Quinones of Azulene. 4. Synthesis and Characterization of the Parent 1,5- and 1,7-Quinones[1]

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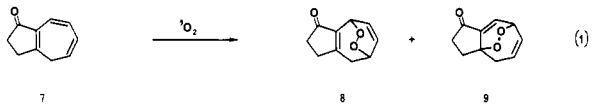
Abstract: The 1,5-quinone of azulene (**4**) and the 1,7-quinone of azulene (**6**) have been synthesized for the first time, nearly 50 years after the first synthesis of azulene (**1**). Both quinones can be isolated as stable, yellow, crystalline solids. Preparation of the new azulene diacetates **12** and **13** in just two steps from the readily available bicyclic trienone **7** provided the key to these syntheses. So far, no discrepancies have been found between the observed properties of these unusual nonbenzenoid quinones and those predicted in 1980 on the basis of theoretical calculations (e.g., isolability, dienophilicity, reduction potential, color).

From before the days of Kekulé and the modern structural theory of chemistry, quinones have been intimately associated with the chemistry of aromatic compounds.[2] Their importance in the dye industry, in medicinal chemistry, in biological electron transport processes, and in numerous other fields has been documented repeatedly over the years.[2] Then in 1935 the first synthesis of azulene (**1**), by Plattner and Pfau,[3] gave birth to a new family of aromatic compounds which have become known as nonbenzenoid aromatic hydrocarbons. The intervening years have seen this family grow to enormous proportions;[4-6] however, surprisingly little is known today about the quinones of such molecules.

In 1980 we published the results of extensive theoretical calculations on the quinones of azulene and made predictions about many of their properties.[7] In that same year, Morita et al. reported a synthesis of the first unsubstituted azuloquinone (**2**).[8] Since that time, we have succeeded in synthesizing four additional azuloquinones (Figure 1). The preceding paper[9] describes our routes to the 1,4- and 1,6-quinones of azulene (**3** and **5**), and herein we detail our syntheses of the 1,5- and 1,7-isomers (**4** and **6**). These four compounds differ simply by the position of the carbonyl group in the seven-membered ring yet exhibit dramatic differences in reactivity, as predicted[7] by theory. Quinones **4** and **6** can be isolated as stable, yellow, crystalline solids whereas quinones **3** and **5** have been trapped only as reactive transient species. Substituted derivatives of **4** and **6** have recently been reported by Morita et al.[10]

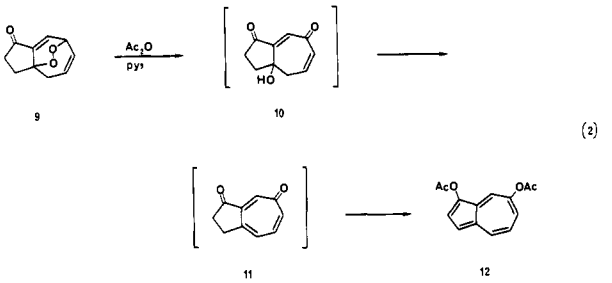
Syntheses

As our starting point we chose the bicyclic trienone **7**, a highly functionalized, readily available compound prepared from the diazo ketone of hydrocinnamic acid via an intramolecular carbene addition.[11] Conversion of **7** to 1,5-azuloquinone (**4**) requires the introduction of an oxygen atom at position 5 (azulene numbering; see **1**), whereas conversion to 1,7-azuloquinone (**6**) requires the introduction of an oxygen atom at position 7. Photooxygenation of **7** accomplishes both of these tasks simultaneously (eq 1). The



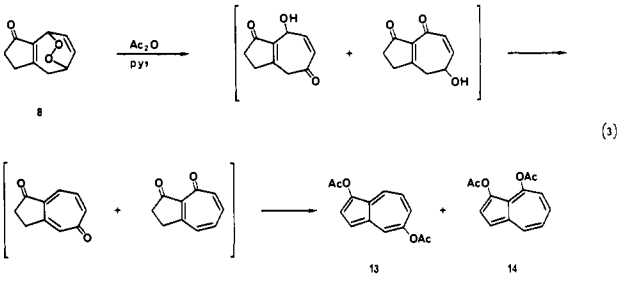
two endoperoxides **8** and **9** are formed in high overall yield, with the former predominating, and can be isolated as stable crystalline substances (mp 121–122 and 86.5 °C, respectively). The elemental composition (C, H analysis) and spectroscopic properties (^{1}H NMR, ^{13}C NMR, IR, UV) of **8** and **9** permit unambiguous assignment of the molecular structures shown.

Having thus introduced oxygen at the desired positions, we were confronted next with the problem of transforming these synthetic intermediates into molecules bearing functionality more nearly resembling that in the azuloquinones. Toward this end it was found that treatment of peroxide **9** with pyridine and acetic anhydride triggers a marvelous cascade of events which continues all the way to the new azulene diacetate **12**, presumably via the pathway depicted in eq 2. The base-catalyzed isomerization of



such singlet oxygen adducts to γ-hydroxy enones has ample precedent,[12] and the final conversion of intermediate **11** to **12** parallels our synthesis of other diacetoxyazulenes from dihydroazulenediones.[9]

In like fashion, endoperoxide **8** gives rise to two additional diacetates (eq 3). Deprotonation of **8** at position 5 (azulene



(1) Preliminary accounts of this work have been presented at the International Symposium on Theoretical Organic Chemistry, Dubrovnik, Yugoslavia, Aug 30–Sept 3, 1982, and at the 185th National Meeting of the American Chemical Society, Seattle, Wash., March 21–25, 1983. For preceding papers in this series on "The Quinones of Azulene", see: Scott, L. T. *Pure Appl. Chem.* **1983**, *55*, 363–368, ref 7, and ref 9.

(2) Patai, S., Ed. "The Chemistry of Quinonoid Compounds"; Wiley-Interscience: New York, 1974; Vol. 1 and 2. Thomson, R. H. "Naturally Occurring Quinones"; Academic Press: New York, 1971.

(3) Plattner, P. A.; Pfau, A. S. *Helv. Chim. Acta* **1937**, *20*, 224–232.

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(8) Morita, T.; Karasawa, M.; Takase, K. *Chem. Lett.* **1980**, 197–200.

(9) Scott, L. T.; Grütter, P.; Chamberlain, R. E., III *J. Am. Chem. Soc.*, preceding paper in this issue.

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(11) Scott, L. T.; Minton, M. A.; Kirms, M. A. *J. Am. Chem. Soc.* **1980**, *102*, 6311–6314.

(12) Balchi, M. *Chem. Rev.* **1981**, *81*, 91–108.

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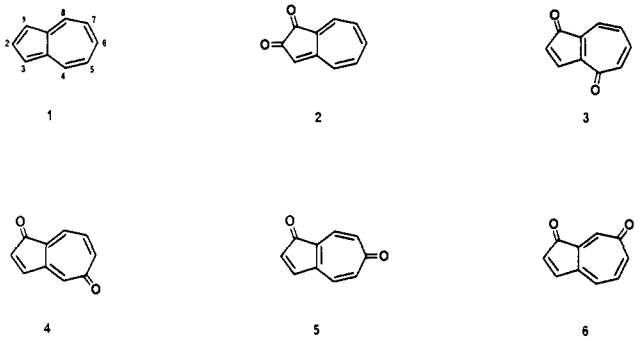
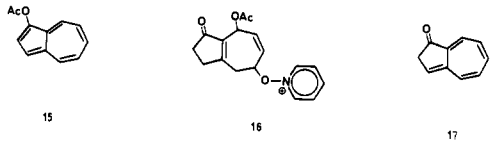


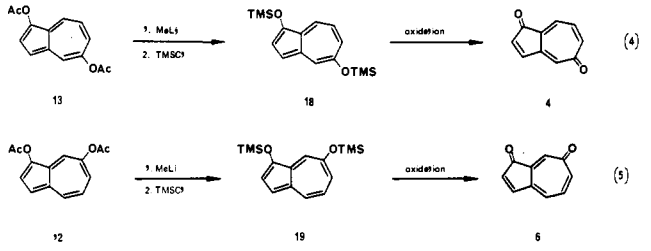
Figure 1. Azulene (**1**) and the five azuloquinones which are now known.

numbering) initiates the reaction sequence leading to **13**, the major isomer formed, whereas deprotonation at position 8 leads to **14**. These two diacetates can be readily separated by chromatography on silica gel. A small amount of 1-acetoxyazulene (**15**) was also obtained and became the major azulenic product when ethyl acetate was used as the solvent for this reaction, but it is easily removed in the chromatography. Formation of **15** obviously entails a reduction at some point and may arise via intermediates such **17**.[13]



The ease with which the new diacetoxyazulenes **12**, **13**, and **14** can be prepared, each in just two steps from a common precursor (**7**), represents a particularly attractive feature of this route to azuloquinones. It is, in fact, quite fortunate that the sequence of reactions depicted in eq 2 and 3 can be carried out in a single operation, for all attempts to effect the simple base-catalyzed isomerization of endoperoxides **8** and **9** to the corresponding γ-hydroxyenones under normal conditions[12] (e.g., Et_3N, $CHCl_3$) invariably led to intractable tars.

The syntheses of quinones **4** and **6** were completed as outlined in eq 4 and 5. Pyridinium chlorochromate (PCC),[14] 2,3-di-



chloro-5,6-dicyano-*p*-benzoquinone (DDQ), and tetrachloro-*p*-benzoquinone (*p*-chloranil) all proved effective for the final oxidation; however, PCC gave the fewest organic by-products and is therefore preferred in our laboratory. Both azuloquinones **4** and **6** can be isolated as stable, yellow, crystalline compounds, similar in appearance to *p*-benzoquinone.

One serious shortcoming of these syntheses, as described above, is the significant loss of material incurred during chromatographic separation of peroxides **8** and **9**. To circumvent this problem, therefore, we normally treat the crude product of photooxygenation directly with acetic anhydride/pyridine and generate all three diacetoxyazulenes **12**, **13**, and **14** at once. Chromatography at this stage removes the 1,8 isomer (**14**), but the 1,5- and 1,7-diacetoxyazulenes travel together. These intermediates are therefore carried on in tandem through the methyllithium–chlorotrimethylsilane-oxidation sequence to give a mixture of azuloquinones

	1,5-AZULOQUINONE	1,7-AZULOQUINONE
Calcd:	371 nm	394 nm
	347	349
	311	314
Found:	389(sh)	425(sh)
	373	401
	350	384
	338	345(sh)
	324	333(sh)
	307(sh)	319

Figure 2. Calculated electronic transitions[7] and observed spectral maxima for 1,5- and 1,7-azuloquinone.

4 and **6** which, fortunately, can be separated on silica gel. The ratio of 1,5- to 1,7-azuloquinone (**4**:**6**) obtained by this method is very nearly 1:1.

Spectroscopic Properties

A complete tabulation of the ^1H NMR, ^{13}C NMR, IR, UV–vis, and mass spectral data for both new quinones can be found in the Experimental Section; however, certain features of these spectra deserve special comment. Inspection of the structural formulas for azuloquinones **4** and **6** reveals the presence of a tropone (cycloheptatrienone) ring in each, and many of the spectral properties which these compounds exhibit resemble those of tropone.[15] Prominent peaks in the 70-eV mass spectra of **4** and **6**, for example, can be seen at M − 28 (loss of CO), which most likely corresponds to indenone. Tropone itself fragments almost exclusively to CO and benzene in the mass spectrometer.[16] These quinones also lose the second carbonyl group to give base peaks at M − 56 (benzocyclobutadiene).

The IR spectrum of tropone has strong bands at 1643 and 1594 cm^{-1} intermingled with several weaker bands of similar frequency.[17] Assignment of the 1594-cm^{-1} band to the C=O stretching mode has been confirmed by an elegant ^{18}O-labeling study.[17] In the IR spectrum of 1,5-azuloquinone (**4**), two strong bands appear at 1650 and 1590 cm^{-1}, adorned with several weak shoulders; 1,7-azuloquinone (**6**) absorbs at 1649 and 1586 cm^{-1}. Such similarities in the characteristic vibrational frequencies of these molecules indicate that the geometries and bond orders in the seven-membered rings of **4** and **6** must differ very little from those in tropone. The five-membered ring C=O stretching band is seen at 1706 cm^{-1} for **4** and at 1709 cm^{-1} for **6**.

The most conspicuous features in the ^1H NMR spectrum of 1,5-azuloquinone (**4**) are the two doublets (J = 5.9 Hz) at δ 6.56 and 7.78 which correspond to the α and β hydrogens, respectively, on the five-membered ring enone. All the peaks for the seven-membered ring hydrogens are clustered between these signals in the region δ 6.8–7.4. A very similar spectrum is observed for 1,7-azuloquinone (**6**), although the doublets at the extrema lie slightly further apart. By comparison, the hydrogens of tropone give rise to a lone broad singlet centered at δ 6.8.

On the basis of PPP π-electron calculations,[7] both the 1,5- and 1,7-quinones of azulene were predicted to appear yellow in color, and indeed they do as a consequence of absorption maxima near the edge of the visible spectrum. Figure 2 shows a comparison between the calculated electronic transitions and the observed spectral maxima for these two azuloquinones. As predicted, the 1,7-isomer absorbs at slightly longer wavelength than the 1,5-isomer (Figure 2). Considering the difficulties associated with calculations of electronic transitions, especially in nonalternant systems, this agreement between theory and experiment must be

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(14) Willis, J. P.; Gogins, K. A. Z.; Miller, L. L. *J. Org. Chem.* **1981**, *46*, 3215–3218.
(15) For a review on the properties of tropones, see: Pietra, F. *Chem. Rev.* **1973**, *73*, 293.
(16) McCollum, J. D.; Meyerson, S. *J. Am. Chem. Soc.* **1963**, *85*, 1739. Wilson, J. M.; Ohashi, M.; Budzikiewicz, H.; Djerassi, C.; Ito, S.; Nozoe, T. *Tetrahedron* **1963**, *19*, 2247.
(17) Krebs, A.; Schrader, B. *Justus Liebigs Ann. Chem.* **1967**, *709*, 46. Junge, H. *Spectrochim. Acta, Part A* **1968**, *24*, 1951.

regarded as quite good. A more detailed analysis of these and other spectra is underway.

Chemical Properties

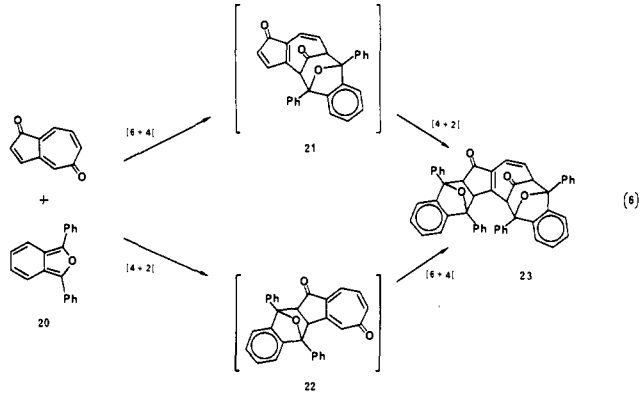
As predicted,[7] the 1,5- and 1,7-quinones of azulene (**4** and **6**) exhibit high "chemical stability". Both can be sublimed at 90 °C under vacuum, and neither shows any tendency to dimerize or polymerize when protected from prolonged exposure to heat and light. We have kept samples of each in a freezer (−20 °C, dark), both in solution and in crystalline form, for many months with no noticeable decomposition. This behavior contrasts sharply with that observed for the 1,4- and 1,6-quinones of azulene (**3** and **5**) which have, so far, proven too short-lived for direct spectroscopic detection, even in dilute solution.[9]

One qualitative explanation for the high reactivity of azuloquinones **3** and **5** relative to that of **4** and **6** can be formulated from simple structural considerations. All four compounds contain a tropone ring, but only **3** and **5** contain a cyclopentadienone ring as well. Since cyclopentadienones generally cannot be isolated under ordinary laboratory conditions,[18] the "chemical instability" of **3** and **5** comes as no surprise. In **4** and **6**, on the other hand, the five-membered ring does not comprise a closed conjugated circuit;[19] consequently, no special instability should be expected.

A more quantitative explanation for the relative reactivities of azuloquinones **3**–**6** can be extracted from the theoretical calculations. The carbonyl groups of all quinones drain electron density from the remaining segments of the π system and thereby render the molecule susceptible to reduction by electron donors and to attack by nucleophilic atoms of other molecules. In molecular orbital terms, such reactions put electrons into the lowest unoccupied molecular orbital (LUMO) of the quinone, and the lower in energy the LUMO lies, the more reactive the compound should be.[20] Our calculations[7] indicate that the LUMOs for **3** and **5** lie at substantially lower enegy than those for **4** and **6**.

Reactivity toward cyclopentadiene in a Diels–Alder reaction likewise correlates with LUMO energies,[20] and the high dienophilicity of quinones **3** and **5** has already been noted.[9] By contrast, quinones **4** and **6** can be recovered unchanged after mixing with cyclopentadiene. These preliminary experiments stand in accord with the prediction that **4** and **6** should be less potent dienophiles even than *p*-benzoquinone. The calculated LUMO energy of *p*-benzoquinone lies below those of **4** and **6** but not as low as those of **3** and **5**.[7]

With diphenylisobenzofuran (DPIBF, **20**), a more reactive diene, 1,5-azuloquinone combines to give a 2:1 adduct (eq 6).

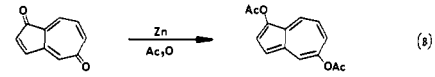


(6)

Whether the [6 + 4] cycloaddition precedes or follows the [4 + 2] addition has not been established, since the 1:1 adduct (either **21** or **22**) reacts more rapidly with DPIBF than does the original quinone. An equimolar mixture of the two cycloaddends gives only the 2:1 adduct **23** and recovered quinone. The 1,7-quinone reacts similarly (eq 7).

(7)

Finally, it should be noted that the reduction potential for azuloquinones **4** and **6** cannot exceed that of *p*-chloranil (E = +0.01 V)[2] since the latter can be used as the oxidizing agent to prepare these compounds from their hydroquinone derivatives. These results also agree with the calculations.[21] A thorough study of the electrochemistry, together with ESR spectra of the semiquinones, will be reported for **4** and **6** in due course. Chemical reduction of the 1,5- and 1,7-azuloquinones with zinc in acetic anhydride gives back the diacetoxyazulenes **13** and **12**, respectively (eq 8 and 9). We are currently exploring the chemistry of these unusual new quinones in much greater detail.



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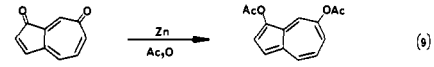

(9)

Experimental Section

General. Tetrahydrofuran (THF) was dried by distillation under nitrogen from the sodium ketyl of benzophenone immediately prior to use. Baker silica gel 60–200 was used for all column chromatography, and Woelm silica gel F was used for preparative layer chromatography. All ^{13}C NMR spectra were recorded at 25 MHz on a JEOL FX100 instrument; ^{1}H NMR spectra were recorded on the same instrument (100 MHz) or on an Hitachi Perkin-Elmer R24B spectrometer (60 MHz); 360-MHz ^{1}H NMR spectra were recorded at the University of California, Davis, NMR Facility (NSF Grant CHE 79-04832); chemical shifts are reported in ppm downfield from tetramethylsilane. Combustion analyses were performed by Spang, Eagle Harbor, MI, and high resolution mass spectra were recorded at the Midwest Center for Mass Spectrometry, Lincoln, NE (NSF Regional Facility). Melting points are uncorrected.

Cyclic Peroxides 8 and 9.[22] A solution of 10.0 g (68.5 mmol) of trienone **7** and 50 mg of tetraphenylporphyrin (TPP) in 500 mL of carbon tetrachloride was purged with dry oxygen and kept under a slight positive pressure of oxygen by means of a balloon. The solution was stirred vigorously and irradiated with a 150-W high-pressure sodium lamp for 12 h. At the end of the reaction, a small amount of insoluble material was removed by filtration and the filtrate was concentrated to one-third of its original volume. The long colorless needles which separated from this solution were collected by filtration and washed with hexane to give 6.302 g (52%) of **8**. Concentration of the mother liquor to remove the remaining carbon tetrachloride gave a mixture of products which was chromatographed on silica gel with 1:1 ethyl acetate/hexane. The first peroxide to elute from the column was obtained as an oil but crystallized from ethyl acetate/hexane to give 0.569 g (5%) of **9** as colorless needles. The slower moving peroxide obtained from the column was recrystallized from ethyl acetate/hexane to give an additional 0.813 g (6%) of **8**. The total yield of crystalline **8** was 58%.

8: colorless needles; mp 121–122 °C; ^{1}H NMR ($CDCl_3$) δ 6.75 (dd, 1, H-7), 6.41 (dd, 1, H-6), 5.13 (dt, 1, H-8), 4.96 (br, t, 1, H-5), 3.20 (dd, 1, H-4exo), 2.68 (d, 1, H-4endo), 2.6 (m, 4, H-2 and H-3), $J_{3,8}$ = 1.4, $J_{4endo,4exo}$ = 20, $J_{4endo,5}$ = 0, $J_{4exo,5}$ = 5.1, $J_{5,6}$ = 6, $J_{6,7}$ = 9, $J_{7,8}$ = 6.9 Hz; ^{13}C NMR ($CDCl_3$) δ 205.5, 174.8, 139.9, 134.1, 126.3, 74.6, 68.7, 38.5, 34.3, 29.9; IR (KBr) 1686 (s), 1634 (s), 1441, 1396 (s), 1330, 1236,

(18) Ogliaruso, M. A.; Romanelli, M. G.; Becker, E. I. *Chem. Rev.* **1965**, *65*, 261.

(19) Disruption of cyclic delocalization of electrons by exocyclic double bonds is well known in other systems, e.g., *o*- and *p*-xylylene exhibit no benzenoid aromatic character, and bismethylenecyclobutene exhibits no cyclobutadienoid antiaromatic character. For one theoretical treatment of this topic, see: Inagaki, S.; Hirabayashi, Y. *J. Am. Chem. Soc.* **1977**, *99*, 7418–7423.

(20) Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: New York, 1976.

(21) Experimentally, the potential for *p*-chloranil lies ca. 0.5 V above that of *p*-benzoquinone,[2] which puts it above the predicted potentials for azuloquinones **4** and **6**.

(22) 3,4,5,8-Tetrahydro-5,8-epidioxy-1(2*H*)-azulenone (**8**) and 3,3a,4,7-tetrahydro-3a,7-epidioxy-1(2*H*)-azulenone (**9**).

1119, 987, 962, 907, 775, 680 cm^{-1}; UV max (EtOH)[23] 237 (log ϵ 3.89), 214 nm (3.91). Anal. Calcd for $C_{10}H_{10}O_3$: C, 67.41; H, 5.66. Found: C, 67.39; H, 5.68.

9: colorless needles; mp 86.5 °C; ^{1}H NMR ($CDCl_3$) δ 7.46 (d, 1, H-8), 6.03 (ddt, 1, H-6), 5.66 (dt, 1, H-5), 4.92 (t, 1, H-7), 2.93 (ddt, 1, H-4exo), 2.61–2.07 (m, 5, H-2, H-3, and H-4endo), $J_{4endo,4exo}$ = 20, $J_{4endo,5}$ = $J_{4exo,5}$ = 3.5, $J_{4endo,6}$ = $J_{4exo,6}$ = 2, $J_{5,6}$ = 11, $J_{6,7}$ = 7, $J_{7,8}$ = 7 Hz; ^{13}C NMR ($CDCl_3$) δ 202.2, 137.4, 136.2, 131.3, 126.9, 84.5, 71.7, 40.0, 35.9, 33.0; IR (KBr) 1718 (s), 1663 (s), 1418, 1247 (s), 1228, 1207, 1171, 994, 910 (s), 763, 711 cm^{-1}; UV max (EtOH)[23] 257 (log ϵ 3.60), 234 (3.63), 210 nm (3.53). Anal. Calcd for $C_{10}H_{10}O_3$: C, 67.41; H, 5.66. Found: C, 67.49; H, 5.61.

1,7-Diacetoxyazulene (12). To a solution of 6.4 mL (68 mmol) of acetic anhydride and 7.6 mL of pyridine was added 2.029 g (11.4 mmol) of peroxide 9; the resulting solution was stirred at room temperature for 5 days. After this time, the brown-black reaction mixture was diluted with 1 L of dichloromethane and washed successively with 4 × 1 L of water, 2 × 1 L of saturated aqueous sodium bicarbonate, 2 × 1 L of 0.5 M hydrochloric acid, and 1 L of saturated aqueous sodium chloride. The organic solution was dried over magnesium sulfate and concentrated under reduced pressure. Chromatography of the crude product on silica gel with 15:85 ethyl acetate/hexane gave 0.633 g (23%) of **12** as a blue solid. For subsequent reactions, the chromatographically purified material proved satisfactory; however, an analytically pure sample was prepared by recrystallization from dichloromethane/hexane: blue plates; mp 152–154 °C; ^{1}H NMR ($CDCl_3$) δ 8.14 (d, 1, H-4), 8.00 (d, 1, H-8), 7.84 (d, 1, H-2), 7.37 (dd, 1, H-6), 7.25 (d, 1, H-3), 6.96 (dd, 1, H-5) 2.39 (s, 3, CH_3), 2.32 (s, 3, CH_3), $J_{2,3}$ = 4.3, $J_{4,5}$ = 9.8, $J_{5,6}$ = 10.1, $J_{6,8}$ = 2.5 Hz; ^{13}C NMR ($CDCl_3$) δ 170.2, 169.1, 144.4, 138.2, 132.8, 132.5, 131.8, 130.8, 129.4, 126.0, 119.2, 114.4, 21.0 (both CH_3); IR (KBr) 1754 (s), 1579, 1506, 1397, 1370, 1310, 1195 (s), 1158, 1094, 1031, 777, 562 cm^{-1}; UV max (EtOH) 750 (sh, log ϵ 2.06), 675 (sh, 2.49), 623 (2.55), 344 (3.59), 278 (4.65), 240 nm (4.18). Anal. Calcd for $C_{14}H_{12}O_4$: C, 68.85; H, 4.95. Found: C, 68.89; H, 5.02.

1,5-Diacetoxyazulene (13) and 1,8-Diacetoxyazulene (14). To a solution of 20.5 mL (217 mmol) of acetic anhydride and 23 mL of pyridine was added 6.302 g (35.4 mmol) of peroxide **8**, and the resulting solution was stirred at room temperature for 5 days. After this time, the brown-black reaction mixture was diluted with 1 L of dichloromethane and washed successively with 4 × 1 L of water, 2 × 1 L of saturated aqueous sodium bicarbonate, 2 × 1 L of 0.5 M hydrochloric acid, and 1 L of saturated aqueous sodium chloride. The organic solution was dried over magnesium sulfate and concentrated under reduced pressure. Careful chromatography of the crude product on a long silica gel column with 15:85 ethyl acetate/hexane gave a trace of 1-acetoxyazulene **15** (see below) followed by 0.763 g (9%) of **13** and finally 0.461 g (5%) of **14**. For subsequent reactions, the chromatographically purified diacetates (blue solids) proved satisfactory; however, analytically pure samples were prepared by recrystallization from dichloromethane/hexane.

13: blue plates; mp 154–155 °C; ^{1}H NMR ($CDCl_3$) δ 8.14 (d, 1, H-8), 8.00 (d, 1, H-4), 7.84 (d, 1, H-2), 7.33 (dd, 1, H-6), 7.25 (d, 1, H-3), 6.96 (t, 1, H-7), 2.39 (s, 3, CH_3), 2.32 (s, 3, CH_3), $J_{2,3}$ = 4.6, $J_{4,6}$ = 2.5, $J_{6,7}$ = $J_{7,8}$ = 9.8 Hz; ^{13}C NMR ($CDCl_3$) δ 170.0, 168.9, 144.5, 138.4, 132.8, 132.6, 131.7, 130.8, 129.4, 126.1, 119.2, 114.4, 21.0 (both CH_3); IR (KBr) 1754 (s, br), 1583, 1507, 1398, 1372, 1196 (s), 1158, 1095, 1031, 924, 780 cm^{-1}; UV max (EtOH) 747 (sh, log ϵ 2.09), 670 (sh, 2.51), 623 (2.58), 344 (3.66), 278 (4.74), 240 (4.23), 217 nm (2.34). Anal. Calcd for $C_{14}H_{12}O_4$: C, 68.85; H, 4.95. Found: C, 68.73; H, 4.95.

14: blue plates; mp 109–110 °C; ^{1}H NMR ($CDCl_3$) δ 8.16 (d, 1, H-4), 7.64 (d, 1, H-2), 7.40 (dd, 1, H-6), 7.22 (d, 1, H-3), 6.96 (dd, 1, H-5), 6.76 (d, 1, H-7), 2.34 (s, 3, CH_3), 2.29 (s, 3, CH_3), $J_{2,3}$ = 4.4, $J_{4,5}$ = 9.3, $J_{5,6}$ = 10, $J_{6,7}$ = 10.8 Hz; ^{13}C NMR ($CDCl_3$) δ 169.1, 168.6, 153.6, 138.5, 137.0, 136.0, 135.8, 129.3 121.6, 118.8, 117.1, 116.3, 21.0 (both CH_3); IR (KBr) 1756 (br,s), 1579, 1511, 1436, 1370, 1318, 1210 (s), 1188 (s), 1123 (s), 1036 (s), 905, 786, 720 cm^{-1}; UV max (EtOH) 700 (sh, log ϵ 2.08), 635 (sh, 2.53), 590 (2.61), 342 (3.60), 278 (4.60), 240 nm (4.37). MS (70 eV) (M+). Calcd for $C_{14}H_{12}O_4$: 244.0735. Found: 244.0748. Anal. Calcd for $C_{14}H_{12}O_4$: C, 68.85; H, 4.95. Found: C, 68.83; H, 4.98.

1-Acetoxyazulene (15). To a solution of 1.006 g (5.65 mmol) of peroxide **8** in 50 mL of distilled ethyl acetate were added 3.2 mL (34 mmol) of acetic anhydride and 3.65 mL of pyridine. The solution was refluxed for 12 h, then cooled and concentrated under reduced pressure. The crude mixture was redissolved in 150 mL of dichloromethane which was then washed successively with 4 × 100 mL of water, 2 × 100 mL of saturated aqueous sodium bicarbonate, 2 × 100 mL of 0.5 M hydrochloric acid, and 100 mL of saturated aqueous sodium chloride. The organic solution was dried over magnesium sulfate and concentrated under reduced pressure. Chromatography of the resulting oil on silica gel with 15:85 ethyl acetate/hexane gave 24 mg (2.3%) of 1-acetoxyazulene (**15**) followed by 13 mg (1%) of 1,5-diacetoxyazulene (**13**) and a trace of 1,8-diacetoxyazulene (**14**). The 1-acetoxyazulene (**15**) was obtained as blue plates: mp 54–55 °C; ^{1}H NMR ($CDCl_3$) δ 8.01 (d, 2, H-4 and H-8), 7.61 (d, 1, H-2), 7.36 (t, 1, H-6), 7.10 (d, 1, H-3), 6.86 (t, 2, H-5 and H-7), 2.29 (s, 3, CH_3), $J_{2,3}$ = 4, $J_{4,5}$ = $J_{5,6}$ = $J_{6,7}$ = $J_{7,8}$ = 9 Hz; IR ($CHCl_3$) 1760 (s, br), 1584 (s), 1500, 1398 (s), 1374 (s), 1321, 1265, 1223 (s), 1212 (s), 1096, 1032 cm^{-1}; UV max (EtOH) 725 (sh, log ϵ 1.95), 650 (sh, 2.38), 605 (2.46), 344 (3.53), 277 (4.62), 237 nm (4.15).

1,5-Azuloquinone (4). A solution of 900 mg (3.69 mmol) of 1,5-diacetoxyazulene (**13**) in 75 mL of dry THF was cooled to −78 °C under a nitrogen atmosphere. While the solution was being stirred with a magnetic spin bar, 13 mL of 1.5 M methyllithium in ether (19.5 mmol) was added from a syringe. A rapid color change from blue to green indicated formation of the azulene-1,5-hydroquinone dianion. After 3 min, 2.5 mL (2.14 g, 19.7 mmol) of chlorotrimethylsilane was added to give a blue solution of the bis(trimethylsilyl) ether **18**. The reaction mixture was then warmed to room temperature and concentrated without heating under reduced pressure. Addition of 200 mL of 1,2-dichloroethane followed by suction filtration, to remove lithium chloride, gave a blue solution which was added dropwise at room temperature to a suspension of 2.394 g (11.1 mmol) of pyridinium chlorochromate in 500 mL of 1,2-dichloroethane. The resulting mixture was stirred vigorously at room temperature for 12 h and then filtered through a pad of silica gel. The silica gel was washed with ethyl acetate, and the combined organic solutions were concentrated under reduced pressure. The orange-brown solid thus obtained was chromatographed on silica gel with ethyl acetate to give 460 mg (80%) of **4** as a light mustard yellow solid. Sublimation at 85 °C (ca. 10^{-5} torr) gave 253 mg (43%) of **4** as a pale yellow solid: mp ca. 100 °C dec; ^{1}H NMR ($CDCl_3$, 360 MHz) δ 7.78 (d, 1, H-3), 7.31 (dd, 1, H-8), 7.11 (dd, 1, H-7), 6.94 (ddd, 1, H-6), 6.82 (d, 1, H-4), 6.56 (d, 1, H-2), $J_{2,3}$ = 5.9, $J_{4,6}$ = 2.6, $J_{6,7}$ = 12.2, $J_{6,8}$ = 1.1, $J_{7,8}$ = 7.8 Hz; ^{13}C NMR ($CDCl_3$) δ 193.9, 187.2, 154.7, 146.2, 143.9, 135.7, 135.4, 134.4, 133.4, 128.8; IR (KBr) 1706 (s), 1650 (s), 1590 (s), 1542, 1435, 1342, 1241, 1184, 919, 853, 813(s), 627 cm^{-1}; UV max (CH_3CN) 389 (sh, log ϵ 3.29), 373 (3.53), 350 (3.60), 338 (3.59), 324 (3.57), 307 (sh, 3.54), 264 (4.27), 254 (4.36), 216 (3.89) nm, (EtOH)[23] 389(sh), 373, 350, 337, 322 nm. MS (70 eV) m/z (rel abundance) 158 (20), 131 (9), 130 (85), 129 (6), 104 (7), 103 (9), 102 (100), 101 (6), 76 (24), 75 (14), 74 (14), 63 (7). MS (M^+). Calcd for $C_{10}H_6O_2$: 158.0368. Found: 158.0374.

1,7-Azuloquinone (6). A solution of 103 mg (0.42 mmol) of 1,7-diacetoxyazulene (**12**) in 25 mL of dry THF was cooled to −78 °C under a nitrogen atmosphere. While the solution was being stirred with a magnetic spin bar, 1.5 mL of 1.5 M methyllithium in ether (2.25 mmol) was added from a syringe. A rapid color change from blue to green indicated formation of the azulene-1,7-hydroquinone dianion. After 3 min, 0.25 mL (214 mg, 1.97 mmol) of chlorotrimethylsilane was added to give a blue solution of the bis(trimethylsilyl) ether **19**. The reaction mixture was then warmed to room temperature and carefully concentrated under reduced pressure. Addition of 50 mL of 1,2-dichloroethane followed by suction filtration, to remove lithium chloride, gave a blue solution which was added dropwise at room temperature to a suspension of 280 mg (1.30 mmol) of pyridinium chlorochromate in 30 mL of 1,2-dichloroethane. The resulting mixture was stirred vigorously at room temperature for 12 h and then filtered through a pad of silica gel. The silica gel was washed with ethyl acetate, and the combined organic solutions were concentrated under reduced pressure. The orange-brown solid thus obtained was chromatographed on silica gel with ethyl acetate to give 25 mg (38%) of **6** as a lemon yellow solid. Sublimation at 85 °C (ca. 10^{-5} torr) gave long lemon yellow needles: mp 100–102 °C dec; ^{1}H NMR ($CDCl_3$, 360 MHz) δ 7.84 (d, 1, H-3), 7.24 (d, 1, H-8), 7.04 (dd, 1, H-5), 6.82 (dd, 1, H-6), 6.76 (d, 1, H-4) 6.50 (d, 1, H-2), $J_{2,3}$ = 5.8, $J_{4,5}$ = 8.0, $J_{5,6}$ = 12.4, $J_{6,8}$ = 2.8 Hz; ^{13}C NMR ($CDCl_3$) δ 194.8, 188.0, 155.6, 144.4, 140.2, 136.5, 135.8, 134.0, 132.9, 127.0; IR (KBr) 1709 (s), 1649, 1586 (s), 1429, 1347, 1231, 1180, 1164, 930, 847 (s), 770, 615 cm^{-1}; UV max (CH_3CN) 425 (sh, log ϵ 3.21), 401 (3.51), 384 (3.54), 345 (sh, 3.59), 333 (sh, 3.75), 319 (3.84), 236 (4.38) nm; (EtOH)[23] 430 (sh), 399, 384, 345 (sh), 327(sh), 319 nm. MS (70 eV) m/z (rel abundance) 158 (38), 131 (7), 130 (71), 129 (4), 121 (7), 104 (5), 103 (9), 102 (100), 101 (6), 76 (31), 75 (16), 74 (17). MS (M^+) Calcd for $C_{10}H_6O_2$: 158.0368. Found: 158.0373. Anal. Calcd for $C_{10}H_6O_2$: C, 75.94; H, 3.82. Found: C, 75.98; H, 4.03.

Tandem Synthesis of 1,5-Azuloquinone (4) and 1,7-Azuloquinone (6). A solution containing 10.0 g (68.5 mmol) of trienone **7** and 100 mg of tetraphenylporphyrin (TPP) in 500 mL of carbon tetrachloride was purged with dry oxygen and kept under a slight positive pressure of

(23) Solutions of this compound in EtOH decompose on standing and must therefore be prepared immediately before the UV spectrum is recorded.

oxygen by means of a balloon. The solution was stirred vigorously and irradiated with a 150-W high-pressure sodium lamp for 8 h. At the end of the reaction, a small amount of insoluble material was removed by filtration, and the filtrate was concentrated to give 11.0 g of a red-brown oil. Correcting for the 100 mg of TPP, the yield of crude peroxides was 90%. NMR analysis identified peroxide **8** as the major product. Without further purification, this mixture was used immediately in the following reaction.

The 11.0 g (ca. 60 mmol) of crude peroxide mixture was added to a solution of 39 mL (0.41 mol) of acetic anhydride and 45 mL of pyridine, and the resulting solution was stirred at room temperature for 5 days. After this time, the brown-black reaction mixture was diluted with 1 L of dichloromethane and washed successively with 4 × 1 L of water, 2 × 1 L of saturated aqueous sodium bicarbonate, 2 × 1 L of 0.5 M hydrochloric acid, and 1 L of saturated aqueous sodium chloride. The organic solution was dried over magnesium sulfate and concentrated under reduced pressure. Careful chromatography of the resulting brown-black oil on a long silica gel column with 15:85 ethyl acetate/hexane gave a trace of 1-acetoxyazulene followed by 1.34 g (8% from trienone **7**) of **12** and **13** as an inseparable mixture and finally 378 mg (2% from trienone **7**) of **14**. Only after oxidation of the **12**/**13** mixture could the 1,5- and 1,7-isomers be separated.

Method A. A solution of 2.62 g (10.7 mmol) of the **12**/**13** diacetate mixture in 100 mL of dry THF was cooled to −78 °C under a nitrogen atmosphere. A second solution comprised of 36.5 mL of 1.5 M methyllithium in ether (54.8 mmol) and 15 mL of dry THF was prepared in a dropping funnel, and this was added to the cold solution of diacetates with constant stirring over a period of 1–2 min. The green color of the azulene hydroquinone dianions developed rapidly. After 10 min, 7 mL (55.2 mmol) of chlorotrimethylsilane in 20 mL of dry THF was added to give a blue solution of the bis(trimethylsilyl) ethers **18** and **19**. The reaction mixture was then warmed to room temperature and concentrated without heating under reduced pressure. Addition of 500 mL of 1,2-dichloroethane followed by suction filtration, to remove lithium chloride, gave a blue solution which was added dropwise at room temperature over a 2-h period to a suspension of 6.98 g (32.4 mmol) of pyridinium chlorochromate in 1 L of 1,2-dichloroethane. The resulting mixture was stirred vigorously at room temperature for 12 h and then filtered through a pad of silica gel. The silica gel was washed with ethyl acetate, and the combined organic solutions were concentrated under reduced pressure. Chromatography of the crude product on a 3 × 100 cm silica gel column with 15:85 ethyl acetate/hexane gave 418 mg (25%) of the 1,5-quinone **4** as a pale yellow solid followed closely by 452 mg (27%) of the 1,7-quinone **6** as a lemon yellow solid.

Method B. A solution of 173 mg (0.71 mmol) of the **12**/**13** diacetate mixture in 10 mL of dry THF was cooled to −78 °C under a nitrogen atmosphere. A second solution comprised of 3.5 mL of 1.7 M methyllithium in ether (5.95 mmol) and 10 mL of dry THF was then added dropwise to the cold solution of diacetates with constant stirring. After 5 min, 0.65 mL of chlorotrimethylsilane (5.98 mmol) in 10 mL of dry THF was added to convert the green solution of azulene hydroquinone dianions to a blue solution of bis(trimethylsilyl) ethers **18** and **19**. After 5 min, 481 mg of tetrachloro-*p*-benzoquinone (*p*-chloranil, 1.96 mmol) was added all in one portion. The reaction mixture was removed from the cold bath and stirred for an additional 1 h. The solvent was removed under reduced pressure and replaced with 100 mL of dichloromethane. The resulting solution was washed successively with 3 × 50 mL of 0.5 M hydrochloric acid, 2 × 50 mL of water, and 50 mL of saturated aqueous sodium chloride, then dried over magnesium sulfate and concentrated under reduced pressure. Simple chromatography of the crude product on silica gel with 50:50 ethyl acetate/hexane gave 57.2 mg (51%) of the 1,5- and 1,7-quinones **4** and **6** as a mixture. No attempt was made to separate the quinones in this case; ^{1}H NMR analysis indicated a ratio of ca. 1:1.

Method C. A solution of 1.337 g (5.48 mmol) of the **12**/**13** diacetate mixture in 50 mL of dry THF was cooled to −78 °C under a nitrogen atmosphere. While the solution was being stirred with a magnetic spin bar, 18.25 mL of 1.5 M methyllithium in ether (27.4 mmol) was added from a syringe. The solution changed color rapidly from blue to green. After 2 min, 3.65 mL (28.8 mmol) of chlorotrimethylsilane was added to give a blue solution of the bis(trimethylsilyl) ethers **18** and **19**. After 15 min, 2.61 g (11.5 mmol) of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) was added all in one portion. The reaction mixture was removed from the cold bath and stirred for an additional 5 h. Evaporation of the solvent under reduced pressure gave a brown product mixture which was chromatographed on silica gel with ethyl acetate. An orange fraction was collected and carefully rechromatographed on silica gel with 15:85 ethyl acetate/hexane to give 189 mg (22%) of the 1,5-quinone **4** and 204 mg (24%) of the 1,7-quinone **6**.

Cycloaddition of Diphenylisobenzofuran with 1,5-Azuloquinone (4). A solution of 261 mg (0.965 mmol) of diphenylisobenzofuran in 15 mL of 1,2-dichloroethane was stirred at room temperature under a nitrogen atmosphere while a solution of 76 mg (0.481 mmol) of 1,5-azuloquinone (**4**) in 15 mL of 1,2-dichloroethane was added dropwise. After 1 h, the resulting orange-yellow solution was concentrated under reduced pressure. Chromatography of the crude product on silica gel with 15:85 ethyl acetate/hexane gave 134 mg (40%) of the 2:1 adduct **23** as fine cream-colored crystals: mp 139–140 °C; ^{1}H NMR ($CDCl_3$) δ 8.02–6.65 (m, 28, ArH), 5.88 (d, 1, H-8), 5.41 (dd, 1, H-7), 4.13 (d, 1, H-4), 3.83 (dd, 1, H-6), 3.45 (d, 1, H-2), 3.07 (d, 1, H-3), $J_{2,3}$ = 6.4, $J_{4,6}$ = 1.8, $J_{6,7}$ = 6.9, $J_{7,8}$ = 10 Hz; IR (KBr) 1713 (s), 1663 (s), 1599, 1502, 1450, 1319, 1227 (s), 940, 751 (s), 706 (s), 646 cm^{-1}; UV max (EtOH) 324 (rel intensity 3), 246 (37), 214 nm (100). MS (FAB) (M^+). Calcd for $C_{50}H_{34}O_4$: 699.2535. Found: 699.2550.

Cycloaddition of Diphenylisobenzofuran with 1,7-Azuloquinone (6). A solution of 83 mg (0.52 mmol) of 1,7-azuloquinone (**6**) in 10 mL of 1,2-dichloroethane was stirred at room temperature under a nitrogen atmosphere while a solution of 293 mg (1.08 mmol) of diphenylisobenzofuran in 10 mL of 1,2-dichloroethane was added dropwise. After 1 h, the resulting orange solution was concentrated under reduced pressure. Preparative thin layer chromatography of the crude product on silica gel with 25:75 ethyl acetate/hexane gave 11 mg of recovered 1,7-azuloquinone (**6**) and 50 mg (14%) of the 2:1 adduct **24** as fine cream-colored needles: mp 122–124 °C; ^{1}H NMR ($CDCl_3$) δ 7.71–6.99 (m, 28, ArH), 5.86 (d, 1, H-4), 5.21 (dd, 1, H-5), 4.35 (d, 1, H-8), 3.76 (dd, 1, H-6), 3.36 (d, 1, H-2), 2.99 (d, 1, H-3), $J_{2,3}$ = 5.4, $J_{4,5}$ = 11.5, $J_{5,6}$ = 7.5, $J_{6,8}$ = 2 Hz; IR (KBr) 1722, 1702 (s), 1666, 1499, 1462, 1452, 1337, 1314, 1281 (s), 1087, 1024, 786, 752 (s), 652 cm^{-1}; UV max (EtOH) 324 (rel intensity 8), 252 (42), 215 nm (100). MS (FAB) (M^+). Calcd for $C_{50}H_{34}O_4$: 699.2535. Found: 699.2485.

Zinc Reduction of 1,5-Azuloquinone (4).[24] A solution of 100 mg (0.63 mmol) of 1,5-azuloquinone (**4**) and 5 drops of pyridine in 5 mL of freshly distilled acetic anhydride was stirred at room temperature while 777 mg (11.9 mmol) of freshly activated zinc dust[25] was added portionwise over a 15-min period. The mixture became green in color during the addition of the zinc. Stirring was continued for 4 h, after which time the reaction mixture was poured into 70 mL of water, and solid sodium bicarbonate was added to neutralize the acid. The aqueous solution and solid precipitate were then extracted quickly (to avoid prolonged exposure of the diacetoxyazulene to aqueous base) with 150 mL of 1,2-dichloroethane. The organic layer was washed with 4 × 150 mL of water and once with 150 mL of saturated aqueous sodium chloride, dried over magnesium sulfate, and concentrated under reduced pressure. The dark oil thus obtained was chromatographed on silica gel with 15:85 ethyl acetate/hexane to give 11.6 mg (7.5%) of 1,5-diacetoxyazulene (**13**).

Zinc Reduction of 1,7-Azuloquinone (6).[24] A solution of 108 mg (0.68 mmol) of 1,7-azuloquinone (**6**) and 5 drops of pyridine in 10 mL of freshly distilled acetic anhydride was stirred at room temperature while 1.20 g (18.4 mmol) of freshly activated zinc dust[25] was added portionwise over a 15-min period. The mixture became dark blue-green in color during the addition of the zinc. Stirring was continued for 3 h, after which time the reaction mixture was diluted with 70 mL of water, and solid sodium bicarbonate was added to neutralize the acid. The aqueous solution and solid precipitate were then extracted quickly (to avoid prolonged exposure of the diacetoxyazulene to aqueous base) with 150 mL of dichloromethane. The organic layer was washed with 4 × 150 mL of water and once with 70 mL of saturated aqueous sodium chloride, dried over magnesium sulfate, and concentrated under reduced pressure. The dark solid thus obtained was chromatographed on silica gel with 15:85 ethyl acetate/hexane to give 45 mg (27%) of 1,7-diacetoxyazulene (**12**).

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Registry No. 4, 74424-63-8; **6**, 74424-65-0; **7**, 52487-41-9; **8**, 90719-94-1; **9**, 90719-95-2; **12**, 90719-96-3; **13**, 90719-97-4; **14**, 90719-98-5; **15**, 19274-89-6; **18**, 90719-99-6; **19**, 90720-00-6; **20**, 5471-63-6; **23**, 90720-01-7; **24**, 90720-02-8; cyclopentadiene, 542-92-7.

(24) This procedure was adapted from that of Boekelheide, V.; Phillips, J. B. *J. Am. Chem. Soc.* **1967**, *89*, 1695–1704.

(25) Zinc dust was activated immediately prior to use by washing with 0.5 M hydrochloric acid for 5 min; it was then collected by filtration, washed with ethanol, washed with anhydrous ether, and briefly air-dried.