

Oxygen Functionalization of Cycloheptatriene via Sensitized Photo-Oxygenation

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One of the mildest and most efficient methods for introducing oxygen functionalities in cyclopolyenes is through photo-sensitized singlet oxygenation¹. For example, recently we have demonstrated² that cycloheptatrienes (**1**) are converted into the tropilidene-type (**T2**) and norcaradiene-type (**N2**) endoperoxides via [4+2]-cycloaddition of singlet oxygen to the tropilidene (**T1**) and norcaradiene (**N1**) val-

ence tautomers, respectively. These endoperoxides are convenient precursors to oxygen-functionalized derivatives. For example, diazene reduction affords the saturated bicyclic peroxides **T3** and **N3**, thermal rearrangement the diepoxides **N4**, triphenylphosphine deoxygenation the ene-epoxides **N5**, and base-catalyzed rearrangements followed by manganese dioxide oxidation³ the homobenzoquinones **N6**. We illustrate this synthetic concept for the 7-alkyl-substituted cycloheptatrienes **1**.

A variety of oxygen-functionalized intermediates are thereby made available for further transformation and manipulation. The potentially most valuable feature of this method is the stereoselective nature of the [4+2]-cycloaddition of singlet oxygen, affording the *exo* product preferentially.

Table 1. Endoperoxides **T2** and **N2**

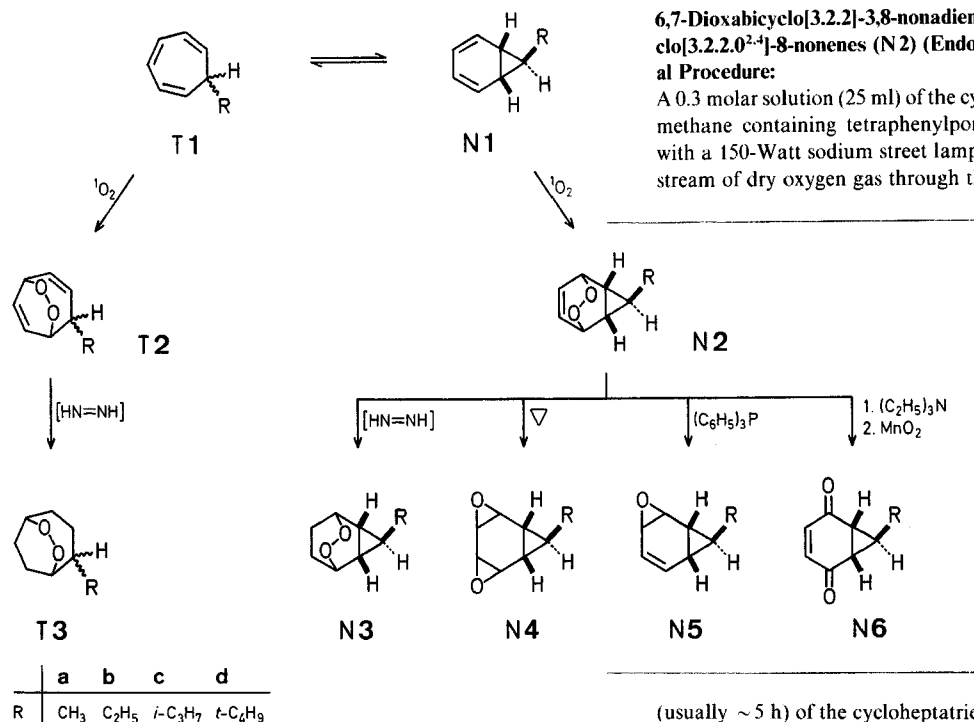
Product ^a	Yield ^b [%]	m.p. [°C] (solvent) or b.p. [°C]/torr (n _D ²⁰)	Molecular Formula ^c	I.R. (CCl ₄) ν [cm ⁻¹]	¹ H-N.M.R. (CCl ₄) δ [ppm] ^d
<i>endo</i> - T2a	10	55°/0.1 (1.5115)	C ₈ H ₁₀ O ₂ (138.2)	3080, 3045, 2990, 2880, 1465, 1400, 1380	1.17 (d, 3H, CH ₃); 2.05–2.55 (m, 1H, 2-H); 4.15 (m, 1H, 1-H); 4.35 (m, 1H, 5-H); 5.25 (m, 1H, 3-H); 5.7 (m, 1H, 4-H); 6.05 (m, 1H, 8-H); 6.4 (m, 1H, 9-H); J _{1,8} =4.33; J _{8,9} =8.83; J _{9,5} =4.49; J _{5,4} =6.33; J _{4,3} =9.99; J _{2,3} =2.83; J _{2,10} =7.16; J _{1,9} =1.66; J _{8,5} =1.16; J _{2,4} =1.58; J _{5,3} =J _{1,3} =1.4 Hz
<i>exo</i> - T2a	34	55°/0.1 (1.5115)	C ₈ H ₁₀ O ₂ (138.2)	3075, 3040, 2980, 2940, 2885, 1460, 1380, 1370	0.90 (d, 3H, CH ₃); 2.5–3.0 (m, 1H, 2-H); 4.25 (m, 1H, 5-H); 4.35 (m, 1H, 1-H); 5.2 (m, 1H, 3-H); 5.65 (m, 1H, 8-H); 5.9 (m, 1H, 4-H); 6.45 (m, 1H, 9-H); J _{8,9} =8.49; J _{4,3} =10.32; J _{1,9} =1.30; J _{1,3} =1.25; J _{9,5} =6.49; J _{3,2} =3.00; J _{4,2} =1.48; J _{4,5} =6.66; J _{2,10} =7.16; J _{5,3} =1.6 Hz
<i>exo</i> - N2a	32	51–52° (pentane)	C ₈ H ₁₀ O ₂ (138.2)	3075, 3040, 3975, 2940, 2915, 1460, 1390, 1375	0.90 (d, 3H, CH ₃); 0.1–0.5 (m, 1H, 2-H); 1.2 (m, 2H, 1-H, 3-H); 4.35–4.8 (m, 2H, 4-H, 8-H); 5.80–6.15 (t, 2H, 5-H, 9-H)
<i>endo</i> - T2b	5	(1.5008)	C ₉ H ₁₂ O ₂ (152.2)		0.8–1.2 (m, 3H, CH ₃); 1.4–1.8 (m, 2H, CH ₂); 1.97–2.3 (m, 1H, 2-H); 4.2–4.55 (m, 2H, 1-H, 5-H); 5.25–5.55 (m, 1H, 3-H); 5.7–5.8 (m, 1H, 4-H); 6.15–6.35 (m, 1H, 8-H); 6.45–6.7 (m, 1H, 9-H)
<i>exo</i> - T2b	37	55–60°/0.05 (1.5009)	C ₉ H ₁₂ O ₂ (152.2)	3070, 3045, 2985, 2945, 2895, 2885, 1460, 1390	0.8–1.4 (m, 5H, C ₂ H ₅); 2.5 (m, 1H, 2-H); 4.2–4.65 (m, 2H, 1-H, 5-H); 5.25–5.5 (m, 1H, 3-H); 5.7–5.85 (m, 1H, 8-H); 5.9–6.1 (m, 1H, 4-H); 6.4–6.7 (dd, 1H, 9-H)
<i>exo</i> - N2b	32	45°/0.01 (1.4982)	C ₉ H ₁₂ O ₂ (152.2)	3085, 3035, 2970, 2965, 2890, 1460, 1370, 1345	0.5–1.2 (m, 7H, 1-H, 3-H, C ₂ H ₅); –0.1 to –0.2 (m, 1H, 2-H); 4.5–4.7 (m, 2H, 5-H, 8-H); 6.1–6.25 (dd, 2H, 4-H, 9-H); J _{9,8} =5.0 Hz
<i>endo</i> - T2c	6	(1.5065)	C ₁₀ H ₁₄ O ₂ (166.2)	3075, 2980, 1455	0.9–1.3 (m, 7H, <i>i</i> -C ₃ H ₇); 2.0 (m, 1H, 2-H); 4.3–4.5 (m, 2H, 1-H, 5-H); 5.3–5.6 (m, 1H, 3-H); 5.7–5.95 (m, 1H, 4-H); 6.1–6.3 (m, 1H, 8-H); 6.4–6.6 (m, 1H, 9-H)
<i>exo</i> - T2c	19	50–55°/0.05 (1.5065)	C ₁₀ H ₁₄ O ₂ (166.2)	3075, 3045, 2980, 2945, 2890, 1460, 1390, 1375	0.95 [d, 6H, CH(CH ₃) ₂]; 2.6 (m, 1H, 2-H); 1.65 [m, 1H, CH(CH ₃) ₂]; 4.4–4.95 (m, 2H, 1-H, 5-H); 5.5–6.9 (m, 3H, 3-H, 8-H, 9-H); 6.40–6.70 (dd, 1H, 9-H)
<i>exo</i> - N2c	64	85–86° (pentane)	C ₁₀ H ₁₄ O ₂ (166.2)	3075, 3040, 3010, 2980, 2965, 2885, 1460, 1385, 1375	0.85–1.05 (m, 7H, <i>i</i> -C ₃ H ₇); 0.15 (m, 1H, 2-H); 1.2–1.4 (m, 2H, 1-H, 3-H); 4.5–4.8 (m, 2H, 4-H, 8-H); 5.96–6.12 (t, 2H, 5-H, 9-H); J _{9,8} =4.0 Hz
<i>exo</i> - T2d	27	67–68° (pentane)	C ₁₁ H ₁₆ O ₂ (180.2)	3060, 3045, 2980, 2885, 1475, 1395, 1365	1.00 (s, 9H, <i>t</i> -C ₄ H ₉); 2.55 (m, 1H, 2-H); 4.40 (br t, 1H, 5-H); 4.85 (m, 1H, 1-H); 5.6 (m, 1H, 3-H); 5.9–6.2 (m, 2H, 4-H, 8-H); 6.60 (dd, 1H, 9-H); J _{5,9} =6.1; J _{9,5} =8.7; J _{8,1} =6.9; J _{3,4} =11.6; J _{3,2} =2.4; J _{1,2} =4.3 Hz
<i>exo</i> - N2d	64	108–110° (ether/CCl ₄)	C ₁₁ H ₁₆ O ₂ (180.2)	3050, 2980, 2910, 2880, 1460, 1395, 1375	0.85 (s, 9H, <i>t</i> -C ₄ H ₉); 0.1–0.3 (m, 1H, 2-H); 1.25–1.5 (m, 2H, 1-H, 3-H); 4.5–4.75 (m, 2H, 4-H, 8-H); 6.00–6.20 (t, 2H, 5-H, 9-H); J _{2,1} =3.8 Hz

^a *endo* and *exo* refer to the R-substituent with respect to peroxide bridge.

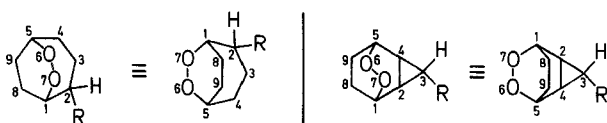
^b Isolated by M.P.L.C. on silica gel, eluting with dichloromethane/pentane.

^c The microanalysis showed the following maximum deviations from the calculated values: C, ±0.20; H, ±0.10.

^d For numbering of the protons, see formulas in text.



Ring Index numbering of the endoperoxide ring systems used in text and in Tables 1 and 2:



6,7-Dioxabicyclo[3.2.2]-3,8-nonadienes (T2) and 6,7-Dioxatricyclo[3.2.2.0^{2,4}]-8-nonenenes (N2) (Endoperoxides T2 and N2); General Procedure:

A 0.3 molar solution (25 ml) of the cycloheptatriene 1 in tetrachloromethane containing tetraphenylporphyrin (~2 mg) is irradiated with a 150-Watt sodium street lamp at 0 °C while bubbling a slow stream of dry oxygen gas through the solution. After consumption

(usually ~5 h) of the cycloheptatriene (monitored by ¹H-N.M.R.), the solvent is roto-evaporated (~5 °C/10 torr), and the residue submitted to medium pressure liquid chromatography (M.P.L.C.) on silica gel using dichloromethane/pentane as eluent. Some minor products are eluted first, followed by the clean products T2 and then N2.

6,7-Dioxabicyclo[3.2.2]nonanes (T3) and 2,3-Dioxatricyclo[3.2.2.0^{2,4}]nonanes (N3); General Procedure:

A suspension of dipotassium diazenedicarboxylate (azodicarboxylate; 972 mg, 5 mmol) in a 0.03 molar solution (20 ml) of the endo-

Table 2. Endoperoxides T3 and N3

Product ^a	Yield ^b [%]	m.p. (solvent) or b.p./torr (n _D ²⁰) [°C]	Molecular Formula ^c	I.R. (CCl ₄) ν [cm ⁻¹]	¹ H-N.M.R. (CCl ₄) δ [ppm] ^d
T3a	92	63°/0.08 (1.4850)	C ₈ H ₁₄ O ₂ (142.2)	2980, 2955, 2930, 1480, 1390, 1350	0.8–2.4 [br. m, 12H, CH ₃ , (2,3,4,8,9)-H]; 3.69–4.05 (br. m, 2H, 1-H, 5-H)
N3a	98	109–109.5° (dichloromethane/ pentane)	C ₈ H ₁₂ O ₂ (140.2)	3040, 2965, 2957, 2917, 2880, 1465, 1340	0.5–2.3 [br. m, 10H, CH ₃ , (1,2,3,5,9)-H]; 3.9–4.3 (m, 2H, 4-H, 8-H)
T3b	80	50°/0.03 (1.4841)	C ₉ H ₁₆ O ₂ (156.2)	2990, 2880, 1460, 1450, 1435, 1380, 1340	0.8–1.5 (m, 6H, CH ₂ —CH ₃ , 2-H); 1.5–2.2 [m, 8H, (3,4,8,9)-H]; 3.8–4.05 (m, 1H, 5-H); 4.05–4.4 (m, 1H, 1-H)
N3b	78	83–84° (ether/ pentane)	C ₉ H ₁₄ O ₂ (154.2)	3025, 2950, 2890, 1460, 1440	0.6–2.1 [m, 12H, CH ₂ —CH ₃ , (1,2,3,5,9)-H]; 4.2–4.45 (m, 2H, 4-H, 8-H)
T3c	73	50°/0.02 (1.4856)	C ₁₀ H ₁₈ O ₂ (170.2)	2960, 2885, 1465, 1390, 1370	0.95–1.1 (m, 7H, <i>i</i> -C ₃ H ₇); 1.5–2.2 [m, 8H, (3,4,8,9)-H]; 4.1–4.4 (m, 2H, 1-H, 5-H)
N3c	30	111–112° (ether/ pentane)	C ₁₀ H ₁₆ O ₂ (168.2)	2980, 2910, 2885, 1460, 1445, 1380, 1365, 1345	0.9–1.05 (m, 7H, <i>i</i> -C ₃ H ₇); 0.6–0.8 (m, 1H, 2-H); 1.2–1.45 (m, 2H, 1-H, 3-H); 1.65–2.05 (m, 4H, 5H, 9H); 4.0–4.2 (m, 2H, 4-H, 8-H)
T3d	70	44.5–45° (pentane)	C ₁₁ H ₂₀ O ₂ (184.2)	2980, 2885, 1480, 1455, 1370, 1345	0.90 (s, 9H, <i>t</i> -C ₄ H ₉); 0.8–0.9 (m, 1H, 2-H); 1.5–1.85 [m, 8H, (3,4,8,9)-H]; 4.05–4.25 (m, 2H, 1-H, 5-H)
N3d	60	107–108° (pentane)	C ₁₁ H ₁₈ O ₂ (182.2)	2975, 2910, 2885, 1460, 1365, 1345	0.90 (s, 9H, <i>t</i> -C ₄ H ₉); 0.7–0.85 (m, 1H, 2-H); 1.35–1.6 (m, 2H, 1-H, 3H); 1.9–2.1 (m, 4H, 5-H, 9H); 4.1–4.3 (m, 2H, 4-H, 8-H)

^a Refers to *exo* isomer.

^b Isolated by recrystallization or distillation (bulb-to-bulb).

^c The microanalyses showed the following maximum deviations from the calculated values: C, ±0.20; H, ±0.10.

^d For numbering of the protons, see formulas in text.

Table 3. 2,3,4,5-Bis[epoxy]-bicyclo[4.1.0]heptanes (N4)

Product ^a	Yield ^b [%]	m.p. (solvent) or b.p./torr (n _D ²⁰) [°C]	Molecular Formula ^c	I.R. (CCl ₄) ν [cm ⁻¹]	¹ H-N.M.R. (CCl ₄) δ [ppm] ^d
N4a	90	103–105° (ether/ pentane)	C ₈ H ₁₀ O ₂ (138.2)	3020, 2980, 1430	0.7–1.4 (m, 6H, CH ₃ , 1-H, 6-H, 7-H); 3.25 (s, 4H, 2-H, 3-H, 4-H, 5-H)
N4b	73	75°/0.01 (1.4920)	C ₉ H ₁₂ O ₂ (152.2)	3000, 2985, 2925, 2890, 1450, 1425, 1375	0.8–1.0 (m, 6H, C ₂ H ₅ , 7-H); 1.2–1.4 (m, 2H, 1H, 6-H); 2.95 (s, 4H, 2-H, 3-H, 4-H, 5-H)
N4c	90	94–95° (ether/ pentane)	C ₁₀ H ₁₄ O ₂ (166.2)	3000, 2980, 2925, 2885, 1460, 1445, 1425, 1390, 1360	1.0–1.2 (m, 9H, <i>i</i> -C ₃ H ₇ , 1-H, 6-H); 0.5–0.7 (m, 1H, 7-H); 2.90 (s, 4H, 2-H, 3-H, 4-H, 5-H)
N4d	55	97–98° (ether/ pentane)	C ₁₁ H ₁₆ O ₂ (180.2)	3000, 2975, 2880, 1460, 1440, 1420, 1365	0.90 (s, 9H, <i>t</i> -C ₄ H ₉); 0.6–0.8 (m, 1H, 7-H); 1.2–1.3 (m, 2H, 1-H, 6-H); 0.97 (s, 4H, 2-H, 3-H, 4-H, 5-H); J _{1,7} = 3.8 Hz

^a Refers to the *exo* isomer.^b Purified by recrystallization and sublimation at reduced pressure.^c The microanalysis showed the following maximum deviations from the calculated values: C, ±0.20; H, ±0.10.^d Numbering of the protons refers to IUPAC numbering of the bicyclo[4.1.0]heptane ring system:**Table 4.** 4,5-Epoxybicyclo[4.1.0]-2-heptenes (N5)

Product ^a	Yield ^b [%]	b.p./torr [°C] (n _D ²⁰)	Molecular Formula ^c	I.R. (CCl ₄) ν [cm ⁻¹]	¹ H-N.M.R. (CCl ₄) δ [ppm] ^d
N5a	38	63°/0.08 (1.4975)	C ₈ H ₁₀ O (122.2)	3075, 3020, 2980, 2950, 2920, 2885, 1650, 1460, 1440	0.8–1.0 (m, 5H, CH ₃ , 6-H, 7-H); 1.3–1.5 (m, 1H, 1-H); 2.55–2.75 (m, 1H, 3-H); 3.43 (dd, 1H, 2-H); 5.25 (dd, 1H, 4-H); 5.65–5.95 (m, 1H, 5-H)
N5b	56	30°/0.02 (1.4832)	C ₉ H ₁₂ O (136.2)	3050, 3020, 2975, 2925, 1650, 1460, 1435, 1380, 1340	0.6–1.8 (m, 8H, C ₂ H ₅ , 1-H, 6-H, 7-H); 2.7 (m, 1H, 3-H); 3.50 (dd, 1H, 2-H); 5.50 (dd, 1H, 4-H); 5.7–6.2 (m, 1H, 5-H)
N5c	83	40°/0.02 (1.4845)	C ₁₀ H ₁₄ O (150.2)	3050, 3025, 2985, 2950, 2890, 1650, 1465, 1440	0.8–1.3 (m, 9H, <i>i</i> -C ₃ H ₇ , 6-H, 7-H); 1.45–1.7 (m, 1H, 1-H); 3.40–3.50 (dd, 1H, 2-H); 2.7 (m, 1H, 3-H); 5.30–5.60 (dd, 1H, 4-H); 5.8–6.7 (m, 1H, 5-H)
N5d	40	40°/0.02 (1.4800)	C ₁₁ H ₁₆ O (164.2)	3020, 2960, 2860, 1650, 1465, 1365	0.85–1.1 (m, 11H, <i>t</i> -C ₄ H ₉ , 6-H, 7-H); 1.55 (m, 1H, 1-H); 3.40 (dd, 1H, 2-H); 2.6 (m, 1H, 3-H); 5.3 (dd, 1H, 4-H); 5.9 (m, 1H, 5-H)

^a Refers to *exo* isomer.^b Bulb-to-bulb distilled (Büchi Kugelrohr).^c The microanalysis showed the following maximum deviations from the calculated values: C, ±0.20; H, ±0.10.^d For numbering of protons, see footnote d of Table 3.

peroxide **T2** or **N2** in dichloromethane is vigorously stirred at 0 °C while a 1.0 molar solution (10 ml) of acetic acid in dichloromethane is added dropwise over a 60 min period. After decoloration of the yellow suspension, an aliquot is analyzed by ¹H-N.M.R. spectroscopy to confirm completion of the reduction. If olefinic protons are still present, another batch of dipotassium diazenedicarboxylate (972 g, 5 mmol) is added and the reduction repeated until completion. For the norcaradiene endoperoxide **N3**, usually one cycle is sufficient, but for the more sluggish tropilidene endoperoxide **T3** sometimes three cycles are required. After completion of the reduction, the solids are removed by filtration, the solvent is roto-evaporated (~30 °C/10 torr), and the residue recrystallized if solid or bulb-to-bulb distilled (Büchi Kugelrohr) if liquid.

Norcaradiene Diepoxides (N4); General Procedure:

A 0.1 molar solution (10 ml) of the endoperoxide **N2** in tetrachloromethane is heated at reflux for ~2 h until complete transformation (consumption of **N2** monitored by ¹H-N.M.R.). The solvent is roto-evaporated (~30 °C/10 torr) and the residue recrystallized.

Norcaradiene Monoepoxides (N5); General Procedure:

A 0.06 molar solution (10 ml) of the endoperoxide **N2** in chloroform containing triphenylphosphine (144 mg, 0.55 mmol) is stirred at 0 °C until complete consumption of the peroxide (monitored by peroxide test with potassium iodide), usually 1 h. The solvent is roto-evaporated (~30 °C/10 torr) and the residue triturated with pentane to separate the ene-epoxide from most of the triphenylphosphine oxide. The solution is roto-evaporated (~30 °C/10 torr) and the residue bulb-to-bulb distilled (Büchi Kugelrohr).

2,5-Dioxabicyclo[4.1.0]-3-heptenes (Homobenzoquinones, N6); General Procedure:

A 0.06 molar solution (10 ml) of the endoperoxide **N2** in dichloromethane containing triethylamine (101 mg, ~1 mmol) is stirred at 0 °C until complete consumption of the peroxide (monitored by peroxide test with potassium iodide), usually ~4 h. The solvent is roto-evaporated (~30 °C/10 torr) and the residue passed through a small silica-gel column (2 g) using chloroform/methanol (95/5) as eluent to remove triethylamine. The crude hydroxyenone thus ob-

Table 5. 2,5-Dioxabicyclo[4.1.0]-3-heptenes (Homobenzoquinones, **N6**)

Product ^a	Yield ^b [%]	m.p. [°C] (solvent)	Molecular Formula ^c	I.R. (CCl ₄) ν [cm ⁻¹]	¹ H-N.M.R. (CCl ₄) δ [ppm] ^d
N6a	84	48–49° (ether/ pentane)	C ₈ H ₈ O ₂ (136.1)	2980–3000, 1680, 1610, 1460, 1350	1.35 (d, 3 H, CH ₃); 1.7–2.4 (m, 3 H, 1-H, 6-H, 7-H); 6.40 (s, 2 H, 3-H, 4-H); $J_{6,7} = 4.0$ Hz
N6b	70	47–48° (ether/ pentane)	C ₉ H ₁₀ O ₂ (150.2)	2995, 2890, 1685, 1600, 1465	1.0–2.15 (m, 6 H, C ₂ H ₅ , 7-H); 2.20 (d, 2 H, 1-H, 6-H); 6.5 (s, 2 H, 3-H, 4-H); $J_{6,7} = 5.3$ Hz
N6c	60	77–78° (ether/ pentane)	C ₁₀ H ₁₂ O ₂ (164.2)	3040, 2990, 2890, 1605, 1460, 1375	1.0 (m, 7 H, <i>i</i> -C ₃ H ₇); 1.6 (m, 1 H, 7-H); 2.1 (d, 2 H, 1-H, 6-H); 6.1 (s, 2 H, 3-H, 4-H); $J_{6,7} = 4.3$ Hz
N6d	77	120° (CH ₂ Cl ₂ / pentane)	C ₁₁ H ₁₄ O ₂ (178.2)	2975, 2880, 1675, 1600, 1475, 1360	0.95 (s, 9 H, <i>t</i> -C ₄ H ₉); 1.85 (t, 1 H, 7-H); 2.4 (d, 2 H, 1-H, 6-H); 6.75 (s, 2 H, 3-H, 4-H); $J_{6,7} = 5.0$ Hz

^a Refers to the *exo* isomer.^b Isolated by column chromatography on silica gel, eluting with dichloromethane.^c The microanalysis showed the following maximum deviations from the calculated values: C, ± 0.20 ; H, ± 0.10 .^d For numbering of protons, see footnote d of Table 3.

tained is dissolved in dichloromethane (15 ml) and the solution stirred with manganese(IV) oxide (500 mg) at $\sim 30^\circ\text{C}$ for ~ 6 h. The solids are then removed by filtration, the solvent is roto-evaporated ($\sim 30^\circ\text{C}/10$ torr), and the residue is column-chromatographed on silica gel (~ 5 g) using dichloromethane as eluent. Recrystallization affords the pure product **N6**.

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