Stereoselective Aldehyde Addition to Rhenium-Coordinated Furans

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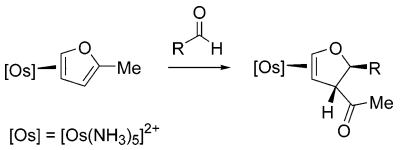
Dihapto-coordinated furan complexes of the form TpRe(CO)(*t*-BuNC)(*2,3-η*^{2}-furan) (Tp = hydridotris(pyrazolyl)borate) react with aldehydes in the presence of BF_3·OEt_2 to yield dihydrofuran complexes. Depending on the reaction conditions, these products take one of three forms: a dihapto-coordinated *trans*-2-alkyl-3-acyl-2,3-dihydrofuran, *trans*-2,3-dialkyl-2,3-dihydrofuran, or 4a,7a-dihydro-4*H*-furo[2,3-*d*][1,3]dioxine. The first two are formed exclusively as *trans*-disubstituted products, whereas the last exhibits *cis* stereochemistry at the ring fusion. These are isolated as mixtures of coordination diastereomers, which are separable by chromatography. Of the two diastereomers of the *trans*-2-alkyl-3-acyl-2,3-dihydrofuran product obtained in each case, only the major isomer undergoes an interfacial isomerization under ambient conditions. Attempts to decomplex the dihydrofurans were unsuccessful.

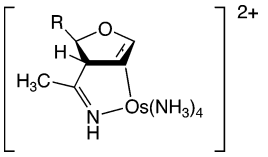
Introduction

The 2,3-dihydrofuran skeleton is contained in a variety of naturally occurring molecules.[1] Additionally, compounds containing this moiety serve as potential synthetic precursors to countless pharmaceuticals, carbohydrates, and other natural and biologically active products.[2−5] Because furans are readily available and easily functionalized at the α positions,[1] they intuitively seem a reasonable starting material for dihydrofuran syntheses.

In 1995, our group reported a new method of generating functionalized 3-acetyl-2,3-dihydrofuran complexes from their furan precursors.[6] The key reaction involved the addition of an aldehyde across C3 and C5 of [Os(NH$_3$)$_5$(*η*^{2}-2-methylfuran)]$^{2+}$, to generate the new heterocyclic ring:



Unfortunately, our attempts to oxidatively decomplex the dihydrofurans were thwarted by an unanticipated condensation of the pendant acetyl moiety with one of the acidic ammine ligands.[6]



The development of a second generation of *π*-bases of the form {TpRe(CO)(L)} (Tp = hydridotris(pyrazolyl)-borate, L = *t*-BuNC, PMe$_3$, pyridine, or *N*-methylimidazole)[7] provides the opportunity to effect this reaction without the possibility of ammine/ketone condensation.[6] Furthermore, the two carbon stereocenters formed in the cyclization reaction could be controlled by the metal. In selecting a rhenium dearomatization agent to explore this transformation, we chose the most electron-deficient member of the TpRe(CO)(L) family hoping that removal of the *π*-acidic dihydrofuran would be most facile.[7] Thus, we embarked on a set of experiments to assess the feasibility of promoting this reaction utilizing the {TpRe(CO)(*t*-BuNC)} fragment.

Results

The furan complex TpRe(CO)(*t*-BuNC)(*η*^{2}-furan) (**1**) is present as a 2.2:1 mixture of coordination diastereomers at 20 °C (Scheme 1; **1A**:**1B**). A solution of **1** was combined with acetaldehyde, and this mixture was treated with BF_3·OEt_2 at −40 °C. The solution was allowed to stand for 12 h. Chromatography of the reaction mixture (TLC) afforded the dihydro-4*H*-furodioxine complex **3**, isolated as a 7:1 mixture of coordination diastereomers (**3A**:**3B**; Scheme 1; only major shown).

The small scale of the reaction prevented an accurate measurement of yield, but the major isomer of complex

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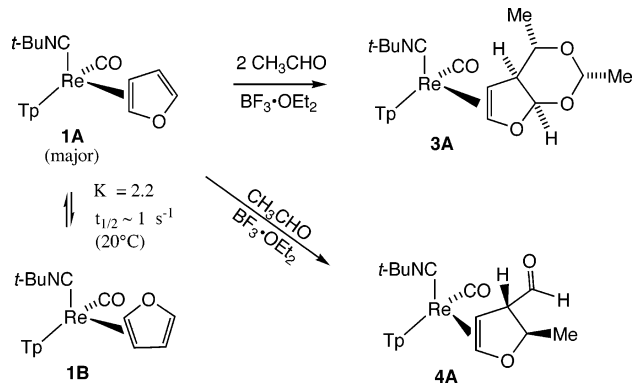
Scheme 1



3 crystallized out of the acetonitrile solution. An X-ray structure determination revealed that **3** was the product of a net [2+2+2] cyclization reaction of 2 equiv of acetaldehyde and the C2−C3 bond of the bound furan (Scheme 1). The ORTEP diagram of this dihydrofurodioxine complex (Figure 1) indicates that the dominant isomer **3A** originated from the major isomer of the η^2-furan complex (**1A**), where the oxygen of the furan ring is oriented away from the *t*-BuNC ligand. The addition at C3 and the addition at C2 occurred on the face of the furan opposite that coordinated to the rhenium, resulting in a *cis* ring fusion. Both methyl substituents occupy equatorial positions of the dioxine ring. The minor isomer **3B** could not be isolated in sufficient amounts to obtain a full characterization, but chemical shifts for resonances corresponding to hydrogens of the bound carbons (C7 and C8) are consistent with the dihydrofuran oxygen being oriented toward the *t*-BuNC such that it originated from the minor isomer of the furan complex (**1B**).[8]

When the reaction of **1** with acetaldehyde and BF_3·OEt_2 was repeated as above, but the reaction mixture was allowed to stand for 5 days (−40 °C), a complex mixture resulted. However, NMR data for the major isolated product (**4A**; TLC) suggested that the desired addition had occurred. For complex **4A**, carbon and proton NMR data were most consistent with the formation of a 3-formyl-2,3-dihydrofuran complex, as shown in Scheme 1. Although a detailed analysis of ^{1}H, ^{13}C, and COSY NMR data provided a reliable stereochemical assignment for **4A**, we were unable to recover sufficient amounts of this material to examine its chemical properties. An analogous reaction with the complex TpRe(CO)(*t*-BuNC)(2-methylfuran) (**2**) was expected to afford a 3-acetyl-2,3-dihydrofuran complex, which we hoped would be more tolerant to the Lewis-acidic reaction conditions than the formyl analogue **4**.

The 2-methylfuran complex **2** exists as a 4.9:1 equilibrium ratio of coordination diastereomers (**2A**:**2B**),[9] as seen in Scheme 2. These two diastereomers readily interconvert at 20 °C ($t_{1/2} \approx 1$ s), such that they exist in dynamic equilibrium. Combining an acetonitrile solution of **2** with acetaldehyde, followed by treatment with BF_3·OEt_2 at −40 °C, yields the desired 3-acyl-1,2-dihydrofuran complex **5** after 20 h as a 1:3 mixture of two isomers (**5A**:**5B**; Scheme 2; 24%). When the reaction is quenched with pyridine after the first 6 h of the reaction, only a small amount of the product mixture is observed, but the ratio is the same as in the final product. This is in contrast to the analogous reaction with the pentaammineosmium(II) fragment,[6] where different ligand stereochemistries are observed earlier in the reaction than at later times. When a neutral NMR solution of **5B** (vide infra) is allowed to stand at room temperature, the complex undergoes an interfacial isomerization with a $t_{1/2}$ of ∼26 h to form a 5.2:1 equilibrium mixture of **5C**:**5B**. In contrast, **5A** exhibits no observable amount of interfacial isomerization, even when allowed to remain in solution for several weeks at 20 °C. In fact, no product of type **D** (Scheme 2) was observed for any of the systems that were investigated. Complexes **5A**, **5B**, and **5C**, were separated by preparatory TLC. As seen in Scheme 2, the *relative* stereochemistry of the acetyldihydrofuran ligand is identical for all three isomers (**5A**−**5C**; vide infra). Therefore, the ratio of (**5B** + **5C**):**5A** reflects the potential enantiomeric ratio of the dihydrofuran stereoisomers for a given configuration of rhenium. In the case of R = methyl, this ratio is 3:1.

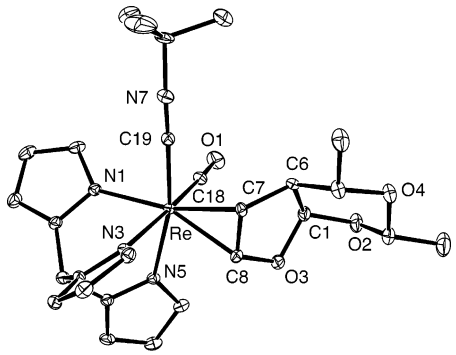


Figure 1. ORTEP diagram of complex **3A** (30% ellipsoids).

Scheme 2

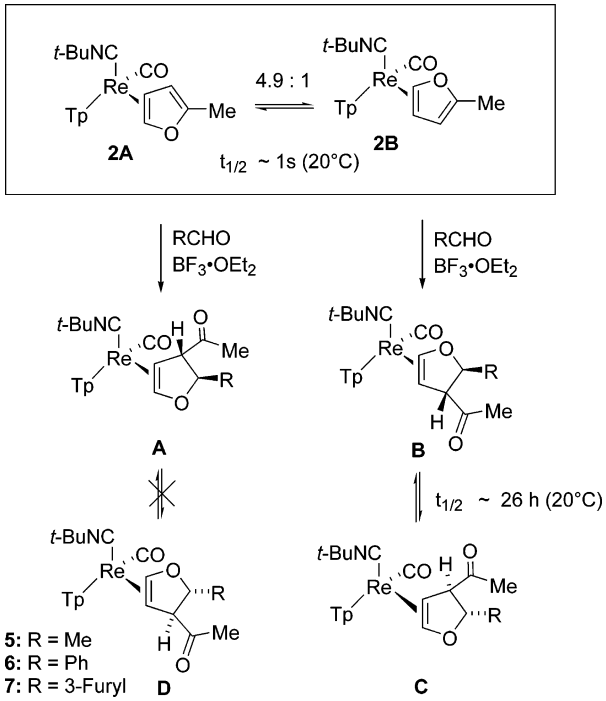


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Table 1. Equilibrium Ratios for Stereoisomers A−C

Product	R	(B + C) : A	B : C
5	Me	3 : 1	1 : 5.2
6	Ph	8.5 : 1	1 : 1.5
7		>20 : 1	1 : 1.2

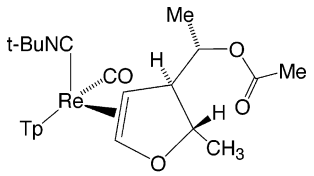
When the reaction sequence was repeated with benzaldehyde (37% isolated yield) or with 3-formylfuran,[10] better control of the stereochemistry was observed. Dihydrofuran complexes **6** and **7** were also isolated as mixtures of isomers, but in these cases the ratio of (**B** + **C**):**A** was much higher, as can be seen in Table 1, reaching a ratio of greater than 20:1 in the case of the 3-furyl products (**7**).

In general, diagnostic features of the acetyldihydrofuran complexes **5**−**7** include a pair of infrared-active stretching frequencies, one from the CO ligand near 1845 cm^{-1} and one near 1700 cm^{-1} (about one-quarter the intensity of the former), arising from the acyl moiety at C3 of the dihydrofuran. An especially convenient diagnostic peak in the ^1H NMR spectrum is that corresponding to the α-bound proton (H(C5)). For example, this proton appears at δ 4.87 for **5A**, 5.40 ppm for **5C**, and δ 6.46 for **5B**. The structure of each isomer was elucidated with COSY and NOE data. The assignment of carbon peaks was made using heteronuclear correlation spectroscopy and by noting systematic variations in the carbon spectra between different products of the same stereochemistry.

In the ^1H NMR spectrum of $[Os(NH_3)_5(4,5\text{-}\eta^2\text{-}2,3\text{-dihydrofuran})](OTf)_2$, H(C5) and H(C4) appear at δ 6.11 and 3.48, respectively.[11] In the {TpRe(CO)(*t*-BuNC)} systems, owing to anisotropic effects from the Tp ligand, either H(C4) or H(C5) is shifted approximately 1 ppm upfield from these values, depending on which is in the proximity of the pyrazole ring *trans* to the isonitrile.[12] The other appears relatively close to the corresponding chemical shift for the osmium system. This observation facilitated identification of ligand orientation. The proposed structure of **5A** is supported by the presence of an 11% NOE enhancement of a Tp proton (δ 8.24) upon irradiation at δ 4.87 (H(C5)). However, a simpler method for determining stereochemical identity exists, obviating the need for NOE spectra of every isomer of every product. In isomers in which the acetyl moiety is *syn* to the rhenium, H(C3) and H(C4) exhibit mutual NMR coupling of about 4.6−5.0 Hz, with very little variation. When the acetyl group is *anti* to the metal, that coupling constant is 2.5 Hz or less. In all cases of addition/rearrangement, the acyl group at C3 is *trans* to the moiety at C2; therefore, the coupling constant between H(C2) and H(C3) is consistently in the 10.0−11.0 Hz range, with few exceptions. Therefore, confident assignment of the stereochemistries of C2 and C3 with respect to the metal can be made by determining the H(C3)−H(C4) coupling constant.

Treatment of the benzaldehyde-derived product **6** with $BF_3{\cdot}OEt_2$ and excess acetaldehyde at −40 °C for 18 h resulted in almost complete conversion to a 3:1 mixture of the acetaldehyde-derived **5C** to **5A**. This observation indicates that the entire mechanism for the formation of the 3-acetyl-2,3-dihydrofuran from furan and aldehyde is reversible in the presence of the Lewis acid.

When the 2-methylfuran complex **2** is combined with a large excess of acetaldehyde (ca. 10 M), significant amounts of a new species, **8**, are isolated (as much as a 1:1 ratio of **5**:**8**). This material is unlike any other product observed from similar reactions, and its assignment was made with the help of COSY, HETCOR, and HMBC data. Of note, complex **8** gives strong signals at 1728 and 1245 cm^{-1} in the IR spectrum, providing evidence for the presence of an ester group. Subjecting a pure sample of **8** to the original reaction conditions did not result in the formation of any isomer of **5**. Detailed spectroscopic analysis reveals that **8** is the 2,3-dialkylated furan complex shown below:



8

Several attempts to demetalate the dihydrofuran ligand of the acetylphenyldihydrofuran complex **6** with heat, AgOTf, or $Cu(OTf)_2$ under neutral or weakly basic conditions all resulted in formation of the complex TpRe(*t*-BuNC)$(CO)_2$, which was identified by strong IR stretches of 1853 and 1920 cm^{-1}, as previously observed in our laboratory.[13] This observation suggests that the rhenium is somehow capable of extracting CO from the acetyldihydrofuran.[14] However, attempts to isolate and characterize the organic product were unsuccessful.

Discussion

The addition of aldehydes to the dearomatized furan and subsequent rearrangement is believed to follow the mechanistic pathway shown in Scheme 3. The first step, electrophilic addition of the activated aldehyde, affords the 3H-furanium/boron enolate zwitterion **I**, which has previously been established as being in equilibrium with **II**, its ring-opened vinyl cation (metallacyclopropenium) form.[8,11] Rotation around the C3−C4 bond to form **III** allows the boron alkoxide to attack the bound vinyl cation at C5 and form the dihydrofuran **IV**, from which compounds **4**−**7** are derived.

Due to the steric bulk of the rhenium fragment, the aldehyde cannot approach the furan *syn* to the metal

(10) Complex **7** was prepared on an exploratory scale (~10 mg), so accurate yield information is unavailable, but the majority of material was recovered in the form of **7B**.

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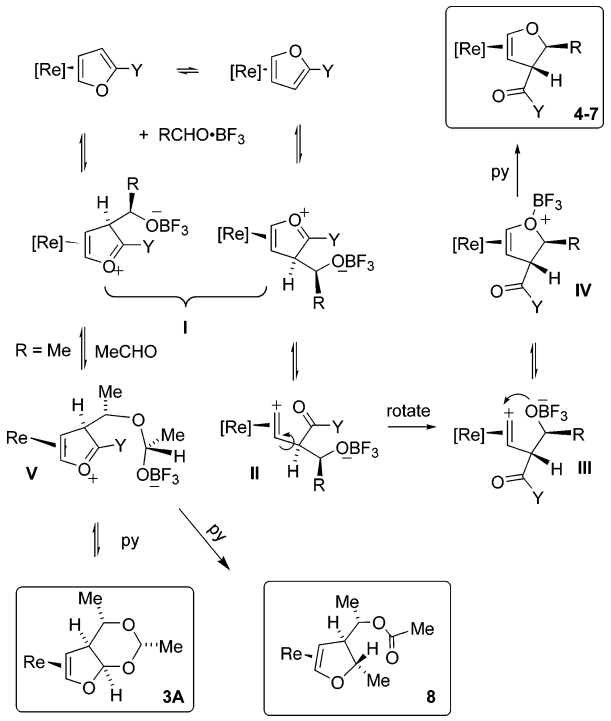
Scheme 3



under the reaction conditions employed in this investigation. This observation is consistent with previous studies in our laboratory[15−17] which have shown that electrophilic additions to dihapto-coordinated aromatics occur *anti* to the metal fragment. Therefore, the stereochemistry at C3 is a direct result of the electrophilic addition, which occurs to the face of the furan opposite that of metal coordination. Upon rearrangement, the acetyl substituent is forced *syn* to the rhenium, despite a steric repulsion between this group and the metal fragment, as suggested by MM3 calculations. (All MM3 computations were performed with the constraint that the dihapto-coordinated double bond should remain orthogonal to the carbonyl ligand.)

In contrast, the initial addition of the aldehyde is reversible (vide supra), and definition of the configuration at C2 is believed to proceed under thermodynamic control (Scheme 3). Specifically, addition to one prochiral face of the aldehyde will give the less stable *cis*-disubstituted dihydrofuran product after rearrangement, while addition to the other face will result in the preferred *trans* stereochemistry.

On the basis of MM3 calculations, we believe the aforementioned steric repulsion between the pendant acetyl moiety and the metal fragment causes the dihydrofuran ring to preferentially adopt the conformation shown in Figure 2, with the acetyl group occupying an equatorial position (isomer **B**). The observation that **4A** is formed in preference to **4B**, while **5B**, **6B**, and **7B** are favored over their respective **A** isomers suggests that steric repulsion between the acyl moiety at C3 and the *tert*-butylisonitrile ligand is a major factor in this selectivity. Because the acetyl group common to **5**−**7** is

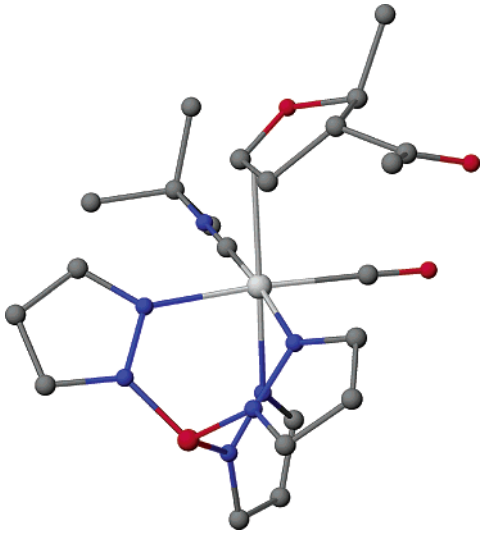


Figure 2. MM3 minimized model of **5B**.

larger than the formyl group in **3**, the former exerts a greater steric influence when placed near the *tert*-butylisonitrile ligand. This interaction will increase the tendency of **5**−**7A** to revert to starting material (**2A**), which can isomerize to **2B**, even at −40 °C. Therefore, equilibration between **A** and **B** isomers more heavily favors **B** when there is an acetyl group at C3. Thus, the *minor isomer* of the 2-methylfuran complex **2** gives the major isomer of the addition products **5**−**7**, as is allowed by the Curtin−Hammett principle. Although the nature of the substituent of the initial aldehyde obviously exerts some control over the initially observed product ratios, it is unclear what subtle factors play into this differentiation.

The conversion of **B** to **C** (Scheme 1), with a half-life of approximately 20−30 h (20 °C), is an example of intrafacial isomerization, similar to other processes studied for {TpRe(CO)(L)} systems (Scheme 2).[9] The thermodynamic preference for products of type **C** over type **B** is likely the result of steric interactions arising from the acyl functionality being forced *syn* to the metal (vide supra).

Nevertheless, products of type **D** are not observed. Assuming that conversion of **A** to **D** occurs at a rate similar to that for **B** to **C**, the complete absence of **D** suggests that form **A** is more thermodynamically stable than **D** for every case investigated. Calculations at the MM3 level show that **D** prefers a conformation with the acyl group in an equatorial position of the dihydrofuran ring (Figure 3). Although this conformation minimizes steric interaction between the substituent at C2 and the metal, it forces H(C3) into an axial position, placing it at odds with the pyrazole *trans* to the isonitrile.

The proposed mechanism for the formation of product **3** is also shown in Scheme 3. The distinguishing feature of this mechanistic pathway is the addition of a second equivalent of aldehyde to structure **I**, resulting in the formation of **V**. Concentration of aldehyde affects the rate of addition, but not the rearrangement to form **II**. Thus at high concentration of aldehyde, the formation of species such as **3** will be maximized. Judging from the reaction of acetaldehyde and the furan complex (**1**), the **II** versus **V** reaction manifold is also dependent on reaction time. The available data suggest that the

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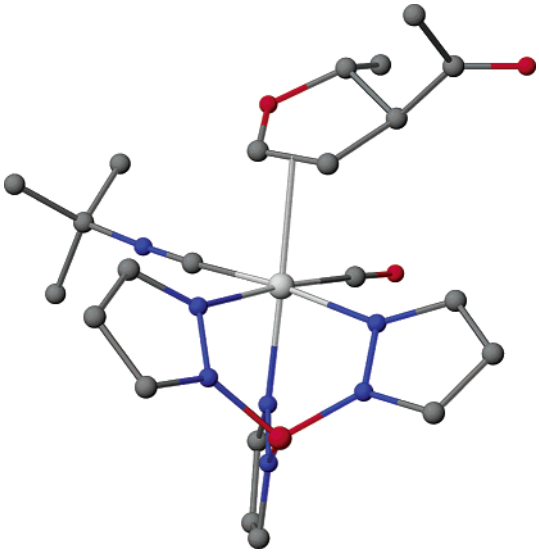
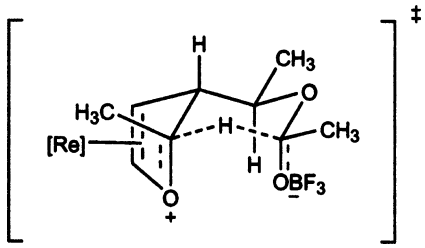


Figure 3. MM3 minimized model of hypothetical complex **3D**.

double addition of aldehyde is faster than rearrangement, but that this reaction is reversible. Over a period of a week, the dioxine **3** gives way to the formyldihydrofuran rearrangement product **4**. In the case of the 2-methylfuran analogue **2**, only acetyldihydrofuran products were formed (**5**−**7**). This contrasting reactivity suggests that intermediate **I** is more prone to ring-open to form **II** where Y = Me (cf. Y = H). This is likely a reflection of the increased stability for the carbonyl of a ketone compared to that of an aldehyde in **II**.

It is unclear exactly how the dialkylated dihydrofuran **8** (Figure 1) is formed, but we propose a sequence similar to that shown in Scheme 3. The crucial step in this process is a hydride transfer from the acetal to C2 of the 3H-furanium intermediate **V**:



This process is akin to the hydride transfer in the Meerwein−Ponndorf−Verley−Oppenauer (MPVO) reaction.[18,19] Coupling data indicate a *trans* stereochemistry consistent with the hydride being transferred to the ring face *anti* to that of rhenium coordination. It is worth noting that the formation of **8** is optimized by carrying out the reaction under high concentrations of aldehyde. As seen in Scheme 3, such action increases the concentration of intermediate **V** relative to that of **II**, assuming that the interconversion between intermediates **I**−**V** is facile.

Unfortunately, several attempts to decomplex the dihydrofuran of **6** by oxidation or by heating yielded TpRe(*t*-BuNC)$(CO)_2$ and unidentifiable organic products. Similar frustration of decomplexation attempts by decarbonylation of the dihydrofuran ligand is also observed for carbonyl-containing dihydrofuran complexes of the {TpRe(CO)(PMe_3)} system.[20] While the mechanism by which this proceeds is obfuscated by the difficulty of characterizing the remnants of the dihydrofuran ligands, we believe that the electron-rich metal facilitates what effectively is the reverse of a carbonyl insertion, which should leave the dihydrofuran as a free ligand with a phenyl substituent at C3. However, the formation of 2-methyl-3-phenyl-2,3-dihydrofuran was not detected.

Conclusion

The electron-rich nature of the {TpRe(CO)(*t*-BuNC)} fragment enables addition of Lewis acid-activated aldehydes to dihapto-coordinated furans. Incorporation of aldehydes into these complexes constitutes a facile method of generating a series of functionalized dihydrofurans. Although mixtures of products result, some of which isomerize, they are easily separated and characterized. Decomplexation attempts were hindered by decarbonylation of the dihydrofuran resulting from benzaldehyde addition. Hypothetically, alteration of the problematic carbonyl moiety could circumvent these difficulties, but the lengthy procedure required to obtain starting material (**1**) [7] has prompted us to explore other η^2-furan complexes for similar reactivity.

Experimental Section

General Procedures. ^{1}H and ^{13}C NMR spectra were recorded on a Varian Inova-300, a Varian Inova-500, or a GN-300 (General Electric) spectrometer. Chemical shifts are reported relative to TMS (tetramethylsilane) using residual protonated solvent (acetonitrile-d_2 = δ 1.94) as an internal standard. Electrochemical experiments were performed under nitrogen using a PAR model 362 potentiostat driven by a PAR model 175 universal programmer. Cyclic voltammograms were recorded (Kipp & Zonen BD90 XY recorder) in a standard three-electrode cell scanning from +1.7 to −1.7 V utilizing a glassy carbon electrode. All potentials are reported versus NHE and were determined in CH_3CN (∼0.5 M TBAH) at a scan rate of 100 mV/s using cobaltocenium hexafluorophosphate ($E_{1/2}$ = −0.78 V) in situ as a calibration standard. Infrared spectra were recorded on a MIDAC Prospect (Model PRS) spectrometer as a glaze using a horizontal attenuated total reflectance accessory (Pike Industries). Elemental analyses were obtained on a Perkin-Elmer PE-2400 Series II CHN analyzer.

Solvents and Reagents. All solvents were purified via distillation under nitrogen or passage through an activated alumina column prior to use.[21] All reagents were used as received from Aldrich, except for **1** and **2**, which were synthesized by literature methods.[7]

TpRe(CO)(*t*-BuNC)(7,8-η^2-3,5-dimethyl-2,4,9-trioxabicyclo[4.2.0]non-7-ene) (3A). In a dry glovebox, solutions of TpRe(CO)(*t*-BuNC)(4,5-η^2-furan) (0.019 g, 0.033 mmol) with acetaldehyde (0.030 g, 0.681 mmol) in 1.0 g of CH_3CN and with $BF_3{\cdot}OEt_2$ (0.011 g, 0.075 mmol) in 0.5 g of CH_3CN each were cooled to −40 °C. The $BF_3{\cdot}OEt_2$ solution was added to the solution of the furan complex and acetaldehyde, and the solution kept at −40 °C for 120 h. The reaction mixture was quenched with 100 mg of cold (−40 °C) pyridine. To this was

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added 20 mL of CH_2Cl_2, and the mixture was filtered through a 3 cm silica plug. The solvent was removed under reduced pressure. The resulting brown residue was purified via thin-layer chromatography using 1:1 hexanes−EtOAc as eluent. The desired fractions were collected and reduced to dryness by rotary evaporation. The resulting oil was dried in vacuo. ^{1}H NMR (CD_3CN, 22 °C):δ 8.31 (d, 1H, J = 2.0 Hz, TpH), 7.94 (d, 1H, J = 2.0 Hz, TpH), 7.80 (dd, 1H, J = 2.2, 1.0 Hz, TpH), 7.74 (dd, 1H, J = 2.2, 0.8 Hz, TpH), 7.72 (dd, 1H, J = 2.2, 0.8 Hz, TpH), 7.46 (d, 1H, J = 2.0 Hz, TpH), 6.33 (t, 1H, J = 2.0 Hz, TpH), 6.28 (t, 1H, J = 2.0 Hz, TpH), 6.19 (t, 1H, J = 2.0 Hz, TpH), 5.54 (d, 1H, J = 5.7 Hz, H(C1)), 5.06 (dd, 1H, J = 4.5, 1.0 Hz, H(C8)), 4.96 (q, 1H, J = 5.1 Hz, H(C3)), 3.69 (dq, 1H, J = 10.3, 6.1 Hz, H(C5)), 2.97 (d, 1H, J = 4.8 Hz, H(C7)), 2.31 (ddd, 1H, J = 10.3, 5.7, 1.0 Hz, H(C6)), 1.51 (s, 9H, *t*-BuNC CH_3), 1.47 (d, 3H, J = 6.2 Hz, C5 methyl), 1.25 (d, 3H, J = 5.1 Hz, C3 methyl). ^{13}C NMR (CD_3CN, 22 °C): δ 145.7, 144.4, 141.1, 137.0, 136.2, 107.5, 107.1, 106.5 (each a Tp), 100.2 (C8), 93.6 (C3), 79.6 (C5), 50.1 (C6), 45.5 (C7), 31.7 (*t*-BuNC CH_3), 21.1 (C3 methyl), 21.0 (C5 methyl).

Partial Characterization of Minor Isomer (3B) (isolated from 1:7 mixture): ^{1}H NMR (CD_3CN, 22 °C): δ 8.24 (d, 1H, J = 2.0 Hz, TpH), 8.00 (d, 1H, J = 2.0 Hz, TpH), 7.77 (dd, 1H, J = 2.6, 0.6 Hz, TpH), 7.71 (dd, 1H, J = 2.5, 0.6 Hz, TpH), 7.70 (dd, 1H, J = 2.5, 0.4 Hz, TpH), 7.50 (d, 1H, J = 2.2 Hz, TpH), 6.51 (dd, J = 4.7, 0.8 Hz, H(C8), 6.34 (t, 1H, J = 2.2 Hz, TpH), 6.28 (t, 1H, J = 2.2 Hz, TpH), 6.22 (t, 1H, J = 2.2 Hz, TpH), 5.48 (d, 1H, J = 5.5 Hz, H(C1)), 4.96 (q, 1H, J = 5.1 Hz, H(C3)), 3.53 (dq, 1H, J = 10.0, 6.1 Hz, H(C5)), 2.54 (ddd, 1H, J = 10.0, 5.6, 0.8 Hz, H(C6)), 1.75 (d, 1H, J = 4.8 Hz, H(C7)), 1.39 (s, 9H, *t*-BuNC CH_3), 1.26 (d, 3H, J = 5.1 Hz, C3 methyl), 1.20 (d, 3H, J = 5.1 Hz, C5 methyl). ^{13}C NMR (CD_3CN, 22 °C): δ 101.1 (C8), 67.9 (C6), 49.7 (C7).

TpRe(CO)(*t*-BuNC)(4,5-η^2-*trans*-3-formyl-2-methyl-2,3-dihydrofuran) (4). In a dry glovebox, solutions of TpRe(CO)(*t*-BuNC)(4,5-η^2-furan) (0.019 g, 0.033 mmol) with acetaldehyde (0.030 g, 0.681 mmol) in 1.0 g of CH_3CN and with $BF_3{\cdot}OEt_2$ (0.011 g, 0.075 mmol) in 0.5 g of CH_3CN each were cooled to −40 °C. The $BF_3{\cdot}OEt_2$ solution was added to the solution of the furan complex and acetaldehyde, and the solution kept at −40 °C for 120 h. The reaction mixture was quenched with 100 mg of cold (−40 °C) pyridine. To this was added 20 mL of CH_2Cl_2, and the mixture was filtered through a 3 cm silica plug. The solvent was removed under reduced pressure. The resulting brown residue was purified via thin-layer chromatography using 1:1 hexanes−EtOAc as eluent. The desired fractions were collected and reduced to dryness by rotary evaporation. The resulting oil was dried in vacuo. ^{1}H NMR (CD_3CN, 22 °C): **4A**: δ 9.86 (d, J = 4.0 Hz, aldehydic H), 8.25 (d, 1H, J = 2.0 Hz, TpH), 7.97 (d, 1H, J = 2.0 Hz, TpH), 7.82 (dd, 1H, J = 2.4, 0.8 Hz, TpH), 7.76 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.73 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.32 (d, 1H, J = 2.0 Hz, TpH), 6.33 (t, 1H, J = 2.2 Hz, TpH), 6.29 (t, 1H, J = 2.2 Hz, TpH), 6.18 (t, 1H, J = 2.3 Hz, TpH), 5.00 (d, 1H, J = 4.5 Hz, H(C5)), 4.55 (dq, 1H, J = 9.3, 6.1 Hz, H(C2)), 3.72 (ddd, 1H, J = 9.3, 5.1, 4.1 Hz, H(C3)), 3.52 (dd, 1H, J = 4.8, 4.8 Hz, H(C4)), 1.28 (d, 1H, J = 6.1 Hz, C2 methyl). **4B**: (partial) δ 10.28 (d, J = 3.7 Hz, aldehydic H), 6.58 (d, 1H, J = 4.4 Hz, H(C5)), 4.33 (dq, 1H, J = 10.3, 6.2 Hz, H(C2)).

TpRe(CO)(*t*-BuNC)(4,5-η^2-*trans*-3-acetyl-2-methyl-2,3-dihydrofuran) (5A−C). In a dry glovebox, TpRe(CO)(*t*-BuNC)(4,5-η^2-2-methylfuran) (0.205 g, 0.346 mmol) in 2.5 g of CH_3CN, acetaldehyde (0.067 g, 1.68 mmol) in 1.3 g of CH_3CN, and $BF_3{\cdot}OEt_2$ (0.242 g, 1.53 mmol) in 1.2 g of CH_3CN were each cooled to −40 °C. The $BF_3{\cdot}OEt_2$ solution was added to the acetaldehyde solution, this combined solution was added to the solution of the 2-methylfuran complex, and the solution was kept at −40 °C for 24 h. The reaction mixture was quenched with ∼300 mg of cold (−40 °C) pyridine. The mixture was diluted with 20 mL of CH_2Cl_2 and then filtered through a 3 cm silica plug. The solvent was removed under reduced pressure. The resulting brown residue was purified via column chromatography using 9:1 hexanes−EtOAc as eluent. The desired fractions were identified by IR spectroscopy and consolidated, and the solvent was removed by rotary evaporation. The orange residue was dissolved in a minimal volume of MeOH and precipitated with 75 mL of water. The resulting orange precipitate was filtered on a fine-porosity frit and dried in vacuo. Yield: 54 mg, 24.5%, in a 5:2 ratio of **5B**:**5A**. ^{1}H NMR (CD_3CN, 22 °C): **5A**: δ 8.24 (d, 1H, J = 2.2 Hz, TpH), 7.94 (d, 1H, J = 2.2 Hz, TpH), 7.80 (dd, 1H, J = 2.4, 0.9 Hz, TpH), 7.73 (dd, 1H, J = 2.4, 0.9 Hz, TpH), 7.72 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.40 (d, 1H, J = 2.0 Hz, TpH), 6.31 (t, 1H, J = 2.0 Hz, TpH), 6.26 (t, 1H, J = 2.0 Hz, TpH), 6.19 (t, 1H, J = 2.2 Hz, TpH), 4.87 (dd, 1H, J = 4.8, 0.6 Hz, H(C5)), 4.47 (dq, 1H, J = 10.5, 5.9 Hz, H(C2)), 3.98 (dd, 1H, J = 10.5, 4.0 Hz, H(C3)), 3.72 (t, 1H, J = 4.8 Hz, H(C4)), 2.48 (s, 3H, acetyl), 1.34 (s, 9H, *t*-BuNC), 1.23 (d, 3H, J = 5.9 Hz, C2-methyl). ^{13}C NMR (CD_3CN, 22 °C): δ 100.0 (C5), 73.7 (C2), 68.4 (C3), 44.7 (C4), buried ∼31.3 (acetyl CH_3), 31.3 (*t*-BuNC CH_3), 18.5 (C2-methyl CH_3). **5B**: δ 8.04 (d, 1H, J = 2.0 Hz, TpH), 7.94 (d, 1H, J = 2.0 Hz, TpH), 7.74 (dd, 1H, J = 2.2 Hz, TpH), 7.73 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.66 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.52 (d, 1H, J = 2.0 Hz, TpH), 6.46 (dd, 1H, J = 4.8, 0.6 Hz, H(C5)), 6.27 (t, 1H, J = 2.2 Hz, TpH), 6.26 (t, 1H, J = 2.0 Hz, TpH), 6.23 (t, 1H, J = 2.4 Hz, TpH), 4.37 (dq, 1H, J = 11.0, 6.0 Hz, H(C2)), 3.77 (dd, 1H, J = 10.7, 4.6 Hz, H(C3)), 2.48 (t, 1H, J = 4.8 Hz, H(C4)), 2.17 (s, 3H, acetyl), 1.46 (s, 9H, *t*-BuNC), 1.23 (d, 3H, J = 6.1 Hz, C2-methyl). ^{13}C NMR (CD_3CN, 22 °C): δ 99.9 (C5), 74.0 (C2), 67.6 (C3), 44.3 (C4), 32.1 (acetyl CH_3), 31.8 (*t*-BuNC CH_3), 19.3 (C2-methyl CH_3). After 5 days, an NMR solution of **5B** converted to a 5.2:1 mixture of **5C** and **5B**, respectively. **5C**: δ 8.34 (d, 1H, J = 2.2 Hz, TpH), 7.96 (d, 1H, J = 2.0 Hz, TpH), 7.79 (dd, 1H, J = 2.4, 0.9 Hz, TpH), 7.74 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.70 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.43 (d, 1H, J = 2.0 Hz, TpH), 6.32 (t, 1H, J = 2.4 Hz, TpH), 6.28 (t, 1H, J = 2.2 Hz, Tp H), 6.17 (t, 1H, J = 2.2 Hz, TpH), 5.40 (dd, 1H, J = 4.8, 0.9 Hz, H(C5)), 4.75 (dq, 1H, J = 11.0, 6.2 Hz, H(C2)), 3.89 (dd, 1H, J = 4.8, 1.9 Hz, H(C4)), 3.70 (dt, 1H, J = 9.9, 1.4 Hz, H(C3)), 2.34 (s, 3H, acetyl), 1.47 (s, 9H, *t*-BuNC), 1.38 (d, 3H, J = 6.4 Hz, C2-methyl). ^{13}C NMR (CD_3CN, 22 °C): δ 101.5 (C5), 85.6 (C2), 68.9 (C3), 49.7 (C4), 31.6 (*t*-BuNC CH_3), 29.4 (acetyl CH_3), 18.8 (C2-methyl CH_3). Product mixture: ^{13}C NMR (CD_3CN, 22 °C): δ 147.5, 146.1, 145.7, 145.6, 144.9, 144.2, 142.0, 141.3, 141.3, 137.0, 136.9, 136.8, 136.3, 136.3, 136.2, 136.1, 136.0, 107.5, 107.4, 107.3, 107.2, 107.1, 107.0, 106.9, 106.7, 106.7 (each a Tp). CV: $E_{p,a}$ = 0.57 V. IR (glaze, HATR): ν_{CN} = 2105 cm^{-1}, $\nu_{C\equiv O}$ = 1841 cm^{-1}, $\nu_{C=O}$ = 1706 cm^{-1}. Anal. Calcd for $ReC_{22}H_{29}N_7O_3B$: C, 41.51; H, 4.59; N, 15.40. Found: C, 41.47; H, 4.23; N, 15.59.

TpRe(CO)(*t*-BuNC)(4,5-η^2-*trans*-3-phenyl-2-methyl-2,3-dihydrofuran)] (6). In a dry glovebox, solutions of TpRe(CO)(*t*-BuNC)(4,5-η^2-2-methylfuran) (0.100 g, 0.169 mmol) with benzaldehyde (0.353 g, 3.33 mmol) in 2.0 g of CH_3CN and with $BF_3{\cdot}OEt_2$ (0.020 g, 0.15 mmol) in 2.0 g of CH_3CN each were cooled to −40 °C. The $BF_3{\cdot}OEt_2$ solution was added to the solution of the 2-methylfuran complex and benzaldehyde, then kept at −40 °C for 24 h. The reaction mixture was quenched with 100 mg of cold (−40 °C) pyridine. To this was added 20 mL of CH_2Cl_2, and the mixture was filtered through a 3 cm silica plug. The solvent was removed under reduced pressure. The resulting brown residue was purified via column chromatography using 7:1 hexanes−EtOAc as eluent. The desired fractions were collected and reduced to dryness by rotary evaporation. The resulting oil was dried in vacuo. Yield: 43.5 mg, 37%, in a 17:2 ratio of **6B** to **6A**. IR (glaze, HATR): ν_{CN} = 2103 cm^{-1}, $\nu_{C\equiv O}$ = 1849 cm^{-1}, $\nu_{C=O}$ = 1705 cm^{-1} (acetyl). ^{1}H NMR (CD_3CN, 22 °C): **6A**: δ 8.27 (d, 1H, J = 2.2 Hz, TpH), 7.92 (d, 1H, J = 2.2 Hz, TpH), 7.89 (d, 1H, J = 2.2 Hz, TpH), 7.80 (d, 1H, J = 2.2 Hz, TpH), 7.46 (d, 1H, J = 2.2 Hz, TpH), 7.43−7.26 (m, 5H, phenyl H), 6.21 (t, 1H, J = 2.2 Hz, TpH), 5.43 (d, 1H, J = 10.8 Hz, H(C2)), 5.11 (d, 1H, J = 4.4 Hz,

H(C5)), 4.39 (dd, 1H, J = 10.8, 4.0 Hz, H(C3)), 3.84 (t, 1H, J = 4.8 Hz, H(C4)), 2.47 (s, 3H, acetyl CH_3), 1.36 (s, 9H, *t*-BuNC CH_3). ^{13}C NMR (CD_3CN, 22 °C): δ 99.8 (C5), 79.1 (C2), 69.5 (C3), 44.4 (C4), 32.0 (acetyl CH_3), 31.3 (*t*-BuNC CH_3). **6B**: δ 8.10 (d, 1H, J = 2.2 Hz, TpH), 7.99 (d, 1H, J = 2.2 Hz, TpH), 7.76 (d, 1H, J = 2.2 Hz, TpH), 7.75 (d, 1H, J = 2.2 Hz, TpH), 7.68 (d, 1H, J = 2.2 Hz, TpH), 7.56 (d, 1H, J = 2.2 Hz, TpH), 7.43−7.28 (m, 5H, phenyl H), 6.65 (d, 1H, J = 4.8 Hz, H(C5)), 6.281 (t, 1H, J = 2.2 Hz, TpH), 6.279 (t, 1H, J = 2.2 Hz, TpH), 6.25 (t, 1H, J = 2.2 Hz, TpH), 5.32 (d, 1H, J = 11.0 Hz, H(C2)), 4.22 (dd, 1H, J = 11.0, 4.7 Hz, H(C3)), 2.60 (t, 1H, J = 4.8 Hz, H(C4)), 2.08 (s, 3H, acetyl CH_3), 1.45 (s, 9H, *t*-BuNC CH_3). ^{13}C NMR (CD_3CN, 22 °C): δ 209.5 (Re−CO), 159.6 (NC−Re), 99.3 (C5), 79.5 (C2), 68.6 (C3), 58.0 (*t*-Bu 4°), 44.0 (C4), 32.2 (acetyl CH_3), 31.7 (*t*-BuNC CH_3). After 5 days, an ambient solution of **6B** converted to a 1.5:1 equilibrium mixture of **6C** to **6B**, respectively. **6C**: δ 8.44 (d, 1H, J = 2.2 Hz, TpH), 7.97 (d, 1H, J = 2.2 Hz, TpH), 7.81 (d, 1H, J = 2.2 Hz, TpH), 7.70 (d, 1H, J = 2.2 Hz, TpH), 7.51 (d, 1H, J = 2.2 Hz, TpH), 7.48 (d, 1H, J = 2.2 Hz, TpH), 7.43−7.25 (m, 5H, phenyl H), 6.34 (t, 1H, J = 2.2 Hz, TpH), 6.29 (t, 1H, J = 2.2 Hz, TpH), 6.13 (t, 1H, J = 2.2 Hz, TpH), 5.77 (d, 1H, J = 10.5 Hz, H(C2)), 5.50 (dd, 1H, J = 5.0, 0.9 Hz, H(C5)), 4.10 (dt, 1H, J = 10.3, 1.5 Hz, H(C3)), 3.97 (dd, 1H, J = 5.0, 2.4 Hz, H(C4)), 2.36 (s, 3H, acetyl CH_3), 1.45 (s, 9H, *t*-BuNC CH_3). ^{13}C NMR (CD_3CN, 22 °C): δ 209.8 (Re−CO), 100.6 (C5), 91.7 (C2), 68.8 (C3), 49.3 (C4), 31.5 (*t*-BuNC CH_3), 29.9 (acetyl CH_3).

TpRe(CO)(*t*-BuNC)(4,5-η^2-*trans*-3-acetyl-2-(3-furyl)-2,3-dihydrofuran)] (7). In a dry glovebox, solutions of TpRe(CO)(*t*-BuNC)(4,5-η^2-2-methylfuran) (0.040 g, 0.068 mmol) with 3-furaldehyde (0.076 g, 0.791 mmol) in 2.0 g of CH_3CN and with $BF_3{\cdot}OEt_2$ (0.028 g, 0.19 mmol) in 0.5 g of CH_3CN each were cooled to −40 °C. The $BF_3{\cdot}OEt_2$ solution was added to the solution of the 2-methylfuran complex and 3-furaldehyde, then kept at −40 °C for 24 h. The reaction mixture was quenched with 100 mg of cold (−40 °C) pyridine. To this was added 20 mL of CH_2Cl_2, and the mixture was filtered through a 3 cm silica plug. The solvent was removed under reduced pressure. The resulting brown residue was purified via thin-layer chromatography using 1:1 hexanes−EtOAc as eluent. The desired fractions were collected and reduced to dryness by rotary evaporation. The resulting oil was dried in vacuo. ^{1}H NMR (CD_3CN, 22 °C): **7B**: δ 8.13 (d, 1H, J = 2.2 Hz, TpH), 7.97 (d, 1H, J = 2.0 Hz, TpH), 7.75 (dd, 1H, J = 2.2, 0.6 Hz, TpH), 7.74 (dd, 1H, J = 2.2, 0.6 Hz, TpH), 7.68 (dd, 1H, J = 2.4, 0.6 Hz, TpH), 7.57 (d, 1H, J = 2.2 Hz, TpH), 7.47 (d, 1H, J = 1.3 Hz, furyl H), 7.47 (s, 1H, furyl H), 6.54 (d, 1H, J = 4.6 Hz, H(C5)), 6.45 (t, 1H, J = 1.3 Hz, furyl H), 6.283 (t, 1H, J = 2.2 Hz, TpH), 6.275 (t, 1H, J = 2.2 Hz, TpH), 6.25 (t, 1H, J = 2.0 Hz, TpH), 5.21 (d, 1H, J = 11.2 Hz, H(C2)), 4.20 (dd, 1H, J = 11.2, 4.6 Hz, H(C3)), 2.59 (t, 1H, J = 4.6 Hz, H(C4)), 2.14 (s, 3H, acetyl CH_3), 1.46 (s, 9H, *t*-BuNC CH_3). ^{13}C NMR (CD_3CN, 22 °C): δ 72.3 (C2), 67.0 (C3), 43.9 (C4), 31.7 (*t*-BuNC CH_3). At 20 °C, **7B** isomerizes to a 1.2:1 mixture of **7C**:**7B**. **7C**: δ 8.33 (d, 1H, J = 2.0 Hz, TpH), 7.98 (d, 1H, J = 2.0 Hz, TpH), 7.79 (dd, 1H, J = 2.4, 0.9 Hz, TpH), 7.75 (dd, 1H, J = 2.4, 0.9 Hz, TpH), 7.71 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.57 (d, 1H, J = 1.3 Hz, furyl H), 7.52 (d, 1H, J = 2.2 Hz, TpH), 6.70 (d, 1H, J = 2.0 Hz, furyl H), 6.32 (t, 1H, J = 2.0 Hz, TpH), 6.30 (t, 1H, J = 2.2 Hz, TpH), 6.15 (t, 1H, J = 2.2 Hz, TpH), 5.57 (d, 1H, J = 10.8 Hz, H(C2)), 5.47 (d, 1H, J = 4.9 Hz, H(C5)), 4.08 (d, 1H, J = 9.5 Hz, H(C3)), 3.99 (t, 1H, J = 4.6 Hz, H(C4)), 2.29 (s, 3H, acetyl CH_3), 1.46 (s, 9H, *t*-BuNC CH_3).

TpRe(CO)(*t*-BuNC)(4,5-η^2-*trans*-3-(1-acetoxyethyl)-2-methyl-2,3-dihydrofuran) (8). 8 was isolated as an impurity in the synthesis of **5**. IR (glaze, HATR): ν_{CN} = 2099 cm^{-1}, $\nu_{C\equiv O}$ = 1840 cm^{-1}, $\nu_{C=O}$ = 1728 cm^{-1}. ^{1}H NMR (CD_3CN, 22 °C): δ 8.35 (dd, 1H, J = 1.7, 0.7 Hz, TpH), 7.96 (d, 1H, J = 2.2 Hz, TpH), 7.78 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.73 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.70 (dd, 1H, J = 2.4, 0.7 Hz, TpH), 7.38 (d, 1H, 2.4 Hz, TpH), 6.32 (t, 1H, J = 2.0 Hz, TpH), 6.28 (t, 1H, J = 2.2 Hz, TpH), 6.17 (t, 1H, J = 2.2 Hz, TpH), 5.34 (dd, 1H, J = 4.6, 0.8 Hz, H(C5)), 5.10 (dq, 1H, J = 6.2, 6.2 Hz, acetoxyethyl methine), 4.46 (dq, 1H, J = 9.2, 6.2 Hz, H(C2)), 3.55 (dd, 1H, J = 4.6, 1.3 Hz, H(C4)), 3.06 (dddd, 1H, J = 9.4, 5.9, 1.4, 1.4 Hz, H(C3)), 2.07 (s, 3H, acetyl CH_3), 1.51 (s, 9H, *t*-BuNC CH_3), 1.39 (d, 3H, J = 6.4 Hz, C2 methyl), 1.37 (d, 3H, J = 6.4 Hz, acetoxyethyl CH_3). ^{13}C NMR (CD_3CN, 22 °C): δ 146.1 (Tp), 144.8 (Tp), 141.8 (Tp), 136.9 (Tp), 136.2 (2 isochronous Tp peaks), 107.4 (Tp), 107.1 (Tp), 106.7 (Tp), 102.2 (C5), 84.4 (C2), 74.4 (acetoxyethyl CH), 59.8 (C3), 50.3 (C4), 31.9 (*t*-BuNC CH_3), 21.7 (acetyl CH_3), 19.5 (CH_3), 18.1 (CH_3). CV: $E_{p,c}$ = 0.45 V, $E_{p,a}$ = 0.57 V.

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