those films were measured in our laboratory. Figure 4 shows space environmental stability as an elongation at break of ISAS-TPI and some aromatic polymers by electron beam. Figure 5 showed color changes of ISAS-TPI and PEI and APICAL-AH thin films by UV irradiation (50 ESD). Table 1 summarized the physical properties and space environmental stabilities for commercial PMDA/4, 4'-ODA film; Apical-AH (KANEKA) and ISAS-TPI prepared by Fujimori co.ltd. Table 2 summarized the physical and mechanical properties of this polyimide films. Novel asymmetric aromatic polyimide: a-ODPA/4,4'-ODA indicates high solubility for NMP and DMAc and excellent heat sealing properties with having high space environmental stability as like APICAL AH polyimide film.

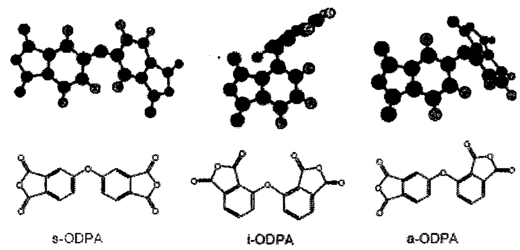


Figure 1, Isomeric s-,a-,i- ODPA structures

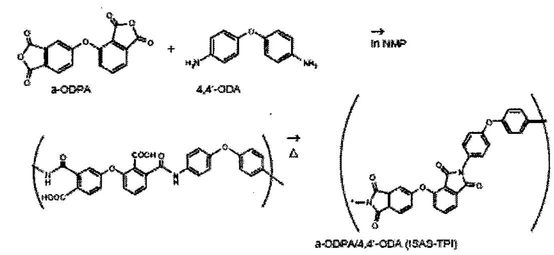


Figure 2 shows a reaction scheme of thermo-plastic and heat sealable a-ODPA/4,4'-ODA : ISAS-TPI

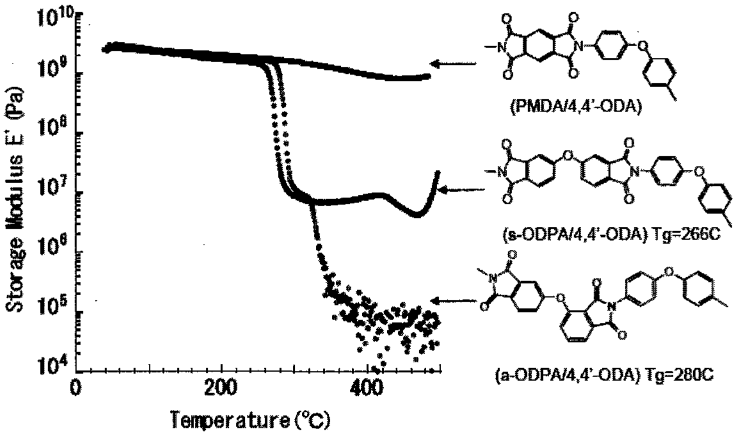


Figure 3, Dynamic tensile properties of symmetric PMDA/4, 4'-ODA, s-ODPA/4,4'-ODA, and a-ODPA/4, 4'-ODA polyimide films.

Table 1, Summary of physical properties and space environmental stability for commercial PMDA/4,4'-ODA film; Apical-AH(KANEKA) and a-ODPA/4,4'-ODA film; ISAS-TPI.

Polyimide	Tg (DMA)	Solubility. (NMP)	Heat sealing	Space environmental stability elongation at break,%							
	(℃)	(%)	(375℃-20sec)	proton (MGy) 0	45	100	electron (MGy) 0	1	20	U.V (ESD) 0	150
Apical AH (KANEKA) PMDA/4,4'-ODA	>360	no	no	61%		22%	62%	58%	54%	62%	62%
ISAS-TPI a-ODPA/4,4'-ODA	265 (250℃ cured)	>20	good	95%	73%	39%	81%	63%	76%	81%	71%

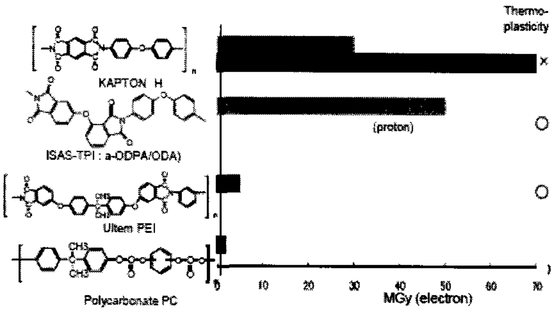


Figure 4, Space environmental stability of ISAS-TPI and aromatic polymers by electron beam: elongation at break 80% ■ 20% ■(JAERI)

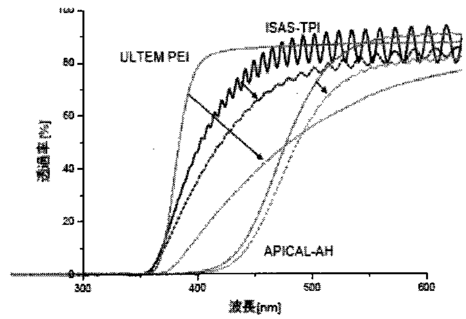


Figure 5, Color changes of ISAS-TPI and aromatic polyimides by U.V radiation (50ESD)

Table 2,

Goal

1. Heat sealing: 320 - 350 ℃, <1min → 340C, 20 sec
2. Solubility in DMAc or NMP 30 % < → 20% <
3. Space environment; proton 10kGy → 20MGy <
   radiation:10~20MGy → 20MGy <
   U.V(150ESD) → OK (mechanical)
   Δ (optical)
4. Thermal stability: Tg = 280 ℃ → Tg = 265-280℃
5. Film (t) 5~7 μm, (w) 100cm width →OK
6. Mechanical properties; σb 100~200MPa → 110MPa
   modulus(E) 1~3GPa → 2,8 – 3.4G
   elongation at break, 50-80% → 80 %<
7. Cost; very expensive so far

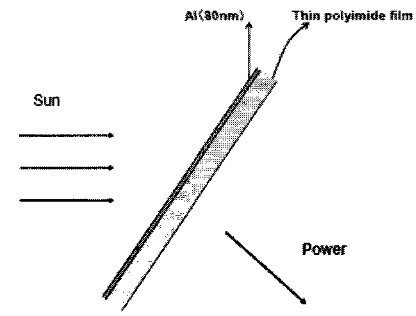


Figure 6, Schematic representation of photon propulsion by Sun

3, Development of solar sail IKAROS membrane

What is a solar sail spacecraft? Fridrikh Tsander proposed the concept of solar sail spacecraft with the solar-photon propulsion obtained by reflecting sunlight of a large, very thin, metalized polymer film for long time ago. However, nobody was success and substantiated the theory in space because there are so many challenges in technologies such as structure, stowage and deployment, system analysis, materials, and so on.

Development of thermal and space environmentally stable polymer film is one of key requirement in addition to the sealing, fabricating, packaging, and deployment ; 1) A very thin(5-7 μ m) high performance films has to be manufactured. 2) Heat sealable, thermo-plastic thin films with a high Tg and high reliability is also a key requirement.

As mentioned already, newly developed ISAS-TPI polyimide is a very promising material if we can make wide, thin film. On the other hands, fortunately, there is a commercially available PMDA/4,4'-ODA polyimide thin film; Apical AH(KANEKA). Therefore both films were nominated for this IKAROS membrane.

The solar sail IKAROS named by **I**nterplanetary **K**ite-craft **A**ccelerated by **R**adiation **O**f the **S**un is the world's first solar powered sail craft employing photon propulsion and experimentally testing the generating solar power by thin film solar cell on the sail surface. Figure 6 showed schematic representation of photon propulsion by Sun. IKAROS was launched from Tanegashima Space Center using the H-IIA on June 21, 2010. Figure 7 illustrates mission sequence of IKAROS. After separation from H-IIA, it was spun up at up to 25 rpm deploying the membrane. Figure 8 showed IKAROS membrane. The membrane was made of 2 different polyimide thin films which are 80nm aluminized APICAL AH/Al for outer area and is 80nm aluminized ISAS-TPI/Al for near the spacecraft, respectively.

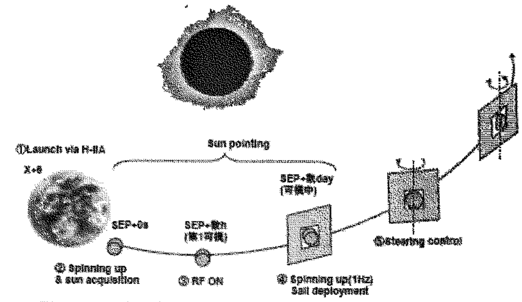


Figure 7, Nominal mission sequence of IKAROS

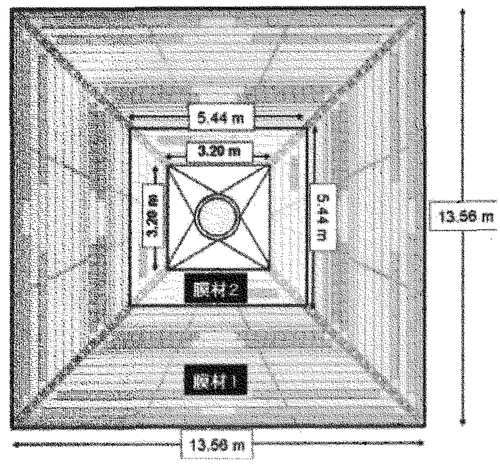


Figure 8, IKAROS membrane1 : APICAL AH, 2 : ISAS-T

Table 3, Nominated 'Ikaros' sail membrane

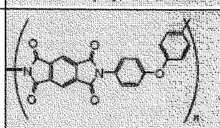
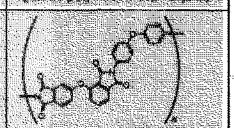
	Membrane1 PMDA/4,4'-ODA	Membrane2 a-ODPA/4,4'-ODA
material	Kaneka APICAL-AH (7.5 μm) comercial polyimide film/Al	Newly developed ISAS-TPI thermo-plastic polyimide film(7~8 μm)
Chemical structure		
properties	modulus: 3.0GPa, elong.n. 80% Tg: 420℃, heat sealing: ×	modulus: 2.8GPa, elongn.: 92% Tg: 280℃, heat sealing: ○
Area (173.63 m²)	154.28 (88.9%)	19.35 (11.1%)
thicness(μm)	7.5	7.5~8.0
Sail wt. (1.849 kg)	1.643	0.206
metal	aluminum	aluminum
thickness(nm)	80	80

Figure 9, Configuration of ¼ IKAROS Sail

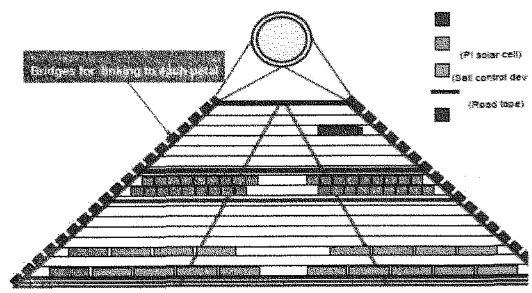


Table 3 summarized the chemical structures and physical properties of polyimide films APICAL AH and ISAS-TPI for sail membranes. Figure 9 was illustrated configuration of 1/4 of IKAROS(one pedal). As you see in Figure 8, Ikaros sail was composed of 4 pedals. The steering devices were applied by film type liquid crystals and dust counter sensors o PVDF films in addition to film type polyimide solar cells are stuck on the membrane. Figure 10 showed sail design and training of stowing. Figure 11 illustrated stowing 4 petals tc IKAROS spacecraft. The stowed IKAROS membrane with a diagonal of 20m will be deployed by its spinning motion. Four masses are attached to the four tips of membrane ir order to facilitate deployment. Deployment is in two stages shown in Figure 12. During firs stage, the membrane is statically, and during the second stage, is dynamically. This method can be realized with simpler and lighter mechanisms than conventional mast o boom type.

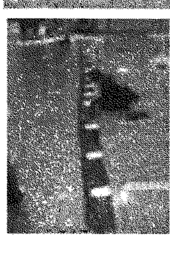


Figure 10, Sail design and training stowing

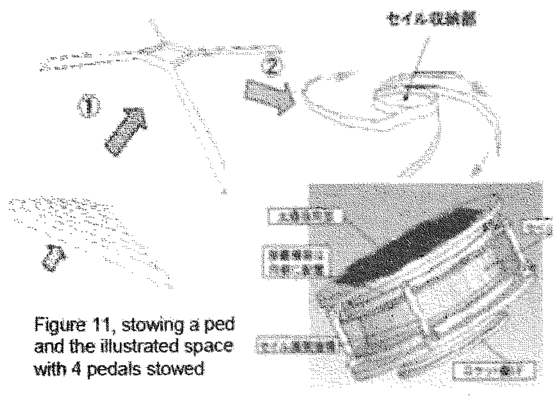


Figure 11, stowing a ped and the illustrated space with 4 pedals stowed

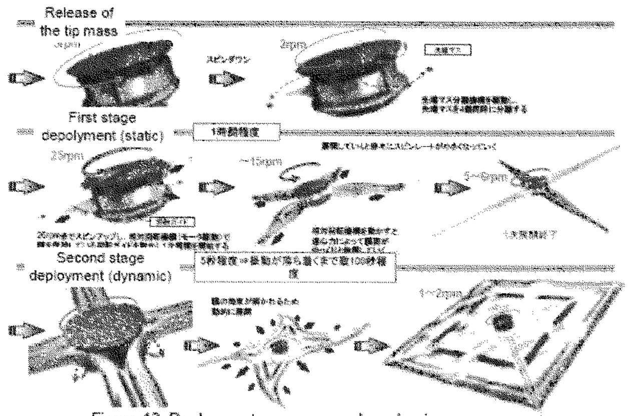


Figure 12, Deployment sequence and mechanism

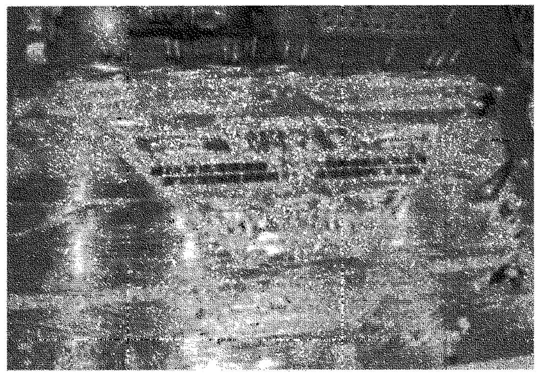


Figure 13, Fulll deployed FM membrane of ¼ IKAROS sail

Figure 14, IKAROS FM spacecraft in clean room

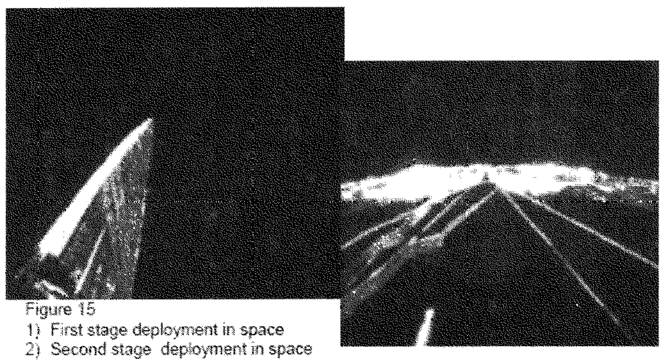


Figure 15
1) First stage deployment in space
2) Second stage deployment in space

Figure 13 showed a 7.5um thin polyimide 1/4 IKAROS flight model membrane deployed in clean room. Figure 14 is a picture of IKAROS spacecraft with 4 membranes stowed around the drum of it. The world's first solar sail having 7.5um thin polyimide APICAL AH and novel thermoplastic asymmetric polyimide ISAS-TPI film aluminized has been launched at Tanegashima space center in Japan on June 21 in 2010. Figure 15 showed a picture of a released tip of mass with a piece of folded membrane (1), and a snap of second stage deployment. Both pictures were taken by a camera in spacecraft. On June 9, 2010, the fully deployed IKAROS is now snapped by an own jumping camera fasten on upper deck as shown in next page.

4, Future plan

Fortunately, we were completely success the world's first solar sail mission: IKAROS. The second mission will take place in the late 2010s. It will provide a medium size solar power sail with a diameter of 50m, and will have integrated ion-propulsion engines. The destinations of the spacecraft will be Jupiter and the Trojan asteroids. However, we have to overcome the many technological challenges such as development of high efficiency solar cell and control devices with high space environmental stabilities in addition to the very light, more reliable polyimide membranes. The development of high performance polyimides is one of key factors for new space technology.

Reference

1, R. Yokota, Kobunnshi, 57 , No.9, p58 (2008).
2, R. Yokota, Proceedings of EP2009, in Dalian, China,

3, Materials and adhesives; IKAROS experimental plan in ISAS/JAXA, 2010, JAXA

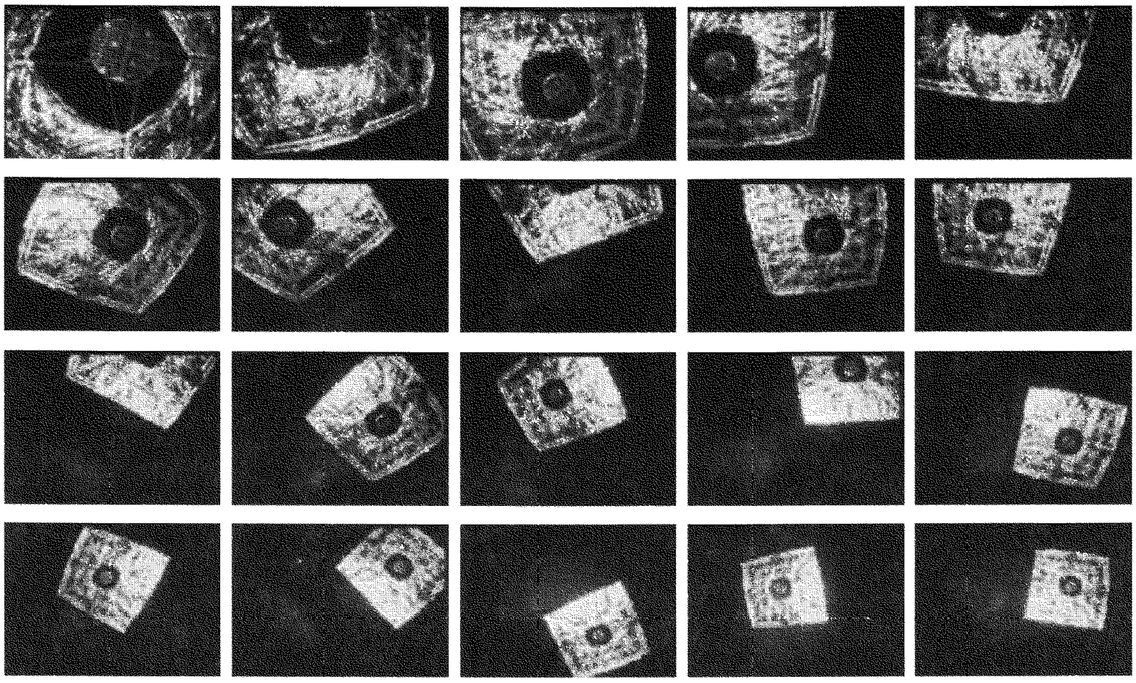


Figure 16, The consecutive pictures of IKAROS sail by own camera

(continuing fromp37)

(8) Hu, X. D.; Jenkins, S. E.; Min, B. G.; Polk, M. B.; Kumar, S. *Macromol. Mater. Eng.* **2003,** 288, (11), 823-843.

(9) Wolfe, J. F.; Arnold, F. E. *Macromolecules* **1981,** 14, (4), 909-915.

(10) Garcia, J. M.; Garcia, F. C.; Serna, F.; de la Pena, J. L. *Prog. Polym. Sci.* **2010,** 35, (5), 623-686.

(11) Vanhaecht, B.; Willem, R.; Biesemans, M.; Goderis, B.; Basiura, M.; Magusin, P. C. M. M.; Dolbnya, I.; Koning, C. E. *Macromolecules* **2003,** 37, (2), 421-428.

(12) Vora, R. H. *Mater. Sci. Eng., B* **2010,** 168, (1-3), 71-84.

(13) Liou, G. S. *Macromol. Chem. Phys.* **2000,** 201, (11), 1141-1147.

(14) Zhou, C. J.; Wang, S. F.; Zhuang, Q. X.; Han, Z. W. *Carbon* **2008,** 46, (9), 1232-1240.

(15) Jung, C. H.; Lee, J. E.; Han, S. H.; Park, H. B.; Lee, Y. M. *J. Membr. Sci.* **2010,** 350, (1-2), 301-309.

(16) Li, J.; Yu, H. *J. Polym. Sci., Part A: Polym. Chem.* **2007,** 45, (11), 2273-2286.

(17) Wang, S.; Wu, P.; Han, Z. *Polymer* **2001,** 42, (1), 217-226.

(18) Farmer, B. L.; Dudis, D. S.; Adams, W. W. *Polymer* **1994,** 35, (17), 3745-3751.

(19) Ree, M.; Kim, K.; Woo, S. H.; Chang, H. *J. Appl. Phys.* **1997,** 81, (2), 698-708.

(20) Yang, C. P.; Hsiao, S. H.; Yang, C. C. *J. Polym. Res.* **2004,** 11, (1), 23-29.

(21) O'Mahoney, C. A.; Williams, D. J.; Colquhoun, H. M.; Mayo, R.; Young, S. M.; Askari, A.; Kendrick, J.; Robson, E. *Macromolecules* **1991,** 24, (24), 6527-6530.